Energy Policy Analysis Towards Clean Energy Transitions in Mexico

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Dedicated to

My beloved parents, Alfredo Castrejon Roman and Rosalinda Campos Pineda, who have always supported my education and personal development.

Abstract

Energy transitions from fossil fuel-based to cleaner energy systems are required to fulfil international commitments on climate change mitigation. To fulfil international climate agreements, Mexico has established ambitious national GHG emissions reduction targets (22% by 2030 from business as usual and 50% from 2000 levels), expecting the electricity sector to be the largest contributor to these emission reductions. However, the targets in clean energy may represent a great challenge for the Mexican energy system as it has been experiencing a period of deep structural changes over time (e.g. institutional restructuring derived from the intense energy reform declared by the Mexican government in December 2013). By considering the effects of historical structural transformations within energy systems and given the right mix of policy instruments, Mexico has the potential to advance clean energy development and therefore diversify its energy mix and significantly reduce its GHG emissions.

Policymakers design and implement policy strategies to solve problems based on the analysis and interpretation of available information. Energy policymaking in Mexico, as in other developing countries, depends largely on limited available information. Traditional policymaking approaches have a deterministic, predictive, and reactive perspective on future issues. However, performance trends of energy systems could be different in the future due to incorrectly predicted changes in economic, technological, social, political, and environmental conditions. The decision-making process becomes even more challenging as the number of variables and decision makers increases. Policymaking within the energy sector, especially in developing countries, is characterised by many stakeholders, information is not always available or imprecise, and complex dynamic interactions among policy, economy, society, environment, and technology that may affect the intended outcomes of policy strategies, and therefore the behaviour of energy systems. These conditions make policymaking for energy transitions to be considered as a problem under deep uncertainty. The application of traditional policy-making approaches to complex, evolving issues (e.g. energy transitions) is limited. Thus, energy policymaking in the context of deep uncertainty calls for an alternative paradigm aimed at connecting short-term decisions with long-term objectives by using models as exploratory tools instead of a prediction tool. The analysis of policy-relevant information using an exploratory approach may help policymakers to identify and select robust policy alternatives towards clean energy transitions.

The aim of this thesis is to explore the effects of robust energy policy mixes towards clean energy transitions in Mexico. To achieve this aim, a new integrated method has been developed and implemented to support policymakers with the design of robust energy policy alternatives. A policy alternative is considered robust if the system of interest (e.g. electricity system) performs satisfactorily under a broad range of plausible futures. The integrated method is developed by combining quantitative and qualitative approaches (i.e. mixed method), integrating sustainability and energy transitions concepts, analytical tools used by robustness-based approaches, quantitative simulation modelling techniques, and exploratory modelling and analysis. Implementing the proposed method encompasses a series of interdependent analytical processes, including policy problem definition, deep uncertainty characterisation, exploratory modelling and analysis, and (the development of) policy recommendations. As policymaking for energy transitions under deep uncertainty is

conceptualised as a learning process, learning may be facilitated by an iterative approach revealing stakeholders' preferences and possible trade-offs among alternative problem framings and solutions. Thus, the stepwise implementation of these analytical processes leads to the development and application of complementary analytical tools to improve the applicability of the integrated method developed.

Following the iterative learning approach of the integrated method, a new theoretical framework has been developed for qualitatively describing the evolution of energy systems at a national level. By integrating concepts from sustainability transitions, policy mixes for energy transitions, and interactive governance literature, this thesis describes the historical evolution of the Mexican electricity sector in general and the role that clean energy technologies have played in particular. In addition, relevant drivers and barriers towards a clean energy transition in Mexico are identified and discussed. Technological learning has been identified as one of these key drivers. Thus, a new integrative technological learning model has been developed to explore the effects of learning processes on technological-based cost developments. The influence of different learning curve approaches is explored by choosing how key parameters and sources of learning are defined. In addition, a new definition of technological experience has been developed and presented in this thesis. This new definition accounts for diverse learning sub-processes (learning-by-doing, learning-by-using, and international experience spillovers) to estimate the total experience gained through technology deployment. By implementing the new definition of experience within the integrative technological learning model, historical and future technology cost developments have been explored for diverse clean energy technologies.

Insights from the development and application of these complementary analytical tools are used in this thesis as inputs to explore the plausible consequences of adopting different policy mixes towards a clean energy transition in Mexico. By implementing the integrated method developed within this study, multiple energy transition pathways are simulated and analysed using statistical and data-mining techniques. Based on the comprehensive analysis conducted here, the exploratory results show that although a broad range of policy mixes could be implemented, policymakers in Mexico could focus on economic signals and performance standards to meet medium and long-term policy objectives on greenhouse gas emissions reduction strategies (i.e. clean energy development, energy efficiency improvement). Thus, this thesis highlights the relevance of applying model-based policy analysis with a robust approach to help policymakers improve the policy exploration process by identifying the consequences of implementing different policy alternatives towards energy transitions under deep uncertainty conditions.

Declaration

This is to certify that:

i. This thesis comprises only my original work towards the PhD except where referred.
ii. Due acknowledgement has been made in the text to all other material used.
iii. The thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies, and appendices.

_____

Signed: Omar Castrejon Campos

Date: 03 August 2022

Preface

This is a thesis with publications. It includes six publications reproduced in their entirely. Chapters 2-5 are author-accepted versions of manuscripts according to the University of Melbourne guidelines. The corresponding published journal papers are included as Appendices.

This thesis includes the following peer-reviewed published and submitted journal papers and datasets for which the candidate is the primary author:

1. Castrejon-Campos, O, Aye, L & Hui, FKP 2020, 'Making policy mixes more robust: An integrative and interdisciplinary approach for clean energy transitions', *Energy Research & Social Science*, vol. 64, article no. 101425, <https://doi.org/10.1016/j.erss.2020.101425>.
2. Castrejon-Campos, O, Aye, L & Hui, FKP 2022, 'Competition, coordination, or institutional change? A multi-perspective analysis of historical electricity transitions in Mexico', *Energy Research & Social Science*, vol. 84, article no. 102362, <https://doi.org/10.1016/j.erss.2021.102362>.
3. Castrejon-Campos, O 2022, 'Evolution of clean energy technologies in Mexico: A multi-perspective analysis', *Energy for Sustainable Development*, vol. 67, pp. 29–53, <https://doi.org/10.1016/j.esd.2022.01.003>.
4. Castrejon-Campos, O, Aye, L & Hui, FKP 2022, 'Effects of learning curve models on onshore wind and solar PV cost developments in the USA', *Renewable and Sustainable Energy Reviews*, vol. 160, article no. 112278, <https://doi.org/10.1016/j.rser.2022.112278>.
5. Castrejon-Campos, O, Aye, L & Hui, FKP 2022, 'Dataset on effects of learning curve models on onshore wind and solar PV cost developments in the USA (Version 2)', Mendeley Data, V2, <https://doi.org/10.17632/82NFWVCGDZ.2>.
6. Castrejon-Campos, O, Aye, L, Hui, FKP & Vaz-Serra, P 2022, 'Economic and environmental impacts of public investment in clean energy RD&D', *Energy Policy*, vol. 168, article no. 113134, < https://doi.org/10.1016/j.enpol.2022.113134>.
7. Castrejon-Campos, O, Aye, L, Hui, FKP & Vaz-Serra, P (*Submitted on 24th March 2022*), 'Robust policy mixes for clean energy transitions in developing countries: An exploratory analysis for Mexico', Nature *Energy*.

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Chapter 1

Introduction

1.1 Introduction

As individuals, every day decide around our lives that may have positive or negative impacts in the future (e.g. what professional path to choose, where to live, whom to marry). Decision-making for the future depends on anticipating potential effects of our decisions. However, the decision-making process becomes more challenging as the number of variables to be considered increases, hindering our ability to think about the combinatorics of plausible consequences of different choices (Marchau et al. 2019). Decision-making in the public sector (e.g. infrastructure expansion planning, pandemic management strategies, strategic planning for energy transitions) is characterised by the interaction of multiple stakeholders, sectors, and government levels with different (sometimes contradictory) priorities, beliefs, and values. Based on the analysis and interpretation of available information, policymakers design and implement policy strategies to solve practical problems that both the society and the government consider paramount at the point of time (Tamayo Sáez 1997). However, the task of identifying suitable policy strategies turns challenging if conditions throughout time change rapidly and stakeholders involved in the policymaking process target different intended outcomes. Implementing a short-term policy strategy chosen from a range of options may impact in different ways the long-term performance of a system. Thus, the application of analytic methods for decision support are needed for investigating the potential effects of implementing alternative policy strategies.

The aim of policy-decision support methods is to produce and analyse information relevant to the parties involved in the policymaking process (i.e. *policy-relevant information*) regarding the consequences of adopting different policy instruments. Policy analysis supports policymakers with this process by identifying possible policy alternatives, relevant uncertainties, stakeholders' preferences, and outcomes of interest (Walker 2000). By using models, policy-relevant information not easily apparent for policymakers can be analysed to improve the policymaking process. Model-based policy analysis is an approach that can be applied to generate and analyse policy-relevant information by systematically exploring the effect of policy alternatives on different contexts and, therefore, the degree to which policy instruments can aid to meet long-term policy objectives.

Traditional policymaking approaches have a deterministic, predictive, and reactive perspective to future issues (Moallemi & Malekpour 2018). When trying to foresee the future using traditional prediction-focused policy analysis (known in the literature as *predict-the-act* paradigm), three key conditions must be considered: (1) the model(s) that state the relationships among key elements that shape the future; (2) the likelihood of occurrence (i.e. probability distributions) of key variables in the model(s); and (3) the desirability of outcomes of interest. However, deep uncertainty emerges when decision makers and analysts, due to different priorities, preferences, or knowledge, cannot agree on or do not know these conditions (Lempert, Popper & Bankes 2003). In the context of policymaking, uncertainty refers to the gap between available knowledge and the knowledge policymakers would need to select or design the 'best' policy strategy (Marchau et al. 2019).

Policymaking within the energy sector is characterised by many stakeholders, with diverse priorities, preferences, beliefs, and worldviews; information is not always available or imprecise; complex dynamic interactions among policy, economy, society, environment, and

technology; and external forces (e.g. fuel prices fluctuation) that may affect the intended outcomes of policy strategies, and therefore the performance of energy systems. These conditions make energy policymaking to be considered as a problem under deep uncertainty. Energy policymaking in the context of deep uncertainty calls for an alternative paradigm aimed at connecting short-term decisions with long-term objectives by using models as exploratory tools (i.e. as an engine for generating and examining plausible futures) instead of a prediction tool (Marchau et al. 2019).

Decision making under deep uncertainty (DMUDU) approaches, also called robustness-based approaches, aims at reducing the vulnerability of policies or strategies to uncertain future developments by using exploratory modelling (Marchau et al. 2019). Exploratory modelling is an analytical tool to explore a variety of methodological, structural, and parametric uncertainties based on computational experiments (Bankes 1993). A computational experiment is a single simulation run based on a specific model structure and a given parametrisation of that structure. By simulating many times, exploratory modelling reveals how the system would behave if the multiple hypotheses about the structure and its parametrisation were correct. Analysts then use statistical methods and visualisation tools of the resulting large outputs of simulation runs to help policymakers identify under what conditions the policy strategies meet and miss their goals. This information supports policymakers in identifying, evaluate, and choose robust policies (Marchau et al. 2019). A policy is assumed to be robust if the outcomes of interest perform "satisfactorily" under a broad range of plausible futures. Policy analysis with a robustness-based approach can be used as a systematic process for analysing the plausible consequences of implementing alternative policy strategies (Walker 2000).

Energy policymaking, especially in developing countries[1], depends largely on available information to policymakers. There is no agreement among scholars and decision makers about what the exact future of clean energy technologies will be and the impact on the energy sector. However, understanding how the energy sector would develop over time is of key importance for policymakers concerned about economic growth and national energy security, while accounting for environmental impacts (e.g. abatement of greenhouse gases emissions). Although energy policymaking must deal with operational, tactical, and strategic challenges due to an extensive range of deep uncertainties (Mutingi, Mbohwa & Kommula 2017), governments play a paramount role to support energy transitions to meet international, national, and/or regional goals (e.g. use of clean energy technologies for decarbonisation). Energy transitions have been conceived as complex, long-term, multi-actor, dynamic, co-evolutionary processes of structural change regarding energy production and consumption (Castrejon-Campos, Aye & Hui 2020). Although the need for and relevance of long-term

[1] In the context of this research, a developing country is defined as a country with a relatively low standard of living, undeveloped industrial base, and moderate to low Human Development Index (HDI). A developed country is defined as a sovereign country with a relatively mature economy, technologically advanced infrastructure, and a high HDI compared to other countries. Developing countries and developed countries are classified based on the basic economic country conditions according to the World Economic Situation and Prospects (WESP) country classifications produced by the United Nations Department of Economic and Social Affairs (UN DESA) for analytical purposes (United Nations 2022).

planning in policymaking for energy transitions is widely acknowledged (Moallemi & Malekpour 2018), the potential effects of technological, economic, social, environmental, and political developments are challenging to predict. Thus, the analysis of policy-relevant information using an exploratory thinking approach may help policymakers to identify and select robust policy alternatives towards clean energy transitions. Policy-relevant information can be obtained by using different research paradigms: quantitative, qualitative or a combination of both (mixed methods) (Johnson, Onwuegbuzie & Turner 2007).

The aim of this research is to develop and implement a new integrated method to explore the impact of robust energy policy strategies towards clean energy transitions. This method is shaped by combining quantitative and qualitative approaches (i.e. mixed method): integrating sustainability and energy transitions concepts, analytical tools used by robustness-based approaches, quantitative simulation modelling techniques, and exploratory modelling and analysis. The focus is on energy policy mixes to meet long-term targets on clean energy, energy efficiency, and greenhouse gas (GHG) emissions reduction for the electricity sector in Mexico.

1.2 Problem statement

Although energy policy strategies are usually designed and implemented based on current available information to policymakers, the performance of energy systems in the future may differ from the intended behaviour due to unpredicted social, economic, technological, and environmental developments. In addition, the identification of suitable policy strategies turns challenging when the valuation of various outcomes might be subject to contention due to different perspectives from the stakeholders involved in the policymaking. Considering different actors and multiple possible energy transitions pathways that can unfold in a range of plausible scenarios, policymaking for energy transitions is identified as a "wicked" problem (Rittel & Webber 1973). Wicked problems are characterised by the interaction of multiple decision makers and stakeholders with conflicting values and diverging viewpoints for solutions, making even the problem formulation contested (Kwakkel, Walker & Haasnoot 2016). Thus, wicked problems are not well-bounded problems with nonlinear dynamics and irreducible uncertainties (Marchau et al. 2019).

Traditional approaches to policymaking cannot adequately cope with the wickedness in policymaking for energy transitions. Traditional policymaking approaches aim to answer the question "What will happen in the future if specific policy strategies are implemented?". Under this approach, analysts and decision makers attempt to determine the 'best' predictive model and mitigate uncertainties by making diverse assumptions or relying on a limited number of scenarios (Moallemi & Malekpour 2018). This process, known as *predict-then-act*, seeks optimal policies. An optimal policy is defined to be one that reaches the best outcomes considering well-defined and narrowed future conditions based on a particular perspective. However, the application of traditional policymaking approaches to wicked problems (e.g. policymaking for energy transitions) is limited if different perspectives and deep uncertainties are considered.

Faced with deep uncertainty, decision may be made using the principle of satisfying rather than optimising (Trutnevyte 2016). *Robustness-based approaches* may be useful when policymakers are trying to find policy alternatives that perform "satisfactorily" across a range

of objectives and multiple plausible future conditions (Hallegatte et al. 2012). Robust policies aim to answer, "Knowing the fact that the future is uncertain, what available strategies are likely to perform well in multiple plausible futures?" (Tegeltija et al. 2018). Thus, a policy is assumed to be robust if the outcomes of interest perform satisfactorily under a broad range of plausible futures.

Although robustness approaches have been applied to policymaking for energy transitions, case studies in developing countries are infrequent for various reasons, such as data requirements, resource constraints, and limited applicability for actual decision-making and surprise events (Bhave et al. 2016). Implementing a robustness approach for energy policymaking in developing countries entails several challenges: a large number of available decision options; conflicting stakeholders' priorities, preferences and risk perceptions; short-run planning spans; political stability (e.g., political opposition); interinstitutional communication and cooperation issues; complex historical contexts; incomplete, inconsistent or unavailable data from various national administrative entities; lack of human capital; changing energy-related institutions (e.g., institutional fragmentation); conflicting time scales, among others.

The energy sector in Mexico has been experiencing a period of deep changes since the intense energy reform declared by the Mexican government in December 2013. This reform has been considered as "the most ambitious [long-term] energy system transformation worldwide in recent years" (IEA 2017). To fulfil international climate agreements, Mexico has set ambitious national GHG emissions reduction targets (22% by 2030 from business as usual and 50% versus 2000 levels) (Veysey et al. 2016; Jano-Ito & Crawford-Brown 2016). The largest contribution to GHG emissions reduction is expected from the electricity sector. Thus, targets for power generation from clean energy sources were set to 35.1% of total electricity generation by 2024, 38.2% by 2030, and 50% by 2050 (Diario Oficial de la Federación (DOF) 2020). Mexican national ambitious targets in clean energy represent a great challenge for the Mexican energy system. However, given the right mix of policy instruments, Mexico has the potential to advance clean energy development, and therefore diversify its energy mix and significantly reduce its GHG emissions (IRENA 2015). Energy policymaking in Mexico, as in other developing countries, depends largely on limited available information to policymakers. Thus, there is a need for tools that allow policymakers to develop and evaluate robust policies while considering deep uncertainty.

1.3 Research aim and scope

The aim of this investigation is to explore the effects of robust energy policy mixes towards clean energy transitions in Mexico. A new integrated method has been developed for exploring energy policy recommendations to accomplish robust policy strategies. The developed method integrates quantitative and qualitative system thinking approaches to better understand the dynamics of electricity transitions. A system dynamics model has been applied to explore the effects of energy-related policy instruments in the future (to 2050). Complementary technology-push and market-pull strategies to meet long-term targets on clean energy, energy efficiency, and greenhouse gas emissions reduction have been investigated.

The project is delimited to geographical, sectoral, and temporal scale.

- Geographical: the case study focuses on a national level (i.e. Mexico).
- Sectoral: according to Mexican laws, clean energy refers to electricity generation through low-carbon technologies. Thus, the focus of this study is on the electricity sector.
- Temporal: long-term energy performance targets in Mexico are to be met by 2050. Thus, the complementary analyses are carried from 1879 (beginning of the electricity industry in Mexico) to 2050. The evolution of electricity systems and the current status of clean energy technologies are covered and discussed in Chapter 3 (from 1879 to 2021). Then, the impacts of alternative policy mixes are explored from 2018 to 2050 in Chapter 6.

1.4 Research questions

To explore robust policy mixes under deep uncertainty in line with long-term energy targets, this thesis focuses on answering the following research questions:

Question #1: How can quantitative and qualitative methods for policy analysis be integrated to explore the potential impacts of energy policy mixes towards clean energy transitions? [methodological contribution]

Q1.1 How can robustness-based approaches, quantitative modelling techniques, exploratory analysis, and concepts from the energy transitions literature be integrated to assess the robustness of energy-related policy mixes?
Q1.2 How can strengths and limitations of the previous analytical approaches complement each other for energy policy analysis?

Question #2: How can concepts from energy transitions, policy mixes for sustainability transitions, and interactive governance theory be integrated to qualitatively explore the evolution of energy systems in developing countries? [theoretical contribution]

Q2.1 What sustainability transitions concepts can be applied to describe historical energy transitions from different perspectives (i.e. techno-economic, socio-technical, and political)?
Q2.2 How can the description of qualitative narratives derived from the multi-perspective analysis be synthesised in a theoretical framework to understand national energy transitions over time?
Q2.3 How can the understanding of historical energy transition inform model(s) development for policy analysis?

Question #3: What key drivers and barriers in the Mexican electricity sector may shape future conditions towards a clean energy transition? [empirical contribution]

Q3.1 How governing structures in the Mexican electricity sector have evolved over time?
Q3.2 What role have these governing structures played in shaping historical electricity transitions?
Q3.3 What have been the main drivers for structural change within the Mexican electricity system?
Q3.4 How clean energy technologies have evolved in Mexico over time?

Q3.5 What have been the drivers and barriers to deploying clean energy technologies in Mexico?
Q3.6 What are the most relevant policy mixes to be explored towards a clean energy transition in Mexico?

Question #4: What is the role of technological learning processes on clean energy development? [methodological contribution]

Q4.1 What is the most suitable model configuration to investigate the plausible effects of technological learning on technology cost changes over time?
Q4.2 What is the influence of different sources of learning in technology cost developments?
Q4.3 How are these sources of learning formally defined for clean energy technologies?
Q4.4 What are the policy implications of using alternative approaches to modelling technological learning?
Q4.5 What is the impact of public investment in research, development, and demonstration (RD&D) for clean energy technologies in energy transitions?

Question #5: What are the most robust policy alternatives to be implemented in the Mexican electricity sector to achieve long-term energy policy objectives? [empirical contribution]

Q5.1 Considering deep uncertain conditions, what are the potential impacts of adopting different policy alternatives on the electricity sector in Mexico?
Q5.2 What are the most influential policy instruments in achieving energy policy objectives in Mexico?
Q5.3 What are plausible scenarios under which robust policy alternatives are vulnerable?

1.5 Relevance of the thesis

The relevance of the thesis can be highlighted from two perspectives: (1) the development of an integrated method for model-based policy analysis for clean energy transitions, and (2) its stepwise implementation. Based on knowledge gaps identified on model-based policy analysis for energy transitions, a new integrated method has been developed and is presented in Chapter 2 of this thesis. It aims at analysing policy-relevant information by implementing a series of interdependent analytical processes. To improve the applicability of these processes, complementary analytical tools were developed and applied within this study (Chapters 3 and 4). The full implementation of the proposed integrated method is presented in Chapter 5.

Adopting a holistic approach, this thesis highlights the relevance of applying model-based policy analysis with a robust approach to help policymakers improve the policy exploration process by identifying the consequences of implementing different policy alternatives towards energy transitions under deep uncertainty conditions. However, as policymaking for energy transitions under deep uncertainty is conceptualised as a learning process, the problem formulation; the understanding of the system operation and its key parameters; the design of policy alternatives; and the exploration of potential effects on various outcomes of interest emerge from an iterative process. Learning may be facilitated by this iterative scheme revealing stakeholders' preferences and possible trade-offs among alternative problem framings and solutions (Herman et al. 2015). Based on an iterative learning process adopted in this thesis, multiple contributions to advancing knowledge have been identified and discussed

throughout the development and implementation phases of the proposed integrated method. Table 1 lists the main contributions and research questions addressed in each chapter of this thesis.

Table 1

Main contributions of the thesis and research questions addressed.

Chapter	Main contributions	Research questions addressed
2	A new integrated method for energy policy analysis was developed	Q1
3	A new theoretical framework for describing the evolution of energy systems was developed and applied at a national level at diverse scales (i.e. electricity transitions and clean energy technologies).	Q2 and Q3
4	An integrative technological learning model was developed and applied to explore technology cost changes over time (i.e. historical and future developments). In addition, a new definition of technological experience was developed and implemented by accounting for diverse learning sub-processes (i.e. learning-by-doing, learning-by-using, experience spillovers).	Q4
5	The integrated method was fully implemented with Mexico as a case study.	Q5

1.6 Overview of the thesis

This thesis is structured in six chapters. Chapter 1 presents the background of the study, the problem statement, the aim and scope, the research questions, the knowledge gaps identified, and the relevance of the study. To address the proposed research questions, a comprehensive literature review was carried out throughout the development of this study. The available documents reviewed include books, journal articles, conference papers, PhD theses, laws, regulation frameworks, reports, datasets, and analyses published by academia, international organisations, and national government bodies. The main topics and themes, and research methods applied for the literature review are also presented in this chapter. Based on knowledge gaps identified, a new integrated method was developed for analysing policy-relevant information regarding the robustness assessment of energy policy alternatives for clean energy transitions. The development of the integrated method is presented in Chapter 2. The implementation of the proposed method encompasses a series of steps (i.e. research design) including policy problem definition, deep uncertainty characterisation, exploratory modelling and analysis, and (the development of) policy recommendations. The stepwise

implementation of the integrated method derived in the development and implementation of complementary analytical tools to improve its applicability.

First, a new theoretical framework was developed for qualitatively describing the evolution of energy systems at a national level. The development of the theoretical framework and its implementation to electricity transitions in Mexico is presented in Chapter 3. Additionally, this chapter also presents the application of the theoretical framework to describe the evolution of clean energy technologies and to identify relevant drivers (and barriers) towards a clean energy transition in Mexico. Chapter 3 contributes to improve the policy problem definition step within the integrated method (first step).

Second, a new integrative technological learning model was developed to explore the effects of learning processes on technological-based cost developments. The model development and its implementation to analyse historical cost developments is described in Chapter 4. By applying the integrative model developed, the potential effects of public investment in energy research, development, and demonstration on future cost developments is also explored in this chapter. Thus, Chapter 4 contributes to enhance the exploratory modelling and analysis process, specifically the model development subprocess (third step within the integrated method).

The full implementation of the integrated method is presented in Chapter 5. Results and insights from previous chapters are used as inputs to explore the plausible consequences of adopting different policy mixes towards clean energy transitions. Policy recommendations to design and implement robust policy alternatives towards a clean energy transition in Mexico are presented and discussed within this chapter. Finally, Chapter 6 presents the conclusions of the thesis and suggests potential avenues for future research. Fig. 1 depicts the research design and general structure followed in this thesis. In addition, the diverse analytical frameworks, tools, and models developed and applied in this thesis are presented in Table 2.

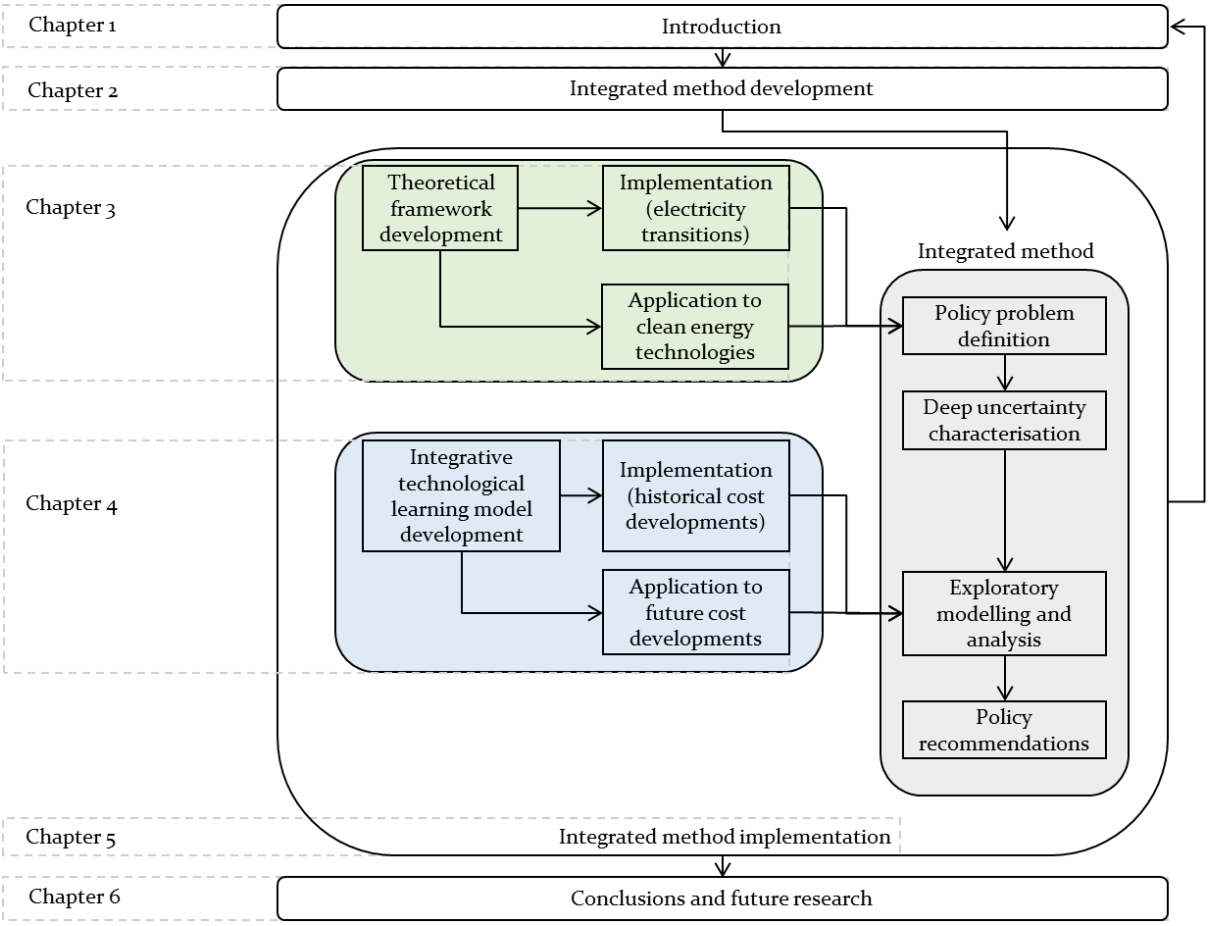


Fig. 1. Thesis structure.

Table 2

Analytic frameworks, tools, and models developed and applied in the thesis.

Research method developed	Analytical processes	Frameworks, tools, and models developed	Underpinning theories/frameworks
Integrated method for model-based energy transitions policy analysis	Policy problem definition	Multi-perspective theoretical framework	Energy and sustainability transitions concepts
			Policy mixes for energy transitions
			Interactive governance
			Governability
		COPRIEMD framework	Policy problem structuring methods
	Deep uncertainty characterisation	Deep uncertainty characterisation matrix	Decision making under deep uncertainty
	Exploratory modelling and analysis	Energy transitions model	System dynamics theory
			Energy economics
		Integrative technological learning model	Learning curve theory
		Technological experience model	Innovation systems
	Policy recommendations		Policy analysis

This thesis follows a modular publication format where relevant topics and themes, as well as specific knowledge gaps and potential solutions are discussed in detail in each publication. Thus, the next section presents a summary of the main topics and themes, and the research methods applied.

1.7 Main topics and themes

During the initial (and continuing) literature review, diverse documents were reviewed on eight main topic areas:

1. Energy policy analysis,
2. Energy transitions,
3. Policy mixes for sustainability transitions,
4. System dynamics,
5. Robust decision making,
6. Exploratory modelling and analysis,
7. Interactive governance,
8. Technological innovation.

The aim of the literature review was to identify the strengths and limitations of current decision-making support approaches to seek more robust energy policy strategies towards clean energy transitions in developing countries. The thesis follows a thematic structure where the chapters are organised around the themes emerging from the analysis, from different dimensions (e.g. political, technical, economic, social) to recurring topics (e.g. energy transitions, robust decision making) (Sovacool, Axsen & Sorrell 2018). Table 3 presents the main topics and themes discussed in the study.

Table 3

Main topics and themes discussed in the thesis.

Main topics	Main themes	Chapters
Model-based policy analysis for energy transitions under deep uncertainty	The development and application of a new integrated method for energy policy analysis towards clean energy transitions may contribute to a better-informed policy advise in developing countries by exploring the potential consequences of adopting different policy mixes towards future clean energy transitions	2 and 5
Energy transitions concepts to qualitatively describe the evolution of techno-socio-economic energy systems	The development and application of a new theoretical framework, developed by integrating energy transitions concepts with interactive governance theory, may improve the in-depth understanding of historical structural changes and future developments of energy systems in developing countries	3
Technological learning in model-based energy policy analysis	An integrative technological learning model, developed by integrating multiple approaches to modelling technological learning processes, may improve the innovation planning process for developing and deploying clean energy technologies by revealing the relative contributions of different variables to reducing capital costs	4

1.8 Research and review methods

Considering appropriateness and balance between codes of practice, this thesis includes various complementary research methods, commonly used in energy social science (Sovacool, Axsen & Sorrell 2018), to search, select, analyse, and synthesise relevant literature. First, a *narrative literature review* process was conducted in Chapter 2 to identify specific knowledge gaps on 'model-based policy analysis for energy transitions under deep uncertainty'. The narrative review approach, also called semi-systematic review process (Snyder 2019), is particularly useful for an exploratory investigation of literature (or a subset of the literature) on a particular topic or familiar theme (Sovacool, Axsen & Sorrell 2018). Then, a *multi-method* approach was adopted to describe the evolution of national energy systems (at different scales) in Chapter 3 (i.e. electricity transitions and clean energy technologies). Within this chapter, a narrative review approach was first adopted to identify and characterise knowledge gaps on the selection and application of 'energy transitions concepts to describe the evolution of techno-socio-economic energy systems qualitatively'. Subsequently, a *systematic literature review* followed by an analysis and synthesis process with a theoretical heuristic approach was

applied to describe 'the evolution of (two) energy systems in Mexico' as illustrative *case studies*. A systematic review approach is particularly relevant when both quantitative and qualitative evidence applies to provide a comprehensive, unbiased, explicit and replicable summary of the state of knowledge on a specific topic (e.g. energy transitions) (Sovacool, Axsen & Sorrell 2018). The systematic review process follows a series of phases, usually including (1) crafting of explicit research questions, (2) systematically searching available literature using a well-defined search design, (3) setting and using explicit criteria for including or excluding literature, (4) determining and applying an analytical protocol (or coding strategy), and (5) analysing or synthesising the collected evidence (Sovacool, Axsen & Sorrell 2018). A detailed description of the application of this review approach is presented in Chapter 3 of this thesis. In addition, case studies are often used to provide in-depth examination of particular subject or phenomena (e.g. energy transitions, energy policy mixes, governance structures) and related contextual conditions (e.g. in Mexico), commonly using multiple sources of evidence (Sovacool, Axsen & Sorrell 2018).

Furthermore, a narrative approach was adopted in Chapter 4 to identify knowledge gaps on 'technological learning in model-based energy policy analysis' (previously identified as a key driver for energy transitions from the systematic literature review discussed in Chapter 3). Additionally, onshore wind and solar PV technologies in the United States of America (USA) were selected as comparative case studies within Chapter 4 to explore the 'effects of different learning curve approaches (i.e. alternative model formulations) on describing energy technology cost changes over time'. Finally, Chapter 5 applied a mixed method (developed and presented in Chapter 2) to explore the 'potential consequences of adopting different policy mixes towards future clean energy transitions in Mexico' as an illustrative single case study. The term 'mixed method' should not get confused with the use of the term 'multi-method'. The former term refers to integrating quantitative and qualitative research methods in a single study (see Chapter 2 for an example), while the latter term is more general and refers to any research design that blends and uses multiple research methods, such as in Chapter 3 (i.e. a narrative literature review, a systematic literature review, and illustrative case studies).

1.9 Knowledge gaps

The literature review process derived from the identification of various knowledge gaps. When addressing knowledge gaps previously identified and characterised, new knowledge gaps may arise. Thus, the literature review should be seen as an iterative learning process. Main knowledge gaps identified through the development of this thesis are summarised in this section. The detailed description of knowledge gaps and proposed solutions to close these gaps may be found in each chapter.

Chapter 2: Knowledge gaps in model-based policy analysis for energy transitions under deep uncertainty.

- Multiple analytical approaches with different theoretical roots have been applied in isolation to study energy transitions. However, how they can be integrated to complement each other for policy analysis is infrequently addressed in the literature.
- Although problem definition is highly emphasised within policy analysis literature, modelling techniques, exploratory modelling and analysis, and robustness-based

approaches, there is little discussion regarding what methods to use when defining the boundaries of a policy system.
- Energy transitions models usually depend on deterministic sensitivity analysis to provide insights regarding long-run changes to energy systems. An exploratory thinking approach is needed to explore the behaviour of complex energy systems characterised by deep uncertainty conditions.
- To capture decision-makers' stand about uncertainty, a large number of formal definitions of robustness have been proposed.
- Many studies in the field rest on qualitative research methods, uncovering partially relevant information to policymakers. An integrated method for energy policy analysis towards clean energy transitions may contribute to a better-informed policy advise.
- Most empirical policy mix research has focused on the European Union only.

Chapter 3: Knowledge gaps in the selection and application of energy transitions concepts to describe the evolution of techno-socio-economic energy systems qualitatively.

- How to conceptualise the system-to-be-governed has been identified as one caveat in interactive governance and governability literature. The system-to-be-governed can be conceptualised in different ways and at different scale levels.
- Transitions in energy systems may occur derived from the interactions of diverse contextual drivers and barriers, with different relative influence from one phase to another. Thus, a more comprehensive explanation of these structural changes is needed by using diverse (complementary) sustainability and energy transitions concepts.
- By using concepts from diverse theoretical perspectives, an inventory of 'micro-logics' can be formulated to explain specific elements or episodes of energy transitions (e.g. the role of clean energy technologies in electricity transitions). However, the use of a broader theoretical construct is needed to synthesise these micro-logics from one episode to another.
- Although interactive governance and governability have been used to analyse and assess energy systems, the application to energy transitions was not yet found in the literature.
- Although different analytical frameworks have been used to describe economic, technological, and socio-political changes in the Mexican electricity system at different periods in time, the detailed evolution of clean energy technologies has received little attention and their development has been marginally described within a broader scope (e.g. electricity systems).

Chapter 4: Knowledge gaps in technological change in model-based energy policy analysis.

- Learning curve is the most common framework for investigating the relationship between technological learning and technology costs changes. However, what sources of learning and key parameters to include as explanatory variables to technology cost changes has been identified as a key caveat within this approach.
- Alternative definitions of experience and knowledge stock are found in the literature, making it difficult to develop policy recommendations for decision makers regarding the role of technological learning processes on future cost developments.
- The high level of aggregation to represent learning processes regarding technology deployment is a key criticism of one-factor learning curve (1FLC) models. When the process

of technological learning is investigated using 1FLC models, little explanation is offered by the statistical correlation between reductions in technology costs and cumulative installed capacity (used as a proxy of technological experience).
- The relative role of learning-by-doing, learning-by-using, and experience spillovers cannot be revealed by using a traditional 1FLC approach. Considered as a partial model for technological learning processes, 1FLCs may produce inaccurate estimates of learning-by-deployment rates.
- 1FLC models may overestimate the actual contribution of experience as this approach uses a single parameter (i.e. experience gained by technology deployment) to explain technology cost changes (i.e. omitted variable bias). Thus, only market-pull recommendations may be developed while ignoring technology-push mechanisms if 1FLCs are applied in energy models.
- If energy models miss critical pathways or inappropriately capture learning processes (e.g. poor representation of energy innovation processes), policymakers might obtain incomplete or misleading policy conclusions.
- Although the impact of RD&D has been discussed in diverse retrospective studies (using historical data), finding future costs to extrapolate its learning effects has been identified as a key challenge for prospective studies.

Chapter 5: Knowledge gap in implementing an integrated method for energy policy analysis under deep uncertainty.

- The analytical tools presented in Chapter 2 were suggested in a conceptual basis to operationalise an exploratory thinking approach for policy analysis. However, it lacks empirical implementation of case studies to verify its applicability.

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Chapter 2

A new approach for investigating robust policy mixes towards clean energy transitions

In the previous chapter, the background of the thesis, the literature review process followed within this study, and knowledge gaps identified were presented and discussed. Based on the knowledge gaps on model-based policy analysis for energy transitions, Chapter 2 presents the development of an integrated method for supporting policymakers with the design of robust energy-related policy alternatives towards clean energy transitions. The method developed and presented in this chapter integrates quantitative and qualitative approaches to better understand the dynamics of historical electricity transitions and to explore the impact of energy-related policy instruments in future clean energy transitions. The implementation of the method encompasses a series of interdependent analytical processes that shape the research design followed by this study. Thus, the set of the chapters aim at demonstrating the applicability of the method.

Chapter 2 methodologically contributes to this study by answering Question #1:

How can quantitative and qualitative methods for policy analysis be integrated to explore the potential impacts of energy policy mixes towards clean energy transitions?

- *How can robustness-based approaches, quantitative modelling techniques, exploratory analysis, and concepts from the energy transitions literature be integrated to assess the robustness of energy-related policy mixes?*
- *How can strengths and limitations of the previous analytical approaches complement each other for energy policy analysis?*

Chapter 2 is based on a journal article with the title "*Making policy mixes more robust: An integrative and interdisciplinary approach for clean energy transitions*" published in *Energy Research & Social Science*. The format and numbering of the sections are according to the original publication style (see Appendix B).

Making policy mixes more robust: An integrative and interdisciplinary approach for clean energy transitions

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ABSTRACT

Energy transitions from a fossil fuel-based to a clean-energy economy are required to meet international commitments on climate change mitigation. Energy-related policies play a paramount role to influence the pace of clean energy transitions. Energy policy makers must deal with operational, tactical, and strategic challenges due to an extensive range of deep uncertainties such as fuel price fluctuations, unpredictable demand behaviour, and climate change. Even though the future is uncertain, policy makers must design strategies to meet diverse long-term energy goals in line with changing societal needs. Analyses of the dynamics of policy decisions, economic development, technological innovation, social changes, and environmental impacts enable designing robust policy mixes consistent with clean energy transitions. A policy mix is considered robust, if the system of interest performs satisfactorily under a broad range of plausible futures. Thus, an integrated method is developed for organising energy policy recommendations to achieve robust policy mixes towards clean energy transitions. The method presented is an integration of energy transitions concepts, robustness-based approaches, quantitative simulation modelling techniques, and exploratory modelling and analysis.

***Keywords**:* policy analysis; clean energy; electricity transitions; policy mixes; deep uncertainty; robustness.

1 Introduction

Every single day we make decisions around our lives that may have positive or negative impacts in the future. Policy decisions (e.g. R&D public investment, infrastructure expansion strategies, urbanisation plans) have long-term effects [1]. Current public policies may support regional, sectoral, and/or national development in long timeframes. Public policies are understood as the set of objectives, decisions, and actions carried out by the government to solve practical problems that both the citizens and the government consider paramount at the point of time [2]. These decisions involve multiple actors, sectors, and government levels. Policymakers develop policy strategies to solve practical problems based on the analysis and interpretation of available information. However, conditions throughout time may change rapidly making current strategies not suited for new conditions. Thus, policymakers may formulate policies capable of withstanding variations of the initial designed conditions [3].

The trends of the performance of energy systems could be different in the future due to incorrect predicted changes in economic, technological, social, political, and environmental conditions. There is no agreement among both decision-makers and scholars about what the exact future of clean energy technologies will be and the impact on the development of the electricity sector. Electricity transitions are conceptualised as co-evolutionary, multi-actor, long-term dynamic processes of structural change in the way electricity is produced and used [4,5]. Multiple barriers to electricity transitions have been identified, including lock-in into fossil fuel-based technological trajectories, resistance to change from incumbent regimes, and path dependency and inertia due to organisational commitments and vested interests within energy systems [5]. Thus, energy-related policymaking plays a key role in overcoming these challenges and promoting electricity transitions to reach national energy objectives (e.g. use of clean energy technologies for decarbonisation).

Choosing and implementing an energy policy instrument, or a mix of instruments, from a range of options may affect different from the intended performance in the future. Analyses of policy mixes for energy transitions consider not only the interaction among policy instruments but also a strategic component (including policy objectives and plans), the dynamic policy processes, and the analysis of actors and institutions involved in developing and implementing such policy mixes [5,6]. Electricity transition processes involve various key actors with diverse interests and roles within energy systems. Thus, when diverse stakeholders are considered in energy policy development identifying suitable policy instruments for clean energy transitions turns out to be difficult. Priorities set to meet the requirements of electricity systems vary among institutions, targeting different (sometimes contradictory) intended outcomes. Considering different perceptions and diverse possible electricity transitions pathways that can unfold in a range of plausible futures, policymaking for clean energy transitions is considered a 'wicked' problem [7]. For a wicked problem the selection of a solution depends upon the interaction among a variety of decision-makers and stakeholders with conflicting values and diverging viewpoints [8].

Traditional energy policy-making approaches aim to answer the question 'What will happen in the future?' by using suited predictive energy models. In general, these models rely on various assumptions to aid policymakers in designing an optimal policy instrument mix based on the system's likely evolution. An optimal policy instrument mix is defined to be one that reach the best results based on a particular perspective and considering well-defined and narrowed future conditions. However, if various perspectives and changing conditions over time are considered, the application of traditional policy-making approaches to wicked problems is limited. Energy policymaking for clean energy transitions must deal with operational, tactical, and strategic challenges due to an extensive range of deep uncertainties such as unpredictable energy demand, fuel prices fluctuations, and climate change [9]. Deep uncertainty is the condition in which analysists do not know or the parties to a decision cannot agree on: (a) the

appropriate models to describe interactions among different variables of a system, (b) the probability distributions to represent uncertainty about key parameters, or (c) how to assess the desirability of alternative outcomes [10].

Various approaches have been proposed to deal with deep uncertainty in policy-making processes [11]. Policy makers can choose a strategy among various options: (1) plan for the worst-case scenario (i.e. resistance), (2) regardless of the conditions in the future, select a policy mix that allow the system to recover rapidly (i.e. resilience), (3) seek a strategy that will be able to perform reasonably well in almost all plausible futures (i.e. static robustness), and (4) in case of a change in conditions, be prepared to change the policy mix (i.e. adaptive robustness) [11].

Robust policy mixes aim to answer, 'knowing the fact that the future is uncertain, what available policy instruments are likely to perform well in multiple plausible futures?' [12]. 'Robustness-based approaches' are considered useful when decision-makers are trying to find policy alternatives that perform satisfactorily across multiple plausible future conditions. To reach this, there is a need for tools that allow policymakers to develop and evaluate robust policy mixes while coping with deep uncertainty. Policy analysis with a robustness-based approach can be used as a systematic process for analysing the plausible consequences of adopting different policy instruments in a dynamic setting [13]. By estimating these plausible consequences, a dataset is generated. Then, the dataset is analysed based on intended performance outcomes. As a result of the analysis, information relevant to the policy-making process is obtained, hereafter referred as *policy-relevant information*. Policy-relevant information can be obtained by using different research paradigms: quantitative, qualitative or a combination of both (integrated methods) [14].

The aim of this paper is to develop an integrated method to explore environmental impacts of robust energy policy mixes towards clean energy transitions. The proposed method is developed in the context of electricity transitions at a national level. In the frame of decarbonisation processes by using clean energy technologies, this integrated method mainly focuses on environmental impacts (e.g. greenhouse gas emissions mitigation). The developed method was formulated by integrating various analytical tools to take their advantages for energy policy analysis. To demonstrate the practical applicability, we introduce and discuss some successful examples of these tools applied to energy and electricity transitions.

The rest of the paper is organised as follows. Section 2 presents the background of this paper by describing diverse analytical tools used in policy analysis for energy transitions. Also, some challenges to energy transitions policy analysis are presented and discussed. An integrated method for model-based policy analysis towards clean energy transitions is developed and presented in Section 3. In Section 4 the advantages and limitations of the method presented are discussed. Conclusions are exhibited in Section 5.

2 Model-based policy analysis for energy transitions

Dunn [15] defined policy problems as "*… unrealized needs, values, or opportunities for improvement attainable through public action.*". When policy problems formulation becomes challenging due to contradicting decision-makers' standpoints, investigating diverse policy alternatives becomes crucial. Policy analysis supports policymakers in selecting lines of action by identifying stakeholders' preferences, possible policy alternatives, deep uncertainties, and outcomes of interest [13]. Thus, the aim of a policy analysis process is to analyse information relevant to the parties involved within the policy-making process about the consequences of adopting different policy instruments [13].

The concept of policy instrument mix (a combination of policy instruments and the interaction among instruments) is considered just as one element within the policy mix

framework proposed by Rogge and Reichardt [6]. In the context of sustainability transitions, a policy mix should incorporate policy-making processes and a strategic component in order to evaluate the impact of energy policy instruments aimed at achieving sustainability-oriented objectives in a dynamic setting [6]. Policymaking for clean energy transitions can be seen as a policy learning process based on a cycle of problem-solving attempts with a focus on repeated analysis of energy policy problems and experimentation with solutions [16]. To facilitate the policy learning process, the exploration of the plausible impacts of policy instruments under deep uncertainty conditions is necessary.

Aiming at supporting policymakers in addressing energy-related policy problems, various approaches can be applied to analyse policy-relevant information. Model-based policy analysis is one approach that systematically explores the effect of policy mixes on different contexts (e.g. current or future transformation processes) and, thus, the degree to which policy instruments can aid to meet specific (long-term) targets [17]. This systematic exploration may be carried out through a structured analytical process (see Fig. 1). A detailed description of the set of steps considered within the policy analysis process may be found in [18] and [19]. Thus, using models, policy-relevant information not easily apparent for policymakers can be analysed to improve energy policymaking towards clean energy transitions. Various analytical tools have been applied for model-based policy analysis to support decision-making for energy transitions. This research focusses on analytical tools used for policy problem identification and policy alternatives analysis (see Fig. 1).

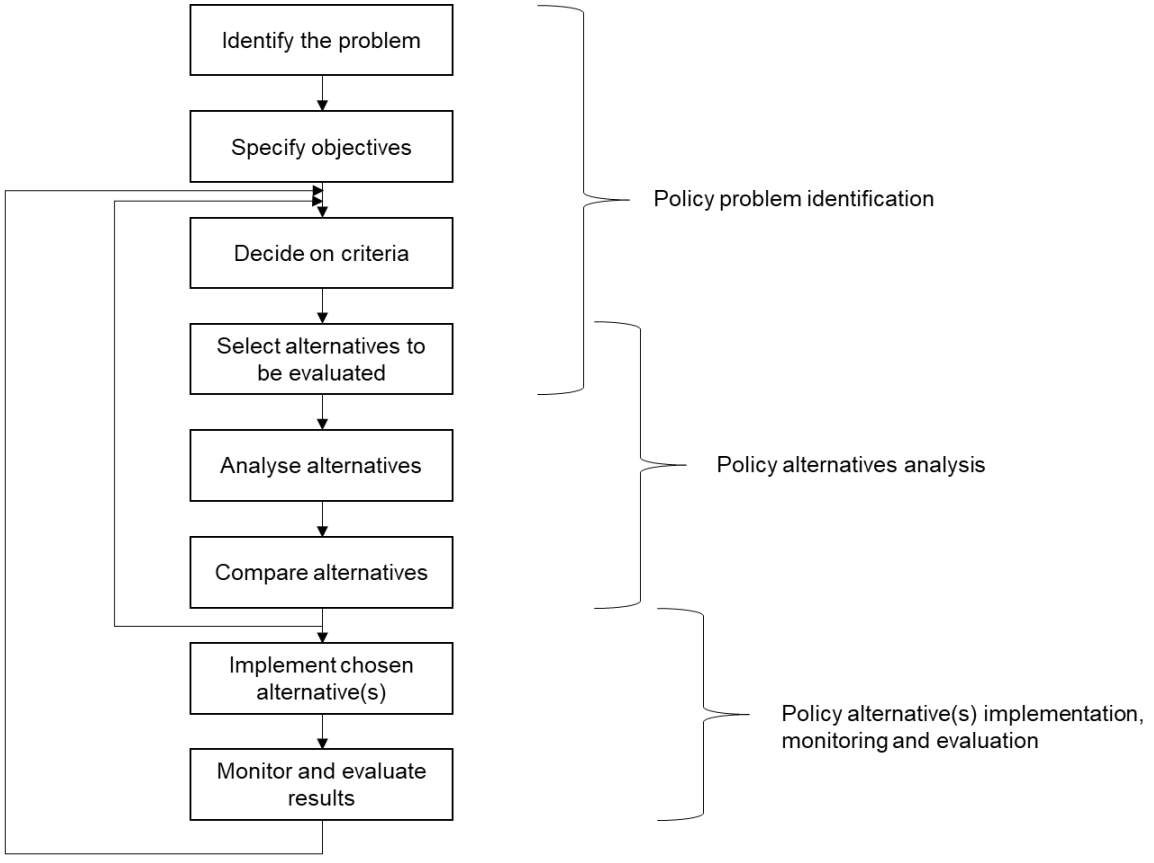


Fig. 1. Steps in a policy analysis study.
Source: Walker [13].

Several model approaches have been developed for energy systems [20]. The analysis of energy-economy models is mainly based on the theoretical paradigm of following the

normative neoclassical assumptions of rational choice, perfect information, and profit and utility maximisation [21]. Thus, traditional quantitative modelling approaches (i.e. integrated energy assessment and optimisation models) tend to depend on economic optimisation and equilibrium assumptions [22]. This type of quantitative energy models narrows its scope by linking only techno-economic factors to understand energy systems and their plausible future development. Therefore, the behaviour of individual actors and organisations, policies, regulations, and social aspects are framed exogenously within formal energy-economic models for energy policy analysis [21]. Reviews of this category of energy models and their application to energy policy analysis may be found in [23, 24].

To capture key societal actors and the co-evolutionary aspects of policy, technology, and behavioural aspects within formal quantitative energy models, 'Socio-Technical Energy Transition' (STET) models were proposed [21]. STET models aim at improving the understanding of the plausible impact of policy design and implementation on normative futures for energy transitions. They integrate techno-economic details, actor heterogeneity, and transition pathway dynamics to capture the elements of socio-technical transitions [21]. Thus, qualitative insights regarding the dynamics of societal actors, socio-technical change, and policy interventions can be included within quantitative energy models to analyse energy transitions.

2.1 Understanding energy transitions for policy problem identification

Ackoff [25] pointed out that "S*uccessful problem solving requires finding the right solution to the right problem. We fail more often because we solve the wrong problem than because we get the wrong solution to the right problem.*". When even the task of defining policy problems is contested and uncertain due to diverse stakeholders' preferences and viewpoints, the use of different tools for framing the policy system turns crucial. Various problem structuring methods (PSMs) have been proposed to deal with the conceptualisation of complex problem situations characterised by multiple actors, multiple perceptions, contradictory interest, important intangibles, and key uncertainties [26]. Aiming at conceptualising and delimiting the system of interest, PSMs use diverse analytical techniques based on different theoretical bases. A summary of most widely applied PSMs may be found in [26–28]. Though one single method can be applied to conceptualise particular problems, there are several case studies where analysts combine parts of methods together (considering qualitative, quantitative, and integrated methods) to deal with their limitations and to improve the problem identification [28]. In order to identify the policy problem, this research focuses on two frameworks: energy transitions concepts for policy analysis and policy problem structuring frameworks.

Several transition theories, with different roots (e.g. economics, social studies, history of technology, political science) have been used for (qualitatively) understanding societal transitions in general and energy transitions in particular [29,30]. Turnheim et al. [29] set out a suggestion for linking three theoretical approaches to the analysis of sustainable transition pathways: quantitative systems modelling, socio-technical transition analysis, and initiative-based learning. On the other hand, Cherp et al. [30] analysed existing approaches focused on energy transition studies and categorised them in three main perspectives: techno-economic, socio-technical, and political. At the view of this framework, long-term changes occur within three major co-evolving sub-systems: (1) techno-economic sub-system, explained by energy flows associated with energy supply and demand coordinated through energy markets; (2) socio-technical sub-system, defined by energy technologies; and (3) sub-system of political actions, influencing energy systems by adopting and implementing energy-related policy instruments. The concept of co-evolution systems (or sub-systems) refers to the idea of systems with their own elements, boundaries and dynamics but interacting among them [30]. In addition, various definitions of core concepts to policy mixes for energy transitions have been proposed. Examples of these concepts and how policy mixes are addressed by three key

disciplinary foundations (environmental economics, innovation studies, and policy sciences) are synthesised in [5].

A complementary approach to energy policy problem identification is the use of policy analysis frameworks. For instance, Moallemi et al. [31] used energy-related examples to illustrate the applicability of the XLRM (exogenous uncertainties, policy levers, relationships, and measures) framework from robust decision making [10] to problem formulation for multi-objective decision making under deep uncertainty. Similarly, Agusdinata and DeLaurentis [32] presented a policy problem formulation framework to study how policy intervention could aid in reducing greenhouse gas emissions in the Dutch household sector. A policy problem structuring framework called 'policy analysis XPIROV framework' (Fig. 2) informs the exploratory modelling and analysis process by identifying key elements for the system-of-systems (SoS) model. The framework is an expanded version of Walker's public policy analysis [13] and XLRM [10] frameworks.

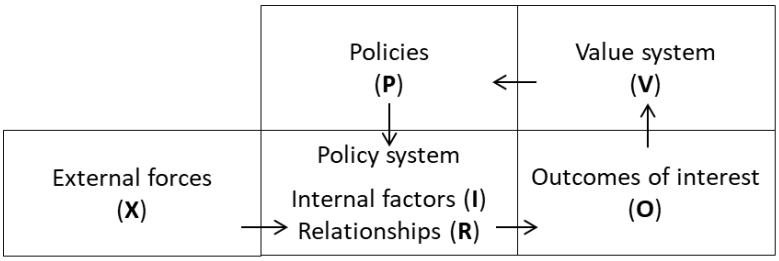


Fig. 2. Policy analysis approach with XPIROV structure.
Source: Agusdinata and DeLaurentis [32].

In Fig. 2, external forces (X) are exogenous factors beyond the control of policymakers (e.g. cost of conventional fuels, renewable access to power grid, technological progress). Policies (P) are the policy instruments (e.g. incentives and regulations for renewable energy) which seek to influence system's behaviour towards the achievement of stated objectives. Internal factors (I) are the endogenous components of the system which may be influenced by policies and external forces (e.g. stock of renewables within the Dutch Renewable Energy System). Relationships (R) refer to the linkages among internal factors, external forces, and policies which produce the outcomes of interest (O). These relationships can be classified into (1) relationships between the system and external forces, (2) relationships among internal factors, and (3) relationships between internal factors and outcomes of interest. The outcomes of interest (O) are considered as a relevant set of characteristics of the system for the evaluation of various policies (e.g. share of renewables in the energy supply). Based on stakeholders' preferences and policymakers' objectives, the value system (V) contains the criteria to identify the desirability of different policy outcomes (e.g. energy security, protection of the environment) [32,33]. Unlike Walker's [13] and XLRM [10] frameworks, XPIROV framework [32] makes an explicit consideration of internal factors within the system of interest with the aim of better explaining the structural change in the policy system [33].

2.2 A robustness-based approach to policy alternatives analysis

Traditional policymaking aims to agree on assumptions about current and future conditions to reduce uncertainty. This 'Agree-on-assumptions' approach (also called 'predict-then-act' [1]) explores how sensitive is the 'best' near-term decision to assumed conditions of the future. A 'best' solution can perform well according to a specific set of assumptions but perform poorly if the assumptions are incorrect. Decision making under deep uncertainty (DMUDU) approaches follow an inverted process known as 'Agree-on-decisions' to encourage consensus about robust solutions (i.e. to perform 'satisfactorily' regardless of uncertain future) by

analysing options first and then seeking agreement. This process considers the identification of vulnerabilities and opportunities of proposed solutions with the aim of developing solution adaptations to reduce the vulnerabilities and focus decision-makers' attention on trade-offs among decision alternatives [10]. In this research, we consider policy alternatives as those policy instrument mixes whose impact on electricity transitions are of interest to policymakers (e.g. energy R&D public investment, clean energy certificates, tax incentives) [34]. The identification of specific conditions in which each alternative does not meet its goals can be revealed using analytical tools [1].

Thus, the focus in 'Agree-on-decision' processes is on testing the available options (policy alternatives in the case of policymaking) under an extensive range of plausible conditions, considering diverse set of uncertainties (see Fig. 3).

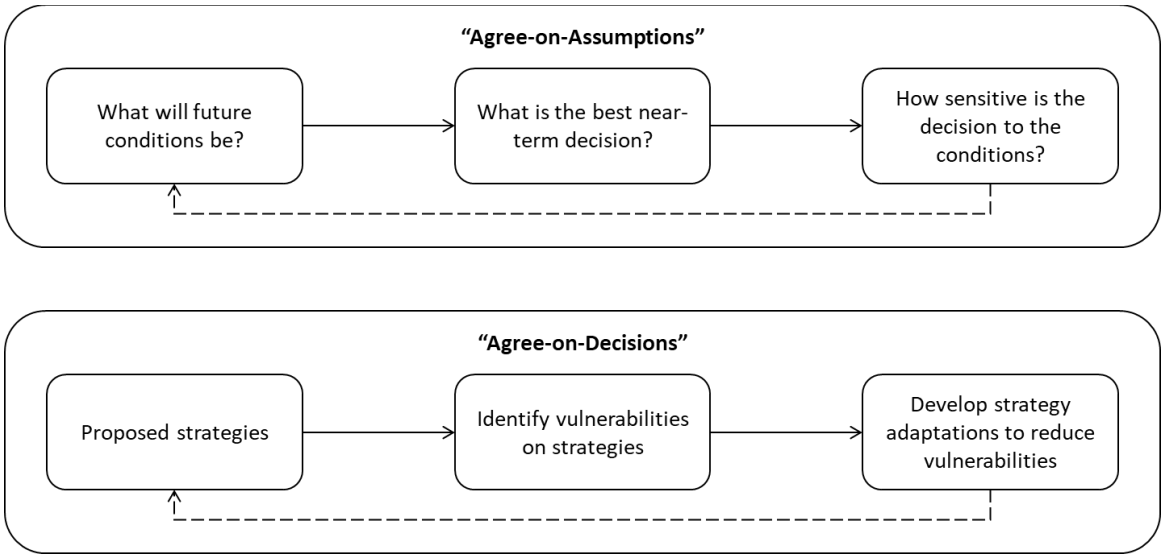


Fig. 3. 'Agree-on-assumptions' and 'Agree-on-decisions' processes.
Source: Kalra et al. [1].

Recently a variety of exploratory model-based frameworks have been proposed. They consider deep uncertainty and aim at designing robust policy strategies as opposite to optimal. These approaches include (but are not limited to) Information-gap Decision Theory (Info-gap) [35,36], Robust Decision Making (RDM) [10], Decision Scaling or Climate Informed Decision Analysis (CIDA) [37], Dynamic Adaptive Policy Pathways (DAPP) [38], and Many-Objective Robust Decision Making (MORDM) [39]. See [40] for a review of DMUDU approaches.

DMUDU approaches (or robustness-based frameworks) provide a structured framework for planning complex systems [41]. They encompass diverse interdependent steps to obtain relevant information through simulations. Nevertheless, model-based policy analysis under conditions of deep uncertainty is problematic due to the complexity of strict model validation. A limitation of DMUDU approaches, pointed out by Kwakkel et al. [42], is that analysts commonly rely on the importance of using existing (energy-economy) models that are accepted by the parties for a decision. Exploratory modelling and analysis (EMA) can be useful when policy-relevant information is to be obtained and analysed by constructing models but is not possible to identify a single model which accurately describes the system behaviour. Thus, models are built in line with available information, but they are not unique [43,44].

EMA uses computational experiments to explore several possible futures shaped by the impact of diverse methodological, structural, and parametric uncertainties [10,44]. By running computer simulations many times, a large dataset of cases is generated and then analysed

using different algorithms and techniques to determine vulnerabilities of the proposed policy alternatives. EMA is commonly applied for three main purposes: (1) to identify under what conditions a plausible future can take place and what combinations of uncertainties could trigger undesirable outcomes; (2) to assess strategies performance under uncertain conditions; and (3) to identify vulnerabilities and possible trade-offs among policy alternatives [45].

2.3 Challenges to model-based policy analysis for energy transitions

Multiple analytical approaches with different theoretical roots have been applied in isolation to study energy transitions. However, how they can be integrated in order to complement each other for policy analysis is seldom addressed in the literature [34]. Thus, in this section some key challenges for policy analysis towards clean energy transitions are discussed and some lines of action to address them are proposed.

First, although problem definition is highly emphasised within policy analysis literature [13,15], modelling techniques such as system dynamics [46], exploratory modelling and analysis [33,44,47], and robustness-based approaches [10,35,37–39], there is little discussion regarding what methods to use when defining the boundaries of a policy system. As stated by Rogge and Reichardt [6], the definition of these boundaries should be seen as an iterative process, improving the policy learning process. Thus, the co-evolution patterns of policy mixes for clean energy transitions and technological innovation can only be revealed through dynamic analyses covering long-term timeframes [6]. Model-based policy analysis with a robust approach may aid policymakers to improve the learning process by exploring the consequences of implementing different policy alternatives towards energy transitions under deep uncertainty conditions.

Second, when models are applied to study complex societal challenges, such as electricity transitions, the concepts of 'dynamic complexity' and 'deep uncertainty' emerge [43]. Deep uncertainty refers to the situation in which the parties to a decision do not know or cannot agree on: (1) models that relate relevant variables and parameters, (2) probability distributions of the model elements, and/or (3) the desirability of outcomes of interest [10]. Dynamic complexity implies that the system is dynamic, non-linear, adaptive, self-organised, history dependent, governed by feedback, policy resistant, counterintuitive, and characterised by trade-offs [46].

To cope with the dynamic complexity of energy systems, non-linear dynamics models can be used such as STET models. They aid analysts and decision-makers to understand the behaviour of complex energy systems by combining the formal rigor of mathematical models with the wealth of verbal models. Several STET models have been applied as a tool to aid policy analysis in energy transitions. However, how they deal with uncertainty analysis is a key limitation pointed out by Li et al. [21]. Usually STET models depend on deterministic sensitivity analysis to provide insights regarding long-run changes to energy systems. This limitation could be overcome by applying an exploratory thinking approach to explore the behaviour of complex energy systems characterised by deep uncertainty conditions.

To deal with deep uncertainty, policymakers seek to develop and implement alternatives to achieve multiple performance goals across a wide range of plausible futures while withstanding modifications in the conditions for which they were designed [3]. Considering changing conditions, the concept of robustness plays an important role in energy policymaking under deep uncertainty. A policy alternative is assumed to be robust if the outcomes of interest perform 'satisfactorily' under a broad range of plausible conditions in future [11]. To capture decision-makers' stance about uncertainty (pessimistic/optimistic attitude), a large number of formal (mathematical) definitions of robustness have been proposed [48–50]. The different ways of quantifying the robustness of a policy alternative is referred by Schneller and Sphicas [51] as 'the meta-problem of deciding how to decide'. For

instance, a recent study by McPhail et al. [50] categorised and compared several robustness metrics to illustrate the difference of choosing one from the others. Eleven robustness metrics, categorised in four main classes, were applied to three case studies to provide understandings regarding the ranking of alternatives. They concluded by stating that the decision of robustness metrics should consider: (1) the decision-context, (2) the preferred level of risk aversion, and (3) the decision-makers' preferences regarding performance, variance or some higher-order moment. To overcome this challenge, explicit decision rules should be included within the policy problem formulation as a normative criterion to 'accept' robust policy alternatives.

Third, based on multiple conceptual and empirical contributions on policy mixes for energy transitions, some key implications for future work were identified [5]. We focus on two of them: methodological and geographical limitations. First, many studies on the field rest on qualitative research methods uncovering partial relevant information to policymakers. However, an integrated method for the analysis of energy policy analysis towards clean energy transitions may contribute to a better-informed policy advise. Second, the majority of empirical policy mix research has focused on the European Union only. To overcome this limitation, we propose to expand the geopolitical coverage by applying the proposed method to developing countries members of the Organisation for Economic Co-operation and Development (OECD). Developing countries within the OECD have some common features in their electricity systems. The need for expansion of infrastructure is due to rapid growth in the electricity demand, continuous structural changes, and greater uncertainties regarding future conditions for energy system transition. The operationalisation of the proposed method may consider available public documents and databases of policy instruments, outcomes of interest, and key parameters encompassed within the electricity system (usually presented at a national level).

To gain insights to overcome these challenges in a holistic manner, this research focuses on answering the following research question: how can quantitative and qualitative methods for policy analysis be integrated to explore the plausible consequences of adopting different policy instruments towards clean energy transitions? With the aim of analysing these potential consequences considering many plausible futures, simulations combined with large data, computational capability, and visualisation tools are required [52]. Thus, an integrated method for policy analysis towards clean energy transitions is developed and presented in Section 3.

3 Introducing an integrated method for policy analysis

In this paper, an integrated method has been developed for policy analysis based on the robustness of energy policy mixes for clean energy transitions. This method integrates diverse quantitative and qualitative analytical tools used for policy design. It aims at analysing policy-relevant information by carrying out a series of interdependent analytical processes (see Fig. 4). Each process is explained in the following sections. By applying the method proposed we expect to aid policymakers in redirecting and accelerating innovation towards clean energy transitions.

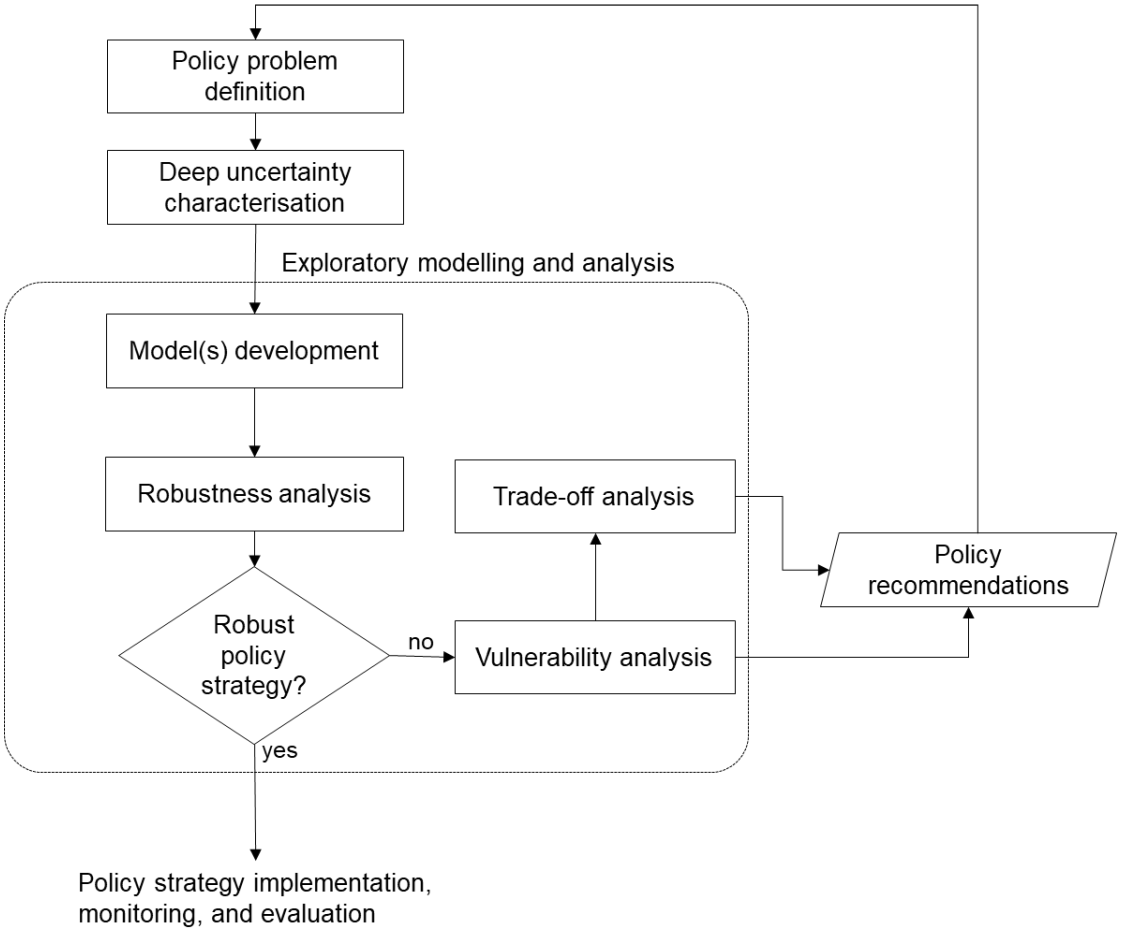


Fig. 4. Stepwise processes considered within the integrated method for energy policy analysis towards clean energy transitions.

3.1 Policy problem definition

The notion of conceptualising the system of interest to formulate model(s) structure(s) and to define the corresponding policy system boundaries is known with various terms: problem identification, problem definition, problem formulation, problem conceptualisation. In this paper, problem definition is used in lieu of problem identification within the policy analysis approach [13]. This first step within the integrated method is critical for obtaining and analysing 'the right' policy information relevant to policymakers.

Based on the understanding and definition of the policy system, model(s) development is carried out by different approaches. Thus, policy-relevant information is analysed differently to support policy-making decisions. Different conceptual framings have been applied to understand energy transitions, and then inform model development for exploratory analysis. For instance, Moallemi et al. [53,54] used qualitative storylines (historical narratives) to understand the dynamics of energy transition pathways in India. Based on a historically-informed review of energy transitions, they pointed out that narratives (i.e. structured storylines) frame the exploratory modelling and analysis process, serving as a conceptual framework to develop the system dynamics model. Kwakkel and Yücel [55] described historical trajectories to explain the internal dynamics within the Dutch electricity system and identify actors' preferences to shape plausible developments paths (i.e. energy transitions). Based on these historical trajectories and actors' decisions, an agent-based simulation model was developed for exploratory analysis.

The examples mentioned above were applied to the electricity sector using different approaches to inform the exploratory modelling and analysis process (structured historical narratives based on a socio-technical perspective and historical actors' behaviour). We argue that an integrated framework for policy systems conceptualisation and contextualisation is needed. Conceptualisation refers to the identification of the policy system boundaries, as well as identifying the key elements of the system of interest. Contextualisation calls for understanding the policy system within a geographical, sectoral, historical, and social context. Thus, to explain historical electricity transitions and their context, and then, define the policy problem, two complementary analytical phases are proposed.

First, based on literature review and policy research, the analyst describes historical electricity transitions to contextualise the current state of the system. The adoption of energy transitions concepts using a multi-perspective analytic framework [30] and core concepts from policy mixes for energy transitions literature [5,6] are suggested for this phase. In a second phase, an elicitation process is carried out with policymakers. This process uses a policy analysis framework labelled as 'COPRIEMD' to explicitly define the boundaries of the policy system to be analysed. The outcome of the first phase is used as starting point to lead the elicitation process towards the identification of key system's elements and to inform the development of the model(s) to be used in an exploratory modelling and analysis process (see Fig. 5).

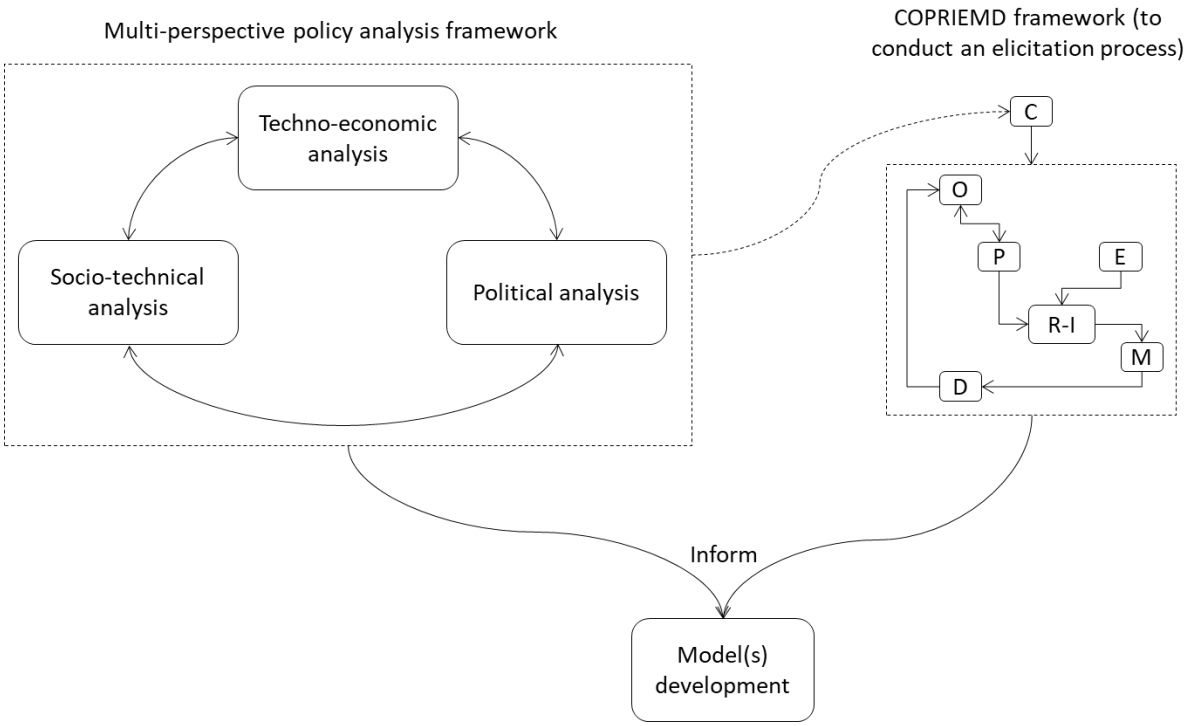


Fig. 5. Integrated framework for policy problem definition. (C = policy problem context, O = objectives values, P = policy alternatives, R = relationships, I = internal components, E = external factors, M = performance metrics, D = decision rules).

Sustainability transitions concepts have been used to describe historical electricity transitions and the role of diverse policy mixes in future transitions. For instance, a multi-perspective analytic framework (based on the interaction of techno-economic, socio-technical, and political processes) was applied to analyse national low-carbon electricity transitions by comparing the evolution of nuclear, solar, and wind power generation technologies in Germany and Japan [56]. In addition, concepts from the emerging literature on policy mixes

for sustainability transitions have been applied to study and assess the impact of policy mixes on electricity transitions in Europe (see, for instance, [57–60]).

A more comprehensive contextualisation of the policy system is sought, by applying a multi-perspective approach in the first phase, reflecting different perceptions of relevant elements of the system. The outcome of this phase is a structured storyline describing historical electricity transitions and the current situation of the policy system. Within this framework, diverse complementary sustainability transitions concepts are used (see Fig. 6) to describe and understand relevant long-term changes within energy systems. In addition, concepts from the policy mixes for energy transitions literature are integrated to explain the impact of policy instruments on historical electricity transitions. The main reason for using different (yet complementary) analyses of energy transitions is due to changes in the system can take place as a result of different contextual driving forces from one episode to another [30]. Aiming at identifying driving forces and main barriers in electricity transitions, that is used for the next phase of the policy problem definition process.

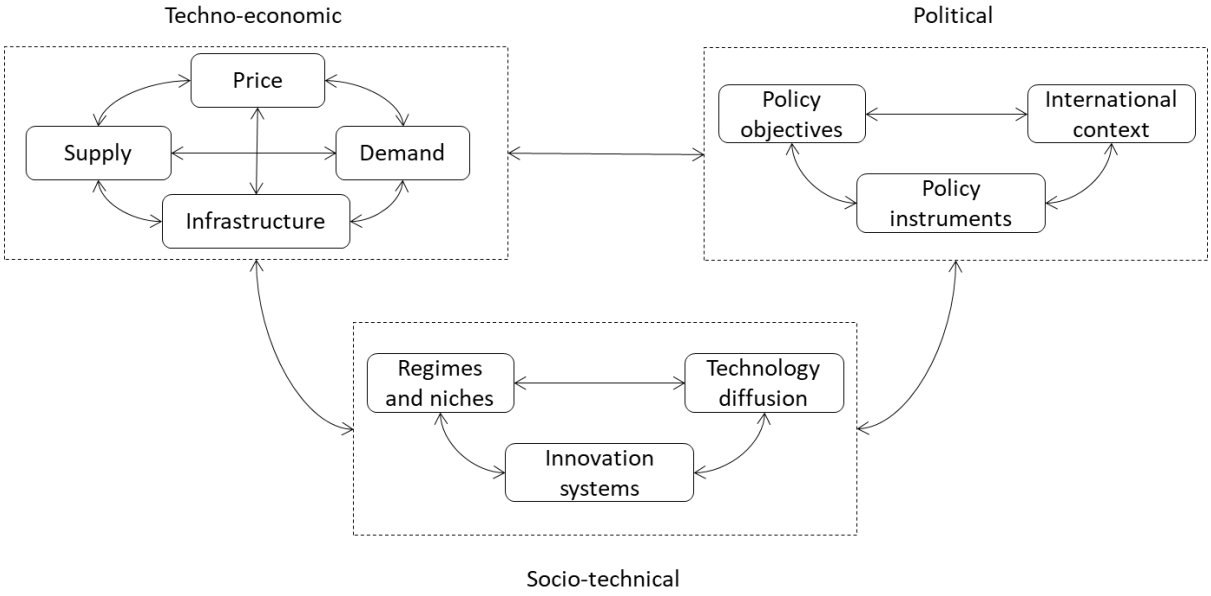


Fig. 6. Energy transitions concepts associated with the three perspectives on national energy transitions.
Sources: Own elaboration based on [5,6,30,56].

An elicitation process is proposed as the second phase to identify and to select the relevant elements to be included within the model(s) for exploratory modelling and analysis. To carry out this participatory technique a structured framework is needed to capture relevant information. Taking previous policy analysis frameworks as a basis [10,13] (see Section 2.1), a new framework for conducting an elicitation process is proposed. It aims to capture system perceptions from different stakeholders (e.g. industry, academia, and policymakers) (Fig. 7). Three key elements are added within this framework: policy problem context (C), objectives values (O), and decision rules (D), which are explained in the following section. For the rest of the elements within 'COPRIEMD' framework we use conventional terminologies within model-based policy analysis and robust decision-making domains: policy alternatives (P), external factors (E), internal components (I), and performance metrics (M) instead of policies, external forces, internal factors, and outcomes of interest, used in 'XPIROV' framework [32,33].

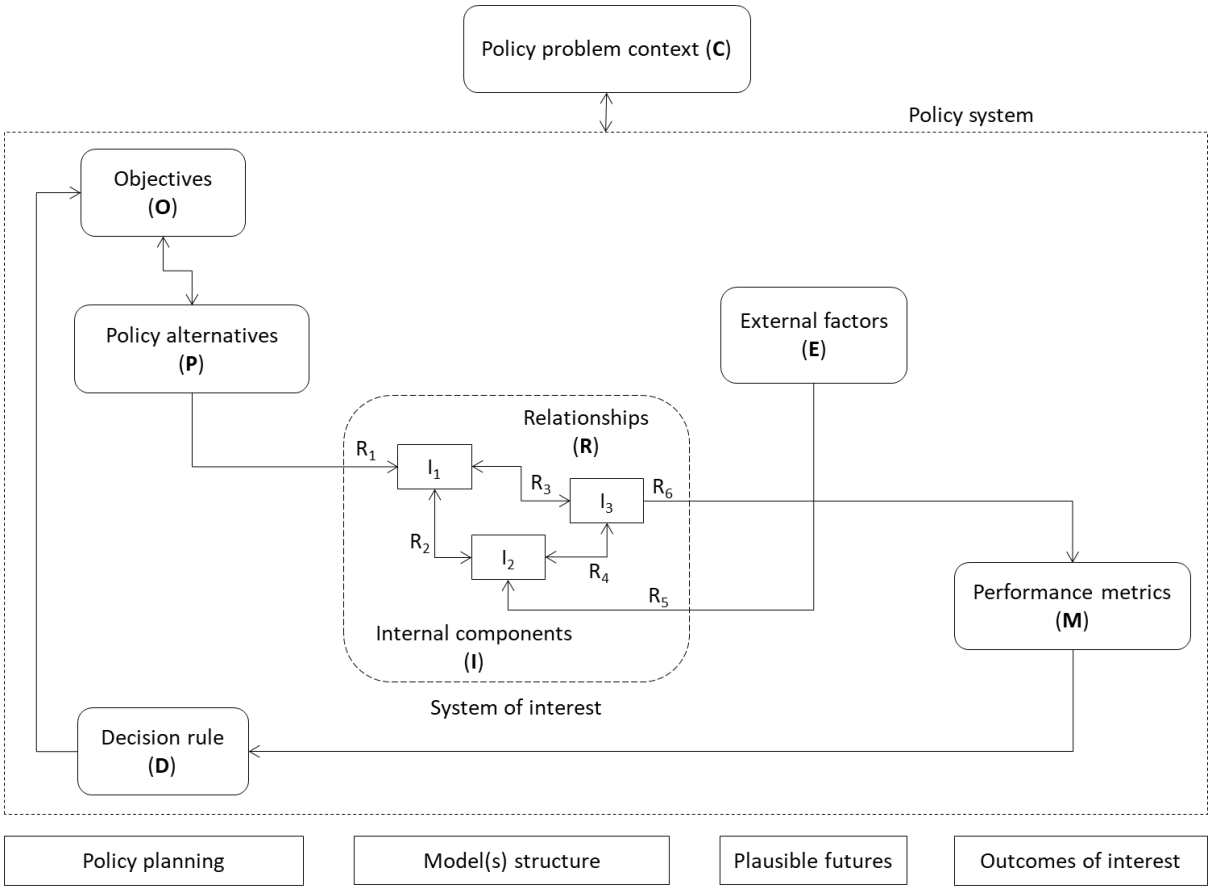


Fig. 7. Policy problem definition through COPRIEMD framework.

Policy problem context (C)
Aiming at identifying policy-relevant information regarding the nature, scope, stakeholders, boundaries, and possible impacts of policy mixes, the context within which different policy alternatives are to be assessed is established explicitly. The explicit policy problem context allows decision-makers to have a preliminary understanding of the policy problem, the context in which the system of interest is immerse, and the purpose of the analysis. For this paper, 'C' corresponds to the structured storyline generated using energy transitions concepts (see Fig. 5).

Objectives values (O)
In line with the policy problem context, and based on usually contested stakeholders' preferences, multiple objectives are involved in public policy problems [13]. To express a set of minimum acceptable performance requirements (i.e. performance thresholds) defined by decision-makers [61], the objectives values are encompassed in the proposed framework. These values are different from the value system proposed by Agusdinata and DeLaurentis [32]: similar to policies, the value system is taken as given within XPIROV framework, while objectives values in the framework proposed here consider possible trade-offs; setting thresholds based on stakeholders' preferences and priorities. The set of requirements can be evaluated in two ways: where all criteria must be met (as an intersection) or where any of the criteria are met (as a union) [61].

Decision rules (D) for robustness assessment
Specifying the decision rules within the policy problem definition process is paramount for analysing and communicating policy-relevant information to decision-makers. The definition

of robustness in this phase is proposed within the framework as a normative criterion for decision-making. Based on alternative robustness requirements, choosing an energy policy alternative among others could vary significantly. Thus, we argue that the policy problem definition process should include the selection of robustness requirements based on policymakers' preferences and system perceptions. The robustness identification can be explicitly established by policymakers or initially proposed by the analyst. Bearing in mind that the method presented is an iterative set of processes, the impact of alternative robustness requirements can be explored in following iterations.

3.2 Deep uncertainty characterisation

The representation of uncertainty has been conceptualised through diverse typologies in the literature [11,62]. Multiple types of uncertainty are presented in complex energy problems [63,64]. For instance, Kwakkel and Yücel [55] assessed the impact of technological, political, and socio-economic uncertainty factors on the development path for the Dutch electricity system. They stated investment and operational costs for various generation technologies, the demand development, decision making by generator companies, and carbon prices as the main uncertainties affecting electricity transitions. On the other hand, Moallemi et al. [53] identified five key deep uncertainties in the future transition pathways of the Indian electricity sector. Using standard sensitivity analysis in Vensim DSS and policy research they found that the learning curve of renewable generation technologies, electricity losses in grids, the potential installed capacity of renewables, the stability of policy supports, and the capacity factor of fossil fuel power plants are the main uncertainty factors in future electricity transitions.

To aid with the definition of what to be considered inside or outside the policy systems, we propose a *deep uncertainty characterisation matrix* (see Table 1) for leading the identification of deep uncertainties. To carry out the deep uncertainty characterisation a series of steps are proposed. First, all the internal components, relationships, external factors, and performance metrics obtained from the elicitation process are listed within the deep uncertainty characterisation matrix. Then, based on different perceptions of the policy system, the matrix is filled out specifying what elements are relevant for the analysis (model structure definition) and the range of possible values to be analysed (parametric definition). By filling the matrix considering different perspectives, diverse (complementary) model structures can be formulated. These models (considering different perceptions) serve as scenario generators for exploratory analysis.

In a single exploratory modelling and analysis approach, is technically feasible to deal with multiple alternative models (i.e. system perceptions) to analyse policy-relevant information [42]. By carrying out an exploratory modelling and analysis process, employing different but complementary models, the focus is on improving the process of learning about stakeholders' preferences and possible trade-offs.

The deep uncertainty characterisation matrix shown in Table 1 is proposed as an analytic tool to systematically obtain information about the elements that should be included within the policy system based on different perspectives. Thus, analysts and users of the model(s) can explicitly identify uncertain factors that may shape the future of clean energy transitions.

Table 1
Deep uncertainty characterisation matrix.

System perception (e.g. policymakers' perception of the system)				
Location		Relevant for analysis?	Initial value	Range
Model structure	Internal components (I)	-	-	-
	Relationships (R)	-	-	-
Future conditions	External factors (E)	-	-	-
Outcomes of interest	Performance metrics (M)	-	-	-

3.3 Exploratory modelling and analysis

3.3.1 Model(s) development and simulation

According to relativism, models are naturally relative, incomplete, and partly subjective [33]. Electricity transitions are characterised by dynamic complexities such as non-linearities among variables of the system, time delays, inter-temporal interactions, and side-effects between system variables. Electricity transitions have been analysed employing different modelling approaches for exploratory analysis (for example, Agent-Based Modelling (ABM) in [55], SoS in [32,33], System Dynamics Modelling (SDM) in [53,54,65]). These model-based analyses apply exploratory analysis to seek robust (policy) alternatives.

According to Bolwig et al. [22], energy transitions should be analysed through an endogenous approach. They pointed out that "*A more realistic representation of energy transition(s) requires consideration of a disequilibrium energy-economy-social system with delays in perception and adjustment, endogenous technological change, feedback effects and explicit behavioural rules, rather than optimization while assuming complete information and instantaneous equilibration of factor inputs to optimal levels.*" [22]. Following an endogenous approach, we propose System Dynamics (SD) [46] as the simulation modelling approach for implementing out the exploratory modelling and analysis process. SDM allow us to integrate socio-technical factors and explicit behavioural rules via information feedback loops and delays in perception and adjustment [22]. Although alternative modelling techniques such as ABM or Discrete Event Modelling (DEM) can be applied to energy policymaking, they require a vast amount of historical or empirical data to simulate the behaviour of individual entities [22].

SD is used to formulate and test structural policies. It is performed by modelling and simulating complex systems and analysing their resulting non-linear behaviour over time [44]. The focus of SD is on the use of simulation models to explore the relationship between a specific system structure and the dynamic behaviour of the system, based on established assumptions [43]. By formulating a dynamic hypothesis, the behaviour of the system can be explained [46]. By changing the system structure (e.g. alternative energy policy mixes), the resulting system behaviour may change over time (e.g. electricity transition pathways).

Koul et al. [64] pointed out that SD methodology had not been able to cope with deep uncertainties in energy systems. However, Kwakkel and Pruyt [43] proposed EMA as a complementary approach to SD to address this limitation by focusing on how policy analysis should be carried out despite multiple plausible models. When available policy-relevant information is not sufficient to choose a single model to explain the system behaviour, multiple (interrelated) models can be analysed using an exploratory approach. Thus, systems can be analysed considering diverse hypotheses around the structure of the system, parameter values, relationships among variables, external factors that affect the system behaviour, and diverse outcomes of interest (i.e. different models created based on different perceptions). By simulating one set of hypotheses, one computational experiment is obtained. The assumption

is, that various hypotheses (or assumptions) about the system are correct, one computational experiment represents how the system would behave according to those various hypotheses encapsulated in one single model [43].

3.3.2 Robustness analysis

Using computer simulations, the performance of policy alternatives is systematically explored across the range of uncertainties identified. Then, these alternatives are assessed according to the requirements of robustness set up during the problem definition process. Based on the performance criteria established by policymakers to 'accept' a policy alternative as satisfactory from the robustness aspect, policy alternatives can be ranked. Herman et al. [61] defined robustness as "*… the fraction of sampled states of the world in which a solution satisfies all performance requirements.*". Based on this definition, energy policy alternatives can be ranked between 0 and 100%. When a policy alternative is ranked with 0%, the alternative fails to meet the objectives thresholds in all plausible futures. On the other hand, a rank of 100% is assigned when a policy alternative satisfies the established performance criteria in all plausible futures. When several objectives thresholds are specified to accept a policy alternative, the analysis can be carried out focusing on each objective; allowing to underline those alternatives which could be of interest for policymakers for further analysis. If a policy alternative is considered robust based on the information analysed using the method presented, policymakers could justify the implementation of a policy instrument mix. If the potential policy alternatives are not robust enough, they can be redesigned aiming at increasing their robustness. A vulnerability analysis is proposed to identify the conditions in which policy alternatives perform poorly (i.e. vulnerabilities), and then propose new or modified policy alternatives to overcome these vulnerabilities.

3.3.3 Vulnerability analysis

In order to explore under what conditions an energy policy would perform well or would fail, an open exploration using EMA can be carried out. The exploration is to be done by generating a set of computational experiments that cover the complete uncertainty space [43]. Then, a large number of scenarios (plausible futures) can be analysed considering an extensive selection of uncertainties by using data-mining techniques. To identify the key uncertainties that lead cases where policy alternatives fail in future conditions, scenario discovery [66,67] uses data-mining and statistical methods to generate computational experiments. The analysis of model simulation results is used for explaining specific future behaviours based on a range of uncertainties. This approach assesses the quality of these ranges based on two metrics: (1) coverage, to measure if the ranges of uncertainty in input parameters completely explain the behaviour of interest (i.e. universality of ranges); and (2) density, to measure the number of cases with irrelevant behaviours within the selected range of uncertainties (i.e. purity of ranges). Then, by making an appropriate trade-off between coverage and density, the result is the best combination of uncertain inputs parameters that explain the vulnerability of policy alternatives in future conditions [45]. Once vulnerabilities of proposed policy alternatives are identified (i.e. key uncertainties influencing system behaviour), new or modified policy alternatives can be proposed to evaluate the robustness.

Scenario discovery has been applied to identify the conditions in which a renewable-dominated transition pathway is more likely to occur and to identify the long-run vulnerabilities of policy instrument mixes [34]. By performing 3000 computational experiments using the EMA Workbench [68], Moallemi et al. [54] demonstrated that solar and wind technologies could gain popular over a coal-dominated system in India if three conditions are met: (1) if the government sets ambitious targets and mobilising public funding and giving facilities to foreign investors to meet these targets, (2) if solar and wind potential available installed capacity outplays the existing estimates, and (3) if the price volatility of

fossil fuels is not protected by government subsidies. Another example regarding the use of scenario discovery to identify the conditions where a subsidy policy could fail in meeting its long-term objectives is found in [69]. Eker and van Daalen [69] studied subsidies as a candidate policy to achieve the minimisation of emissions and costs while maximising the biomethane production in the Netherlands. They found that the uncertain behaviour of producer's investment is the main uncertainty associated with the vulnerability of the subsidy policy investigated.

3.3.4 Trade-off analysis

By applying EMA for analysing clean energy transitions, a large set of computational experiments is generated, holding a vast amount of information regarding plausible transition pathways. Communication (visualisation, presentation) of policy-relevant information to policymakers is critical for successful implementation of policy alternatives in the system of interest [44]. Thus, visualisation techniques are required to aid policymakers with understanding insights obtained through computational experiments within the analytical method proposed. Diverse visual analytic techniques have been analysed to communicate these insights [33,39]. We propose to use Pareto sets of policy alternatives to compare them and to provide a clear understanding of trade-offs and possible consequences of each alternative [3]. However, depending on decision-makers' requirements and limitation, different techniques can be applied to explore trade-offs among policy alternatives.

3.4 Policy recommendations

By carrying out the proposed integrated analytical method, the aim is to analyse policy-relevant information and to create consensus about the selection of robust policy alternatives rather than specifying a single best policy mix. The selection, implementation, monitoring, and post-evaluation of policy alternatives is beyond the scope of this method. Policymaking in wicked conditions may be conceptualised as a learning process. When the policy problem definition, the development of policy alternatives, and the expected outcomes emerge from a collaborative process among stakeholders, policymakers, and analysts, an iterative approach is needed. Thus, learning may be facilitated by this iterative scheme revealing stakeholders' preferences and possible trade-offs among alternative problem definitions and solutions [3]. The method presented can aid in discovering robust policy alternatives based on stakeholders' priorities and preferences, making the possible trade-offs more evident and transparent within the policy-making process.

4 Discussion

The method developed and presented integrates quantitative and qualitative approaches to better understand the dynamics of historical electricity transitions and to explore the impact of energy-related policy instruments in future clean energy transitions. By integrating diverse analytical tools used for model-based policy analysis, it can bring several benefits for energy policymaking under deep uncertainty.

First: by understanding historical electricity transitions and the current state of electricity systems, the exploration of how different policy alternatives can influence clean energy transitions would be clearer to policymakers. That is, by using concepts of the policy mixes research and a multi-perspective analytical framework (via techno-economic, socio-technical, and political analyses) the dynamics of historical electricity transitions can be explained; highlighting the role of policy mixes as a major focus of analysis [30]. Then, to systematically define the boundaries of the policy system (objectives, policy alternatives, internal components, external factors, etc.), we proposed a new analytical framework for model-based policy analysis. This framework, explained in Section 3.1, differs from earlier frameworks in making explicit the context of the policy system, the objectives values, and the decision rules

(i.e. robustness) to choose robust policy alternatives. By integrating these two analytic frameworks a more comprehensive policy problem definition is sought.

Second: energy-related policy decisions for clean energy transitions occur under deep uncertainty conditions. To make an explicit effort to characterise deep uncertain factors, a deep uncertainty characterisation matrix was proposed. This matrix serves as an analytic tool to develop different model structures (according to different perceptions about the system), which can be analysed using an exploratory thinking approach, and thus, to obtain information about the influence of energy policy mixes on clean energy transitions. To deal with deep uncertainty, a robustness-based approach is adopted in the method presented. Though several robustness requirements have been proposed a priori with different impacts on policy decisions, we argue that the decision rules (i.e. robustness) should be clear based on decision-makers' preferences and their pessimistic/optimistic attitude about uncertain future conditions.

Third: once the elements of the model(s) have been defined and deep uncertainties are characterised, we proposed System Dynamics (SD) as an approach to develop the clean energy transition model(s). Although different quantitative modelling techniques have been applied for understanding energy transitions, system dynamics outstands from others due to its endogenous approach (i.e. focused on the system structure as the responsible of its dynamic behaviour). Following the notions of scenario discovery, multiple analyses are carried out within the exploratory process: (1) robustness analysis, (2) vulnerability analysis, and (3) trade-off analysis. These complementary analyses seek to obtain policy-relevant information regarding under what conditions a plausible future can take place and what combinations of uncertainties could trigger undesirable outcomes; to assess the robustness of policy alternatives under key deep uncertainty conditions; and identify possible trade-offs among alternatives.

A coordinated policy mix should combine technology-push and demand-pull policy instruments to address policy objectives such as GHG mitigation. By implementing this integrated method, policy recommendations can be structured to support policymakers in the development of more robust energy-related policy mixes towards clean energy transitions. However, following the stepwise interdependent analyses proposed in this paper, the method may be applied to other societal transitions such as transportation and water management.

The method proposed has some limitations. Based on the selection of relevant energy transitions concepts (from sustainable transitions literature and policy mixes for energy transitions research) to explain the dynamics of historical energy transitions, the perception of future electricity transitions could be different and, thus, influence the definition of the policy problem. Future research can be made by using additional complementary concepts to generate alternative narratives about electricity transitions. Model-based decision support under conditions of deep uncertainty is challenging due to the complexity in model validation. To increase the reliability of policy recommendations, we highly recommend involving stakeholders and policymakers in all phases of the process. The analytical tools presented in this paper are suggested in a conceptual basis to operationalise an exploratory thinking approach for policy analysis. The lack of empirical validation about the integration of these tools is perceived as a key limitation. Future research can be oriented towards applying the integrated method to case studies to verify its applicability. Some other limitations may exist during the application of the method to empirical case studies. Thus, depending on the types of policy problem, stakeholders, available information, and resources limitations complementary analytical tools and energy transitions concepts can be employed to address diverse energy policy issues.

5 Conclusions

Understanding how energy-related policy alternatives have affected electricity transitions and how they can influence future transitions aids policymakers in developing more robust policy alternatives. An integrated method for supporting policymakers with the design of robust energy-related policy alternatives towards clean energy transitions has been developed and presented. The method integrates quantitative and qualitative approaches to better understand the dynamics of historical energy transitions and explore the impact of energy-related policy mixes in future transitions. Policy-relevant information about clean energy transitions can be analysed by carrying out the interdependent analytical processes presented in Section 3.

The proposed method was formulated by combining the strengths of various analytical tools found in sustainability transitions literature [30], policy mixes for energy transitions [5,6], robustness-based frameworks [10,39], dynamic modelling techniques [46], and exploratory thinking [33,44,47]. First, by integrating a multi-perspective analytic framework [30], concepts from policy mixes for energy transitions literature [5,6], and a new analytical framework for policy analysis, a more comprehensive policy problem definition was sought. Based on the main economic, technological, social, and political drivers for historical energy transitions, the boundaries of the policy system can be defined aiming at analysing the possible consequences of implementing different policy instruments. Second, to make an explicit effort to characterise deep uncertain factors, a deep uncertainty characterisation matrix was proposed. This matrix serves as an analytic tool to systematically elicit information about what set of elements should be included in the model, based on different perspectives about the system (e.g. when there are different parties deciding). Thus, different model structures can be formulated (structural uncertainty) with diverse parameter values to be analysed (parametric uncertainty). By characterising deep uncertainty factors, diverse models and parameters can be analysed using an exploratory thinking approach to obtain information about clean energy transitions for policy analysis. Third, we propose System Dynamics (SD) [46] as the simulation modelling approach to build a clean energy transition model(s). That is due to its focus on the system structure as the responsible of its dynamic behaviour (endogenous). Models created serve as scenario generators for exploratory analysis to obtain policy-relevant information upon: (1) under what conditions a plausible future can take place and what combinations of uncertainties could trigger undesirable outcomes, (2) the estimation of the robustness of policy alternatives under key deep uncertainty conditions, and (3) possible trade-offs among policy alternatives.

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Chapter 3

Energy transitions governability: past, present, and future driving forces of clean energy development in Mexico

In the previous chapter, a new integrated method for exploring policy mixes towards clean energy transitions was developed and presented. The stepwise implementation of the method is based on an iterative set of processes. The first analytical process within the proposed method is the conceptualisation and contextualisation of the system of interest (i.e. policy problem definition). Thus, Chapter 3 presents the development and application of a new theoretical framework for analysing energy transitions governability. It describes the evolution of historical electricity transitions in Mexico (1879–2012) from the perspective of the interactive governance approach. By using concepts from three perspectives (i.e. socio-political, sociotechnical, and techno-economic) and policy mixes for sustainability transitions an inventory of 'micro-logics' was formulated to explain specific elements and episodes of energy transitions in Mexico. Interactive governance theory was proposed to synthesise these micro-logics into a broader theoretical construct (i.e. energy transitions governability framework). In addition, this chapter presents the empirical application of the developed theoretical framework to describe the evolution of clean energy technologies in Mexico (1879–2021) and to identify drivers and barriers to their development in the future, demonstrating the broader applicability of the framework to energy systems at different scales. Also, current policy objectives, specific targets, performance indicators, and potential policy instruments towards a clean energy transition in Mexico are identified and discussed within this chapter.

The outcome of this chapter is used to guide the elicitation process and to inform the development of the model to be used in the EMA process.

Chapter 3 theoretically and empirically contributes to this study by answering Question #2 and Question #3:

How can concepts from energy transitions, policy mixes for sustainability transitions, and interactive governance theory be integrated to qualitatively explore the evolution of energy systems in developing countries?

- *What sustainability transitions concepts can be applied to describe historical energy transitions from different perspectives (i.e. techno-economic, socio-technical, and political)?*
- *How can the description of qualitative narratives derived from the multi-perspective analysis be synthesised in a theoretical framework to understand national energy transitions over time?*
- *How can the understanding of historical energy transition inform model(s) development for policy analysis?*

What key drivers and barriers in the Mexican electricity sector may shape future conditions towards a clean energy transition?

- *How governing structures in the Mexican electricity sector have evolved over time?*
- *What role have these governing structures played in shaping historical electricity transitions?*
- *What have been the main drivers for structural change within the Mexican electricity system?*
- *How clean energy technologies have evolved in Mexico over time?*

- *What have been the drivers and barriers to deploying clean energy technologies in Mexico?*
- *What are the most relevant policy mixes to be explored towards a clean energy transition in Mexico?*

Chapter 3 is based on two journal articles:

"*Competition, coordination, or institutional change? A multi-perspective analysis of historical electricity transitions in Mexico*" published in *Energy Research & Social Science*, and

"*Evolution of clean energy technologies in Mexico: A multi-perspective analysis*" published in *Energy for Sustainable Development*.

Although both articles follow a similar analytical approach, the empirical application of the developed theoretical framework to the Mexican case at different scales (i.e. electricity systems in general and clean energy technologies in particular) contributes to the policy problem formulation process by identifying drivers and challenges in energy transitions at different structural levels, using complementary energy and sustainability transitions concepts. The periods of analysis covered by each article were selected based on reviewers' comments and the word limitation established by each journal.

The format and numbering of the sections are according to the original publication styles (see Appendix C). Due to different review and publishing processes and times, in-text citations and references in each article were incorporated following journal requirements.

Chapter 3

Competition, coordination, or institutional change? A multi-perspective analysis of historical electricity transitions in Mexico

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ABSTRACT

The electricity sector is a complex dynamic system that has experienced continuous changes since its beginning. The aim of this article is to explore the evolution of historical electricity transitions in Mexico from 1879 to 2012 under the interactive governance approach. Governability provides an analytical framework for investigating the role of actors, technologies, and policies in national energy transitions. By integrating a multi-perspective analytical framework, we applied concepts from energy transitions and policy mixes for sustainability transitions to qualitatively describe social, economic, and technological changes and their relative role in historical transitions. The case study revealed that governability of national energy transitions may vary considerably from one episode to another depending on how governance systems have handled national societal needs and international cooperation agreements. Additionally, different drivers have been identified in shaping electricity transitions in Mexico. First, governance decisions have depended on specific (policy) paradigms that relevant actors have adopted. Second, the article highlights the key role that available (indigenous) energy resources have played in directing the path and pace of electricity production technologies. Third, increasing environmental and climate change concerns have improved the way electricity is produced and used. The analysis conducted suggests that energy transitions governability may be improved by fostering communication and cooperation among actors and institutions to define policy mixes in line with societal needs.

***Keywords*:** Governability; interactive governance; energy transitions; multi-perspective analysis; electricity sector; Mexico.

Abbreviations

CFE	Federal Electricity Commission (Comisión Federal de Electricidad)
CIDE	Centre for Economic Research and Teaching (Centro de Investigación y Docencia Económicas)
CLyF	Mexican Light and Power Company (Compañía de Luz y Fuerza)
CNEN	National Nuclear Energy Commission (Comisión Nacional de Energía Nuclear, CNEN)
CNFM	National Power Commission (Comisión Nacional de Fuerza Motriz)
CNSNS	National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias)
CO_2-e	carbon dioxide equivalent
CONACYT	National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología)
CONAE	National Energy Saving Commission (Comisión Nacional para el Ahorro de Energía, CONAE)
CONUEE	National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía)
CPP	cogeneration power producer
CRE	Energy Regulatory Commission (Comisión Reguladora de Energía)
CSS	continuous self-supply
CUF	Committee for the Unification of Frequencies (Comité de Unificación de Frecuencia)
FH	Hydrocarbons Fund (Fondo de Hidrocarburos)
FIDE	Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica)
FSE	Energy Sustainability Fund (Fondo de Sustentabilidad Energética)
GDP	gross domestic product
GHG	greenhouse gas
GI	governing interactions
GS	governance system
IER	Institute of Renewable Energy (Instituto de Energías Renovables)
IIE	Electricity Research Institute (Instituto de Investigaciones Eléctricas)
IINGEN	Institute of Engineering (Instituto de Ingeniería)
INECC	National Institute of Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático)
INEEL	National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias)
ININ	National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares)
IPP	independent power producer
kW	kilowatts
LAERFTE	Use of Renewable Energy and the Financing of the Energy Transition Law (Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética)
LASE	Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía)
LGCC	General Climate Change Law (Ley General sobre Cambio Climático)

LGEEPA	General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente)
LUCF	land use change and forestry
MW	megawatts
NAFTA	North American Free Trade Agreement
NGCC	natural gas combined cycle
NGT	natural gas turbine
NO_x	oxides of nitrogen
OECD	Organisation for Economic Co-operation and Development
PAESE	Energy Saving Program for the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico)
PE	power exports
PEMEX	Mexican Petroleum (Petróleos Mexicanos)
PI	power imports
PPA	power purchase agreement
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSS	power self-supply
PV	photovoltaic
R&D	research and development
RD&D	Research, development, and demonstration
SE	Secretariat of Economy (Secretaría de Economía)
SEMIP	Secretariat of Energy, Mining and Parastatic Industry (Secretaría de Energía, Minas e Industria Paraestatal)
SEN	National Electricity System (Sistema Eléctrico Nacional)
SENER	Secretariat of Energy (Secretaría de Energía)
SG	system-to-be-governed
SME	Mexican Electricity Labour Union (Sindicato Mexicano de Electricistas)
SO_x	oxides of sulphur
SPP	small power producer
UAM	Metropolitan Autonomous University (Universidad Autónoma Metropolitana)
UK	United Kingdom
UNAM	National Autonomous University of Mexico (Universidad Nacional Autónoma de México)
UNFCCC	United Nations Framework Convention on Climate Change
US	United States

1. Introduction

Electricity is vital for supporting economic development. The electricity sector has been experiencing deep-structural changes worldwide since the 19th century. These changes in electricity system configurations are the result of complex, dynamic interactions between multiple actors (e.g. policymakers, generation companies, consumers) and societal systems (including infrastructure, markets, policies). Electricity transitions have been conceptualised as multi-actor, long-term dynamic processes of structural change in the way electricity is produced and consumed [1]. These processes are the result of the interactions between a set of interconnected transformations at different sublevels and scales that take place over long periods of time. Although there is no universal agreement on how large these changes would establish a transition, relationships between the scale, the depth, the speed, and the complexity of change have been discussed to gain better understanding on energy transitions [2–5].

Electricity generation and consumption has contributed considerably to greenhouse gas (GHG) emissions and thus to anthropogenic climate change, especially in developing countries. Transitions towards low-carbon economies require the understanding of past structural transformations within electricity systems and the role that governance systems have played in those transitions. Interactive governance theory and governability provide a conceptual basis for exploring changes in governance of dynamic societal systems, such as electricity transitions [6]. Mexico is an appealing case study due to its fossil fuel-intensive energy mix which has positioned the country as the 11th largest GHG emitter worldwide [7,8]. To comply with international agreements on climate change mitigation, Mexico has set ambitious targets on GHG emission reductions with the electricity sector to be the largest contributor of these reductions [9]. However, the (ever-growing) electricity demand in Mexico may exhibit significant challenges for future transitions if previous structural system transformations and their drivers are not fully understood. To improve the in-depth understanding of historical structural changes in the electricity system in Mexico, this work focuses on answering the following research questions: how governing structures in the electricity sector have evolved over time? What role have these governing structures played in shaping electricity transitions? What have been the main drivers for structural change within the Mexican electricity system?

The aim of this article is to explore the governability of historical electricity transitions in Mexico from 1879 to 2012. By integrating energy transitions concepts with interactive governance theory, we seek a more comprehensive qualitative explanation of historical national energy transitions in developing countries. This work builds on previous energy transitions literature by integrating the interactive governance approach as an analytical framework for describing the co-evolution of techno-socio-economic systems. Simultaneously, a national energy system is conceptualised by using complementary perspectives (i.e. socio-political, techno-economic, and socio-technical) to explore governing interactions over time. This adds to interactive governance literature by integrating a multi-perspective framework for conceptualising the system-to-be-governed and expanding its application to electricity transitions. Also, concepts from energy transitions, policy mixes for sustainability transitions, and interactive governance theory are integrated and applied (i.e. theoretical synthesis [10]) to describe historical electricity transitions in Mexico, expanding their relative application to developing countries (i.e. empirical contribution).

The rest of this article is organised as follows. Section 2 sets the theoretical framework for analysing energy transitions governability. An empirical application of the framework to Mexican historical electricity transitions from 1879 to 2012 is presented in Section 3. Findings of the analysis, limitations, and potential future research are discussed in Section 4. Conclusions are exhibited in Section 5.

2. Energy transitions governability for techno-socio-economic systems

2.1. Interactive governance and energy transitions governability

The concept of governance has been defined and applied in different ways by different social science (sub)disciplines (e.g. political science, economics, public administration) [11]. The main difference is on the perceived role of the state as a governance agency, following a normative or an analytical approach. Traditionally the idea of governance has been related to governments and their functions within society (e.g. acting as governor). However, it has been recognised within the governance theory that governance is beyond government and that societies are formed by a large number of governing actors (i.e. social units), who are constrained or enabled by social frameworks (including culture, law, politics, economics, material and technical possibilities) [6,12]. Thus (interactive) governance refers to the collective governing activities carried out by societal actors (including non-state institutions) in response to public needs and visions [6]. Kooiman [12] defines interactive governance (also called social-political governance [11]) as "the whole of interactions taken to solve societal problems and to create societal opportunities, including the formulation and application of principles guiding those interactions and care for institutions that enable them.".

The interactive perspective of governance suggests that societal needs and public goals are not given but negotiated, and are not stable but dynamically crafted relatively to the agency of participants engaged in socio-political processes [12]. These (complex) processes occur within societal (sub)systems. A societal system (or subsystem) is broadly understood as the interrelations between a number of entities belonging to the social and natural world [6]. The interactive governance perspective suggests that societal systems are made up of three interrelated components: a system-to-be-governed (SG), a governance system (GS), and the governing interactions (GI) between these two [6]. The system-to-be-governed can be conceptualised in different ways and at different scale levels [12]. This is, the questions on what the relevant elements of a system are, how to define its boundaries, and how it may be broken down analytically depend on the observers' paradigms and on the nature of the research enquiry [13]. A governing system encompasses the total set of processes and mechanisms that are available for guidance, control, and steerage of the SG to be analysed. Governing interactions refers to mutually influencing relationships among two or more actors or entities in a governance setting [12,13]. Under systems theory, societal systems are partially open systems that must take action in response to environmental changes [14]. Thus, external factors may influence governing interactions, since these three interrelated systems interact with the external environment as well [15].

Based on the interactive governance perspective, governability has been defined as: "the overall quality for governance of any societal entity or system consisting of SG, GS and GI." [6]. Governability depends on the ability of a governance system to perform on the challenges (and opportunities) than the SG raises in the presence of governing interactions [12]. Thus governability is conceptualised as a property of the system of interest built upon a holistic approach (i.e. the system is a whole formed of interrelated and interdependent parts, interacting to maintain that whole) [14]. The interactive governance theory states the recognition of diversity, complexity, dynamics, and scale of the system to define the boundaries of analysis [13]. Diversity refers to qualities of actors and entities within the system. Complexity denotes the examination of societal structures, the relationships among the system as a whole and their parts, as well as the interactions between the system and its environment. Dynamics points out at the non-linear feature of societal change, creating the possibility of change over time. Scale refers to the spatial, temporal, quantitative or analytical dimension of the analysis [11,13].

Energy systems become more complex and dynamic as more actors and institutions are involved in governance processes for (energy) transitions to low-carbon economies. Energy

transitions have been conceptualised as co-evolutionary, multi-actor, long-term dynamic processes of structural change in the way energy is produced and used [1]. It has been recognised that energy transitions may be better analysed and explained by using several complementary theories, as opposite of using a single theory of transitions [2]. How to conceptualise the system-to-be-governed has been identified as one caveat in interactive governance and governability literature [16]. Thus, we proposed the integration of a meta-theoretical framework [1,2] to conceptualise and describe national energy transitions as a set of three co-evolving systems: energy flows and markets, energy technologies, and energy-related policies (i.e. techno-socio-economic systems). In this article we use the interactive governance perspective which focuses on the interactions between the state, private actors, and civil society aimed at solving societal needs (or creating societal opportunities) in the electricity sector over time (see Fig. 1) [11,13]. Thus, we introduce the term 'energy transitions governability' to analyse governance processes of historical national energy transitions. Although interactive governance and governability have been used to analyse and assess energy systems (see for instance [15,17–19]), the term was not yet found in the literature.

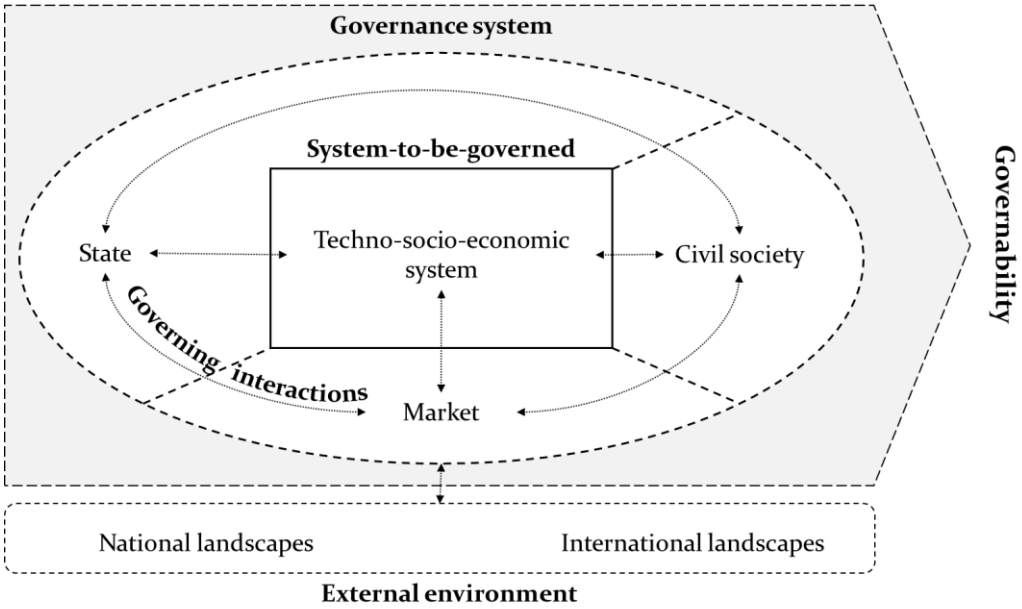


Fig. 1. Interactive governance perspective for governability of societal systems. Adapted from [6,18].

2.2. Multi-perspective energy transitions analysis

Energy transitions have been analysed using diverse transitions theories with different roots (e.g. social studies, political science, economics) (see for instance [2,20]). Cherp et al. [2] suggested that long-term changes in energy systems occur within three main co-evolving subsystems: (1) techno-economic subsystem, explained by energy flows related to energy supply and demand coordinated through energy markets; (2) socio-technical subsystem, defined by energy technologies; and (3) socio-political subsystem, influencing energy systems by developing and implementing energy-related policy instruments [1,2]. Within this framework, different sustainability transitions concepts are used to describe energy transitions (see for instance [21]). Complementarily, Castrejon-Campos et al. [1] proposed the integration of concepts from the policy mixes for sustainability transitions literature to explain the impact of policy instruments on historical energy transitions. The main reason for using diverse energy and sustainability transitions concepts is due to changes in the system may take place as a result of different contextual and structural driving forces (or barriers) from one episode to another [1].

Concepts from the three perspectives (i.e. socio-political, socio-technical, and techno-economic) are considered in this work to gain understanding on historical electricity transitions, and what possible factors may shape the future changes towards clean energy transitions. Fig. 2 depicts the main energy transitions concepts to be included within the analytical framework for analysing the governability of national energy transitions. A detailed description of each concept may be found in [2,22–25]. Different (complementary) concepts based on the same disciplinary roots may be found in [1,2,21].

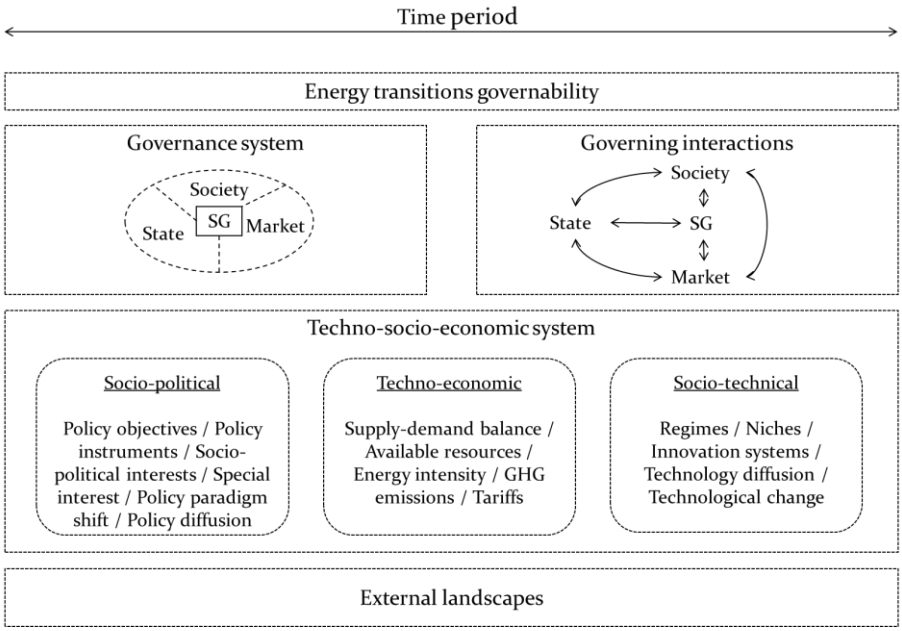


Fig. 2. Analytical framework for energy transitions governability.

The main analytical method used to describe the governability of historical electricity transitions in Mexico was the systematic literature review and analysis of quantitative data with a theoretical heuristic approach. The flow of information through the different steps of the systematic review followed is depicted in Fig. 3 (based on the four-step flow diagram within the PRISMA statement [26]). A detailed description of the research method is presented in Appendix A and the limitations are discussed in Section 4. The documents reviewed include books, reports, datasets, scholarly articles, analyses, laws, and regulation frameworks published in academia, international organisations (e.g. International Energy Agency), and national government bodies (e.g. Mexican Secretariat of Energy, Federal Electricity Commission). The systematic review generates qualitative storylines (i.e. stylised facts) for a better interpretation of data to readers [27].

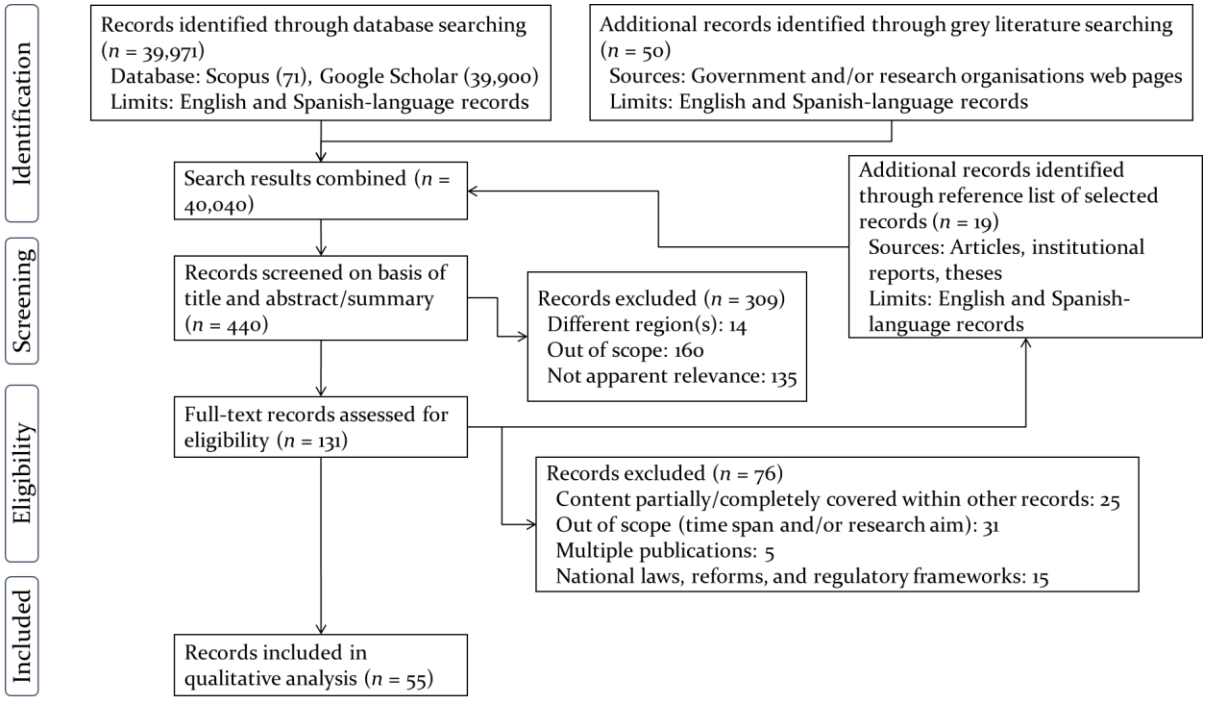


Fig. 3. Flow of information through the different phases of the systematic review. Adapted from [26].

3. Historical electricity transitions in Mexico

3.1. The beginning of the electricity industry and control of private monopolies (1879-1936)

The first use of electricity in Mexico dated from 1879 when electricity was first used in a textile factory in the city of León, Guanajuato. From 1880 electricity was mainly used for public lighting in Mexico City and a few years later in other main capital cities (e.g. Guadalajara in 1884, Monterrey in 1888, and Veracruz and Mérida in 1889). The use of electricity was further extended to strategic sectors such as mining, manufacturing (e.g. textile and paper factories), and transport (e.g. trams) [17,28,29].

[Actors] From 1879 to 1937 electricity was generated, transmitted, and distributed by private companies only. The period from 1890 to 1910 was characterised by the increasing electricity demand from manufacturing plants and workshops that were not able to generate their own, as well as for public services (e.g. lighting, water pumping, trams). During this period more than one hundred light and power companies were established within the country to satisfy local or regional needs. With an increasing demand and lack of state regulation a process of monopolisation took place where three private companies dominated the electricity industry until a state-owned company was created in 1937.

[Socio-political] During the beginnings of the electricity industry in Mexico, the government of Porfirio Díaz (1884-1911) adopted economic policies to attract investment and technological developments mainly from United States (US) and Europe with the aim of modernising the country [29]. Díaz's (export-oriented) ***policy objectives*** on progress and economic growth were based on exploitation of the country's ***natural resources*** (mainly water in the case of electricity generation). However, the modernisation of the country led to wealth disparity and growing social injustice triggering the Mexican Revolution of 1910.

[External landscapes] The Mexican Revolution was a domestic ***landscape*** aimed mainly at increasing the influence of working classes [29]. The armed movement ended with the promulgation of the political constitution of Mexico in 1917 (another domestic ***landscape***). The articles relevant to the electricity sector were those related to property of land and water

(article 27) and the rights of workers (article 123). Article 27 stated that all land and water within the national territory were owned by the Nation, which had the right to transfer the ownership to particulars; and that the state would regulate the exploitation of natural resources based on ***societal needs***. Article 23 established the rights of workers including the eight-hour workday, the right to strike, and the right to a rest day per week [28].

[Socio-political] - [Actors] The ***regime*** from 1879 to 1917 was characterised by neither public investment nor state regulation for the electricity industry and informal rules (***interplays*** within the interactive governance theory) in the ***governance system*** [28]. The constitution of 1917 (article 27 in particular) represented the starting point of a formal ***state intervention and regulation*** in the development of the energy sector. However, from 1917 to 1934 intervention and regulations on the electricity industry were limited [28]. State regulation formally started in 1926 with the creation of the National Power Commission (Comisión Nacional de Fuerza Motriz, CNFM) and publication of the National Electricity Code (Código Nacional Eléctrico). The code contained the technical specifications for generation and use of electricity and was later expanded to give more control to the state by allowing routine inspections to power plants, tariff regulation, and conflict resolution between producers and consumers [29]. Due to legal inconsistencies and lack of a robust regulatory framework, the code did not have the impact expected until 1934 when a constitutional reform (article 73) gave the Congress the power to (constitutionally) regulate the electricity industry and thus power generation and distribution were declared as 'public interest' activities [28].

[Techno-economic] After the revolution, the period from 1920 to 1936 was characterised by the consolidation of private monopolies, an increase in electricity tariffs, and a ***technological regime*** restructuring process [28]. Although electricity tariffs had to be approved by the state, private companies were able to establish them according to their financial structure and own (economic) interests [30]. Thus, electricity companies increased their investments without concrete government interventions. The lack of coordination within the ***governance system*** brought several tensions to the system, including complains regarding high and dissimilar tariffs throughout the territory, lack of service in areas under development, poor security of supply, and poor labour conditions (e.g. heavy workloads, low salaries, poor health conditions).

[External landscapes] The Great Depression was an international ***landscape*** that affected the national economy in general and the electricity sector in particular. Between 1930 and 1935 many small electricity companies went bankrupt due to financial constraints. Also, large consumers of electricity were economically affected, reducing revenues for power generation companies [29].

[Socio-technical] The first power equipment installed for electricity generation in Mexico was a 1.8 kW thermal plant (coal-fired) for lighting purposes. Hydroelectric power was first generated in 1889 (ten years after the first recorded use of electricity in Mexico). However, due to vast water ***resources available*** throughout the country, a technology transition from thermal to hydropower occurred during this period (see Fig. 4). During the early stages of the electricity industry in Mexico all electric equipment was imported (mainly from Europe and US) and technical specifications were set by producers, making challenging to adapt specific equipment to national needs [28]. The period from 1917 to 1936 was characterised by construction of medium-size power plants (both hydro and thermoelectric). Necaxa, in Puebla, was the first medium-size hydro power plant (5 MW) built from 1938 to 1944. Also, piston engines were replaced by turbines in the 1920s [28], increasing efficiency and productivity.

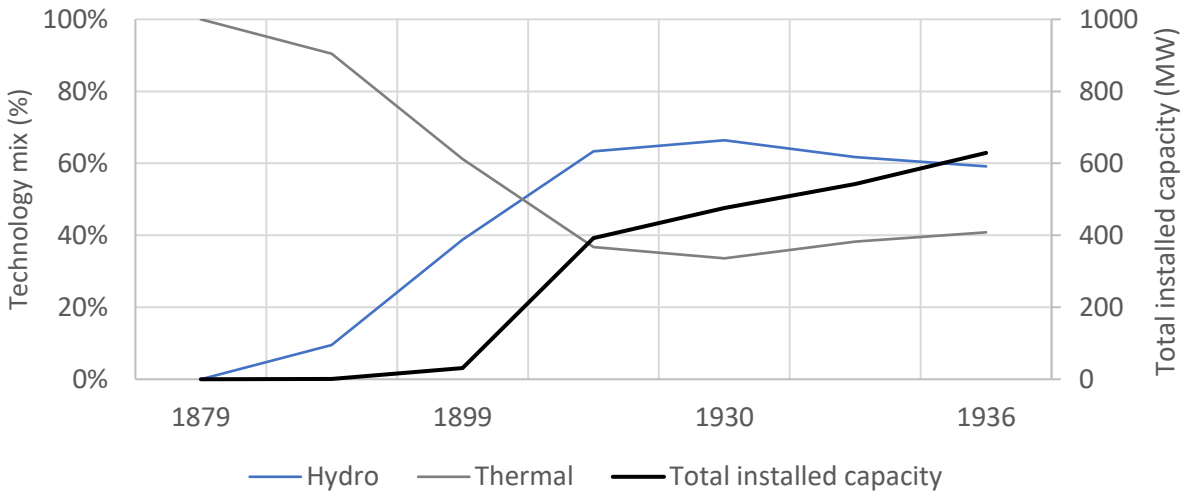


Fig. 4. Technology mix (left) and total installed capacity (right) from 1879 to 1936. Constructed with data from [28,31,32].

[Socio-technical] - [Actors] Interest in innovation processes within the electricity sector dated from 1911 when a gremial organisation established support for innovation as one of their main objectives [28]. This organisation was the predecessor of the first formal electricity labour union (Sindicato Mexicano de Electricistas, SME) which was formally created in 1914. Due to poor working conditions offered by private companies, labour unions started playing an important role in electricity transitions as ***organised social movements*** creating ***socio-political interests***. Fig. 5 depicts the main governance actors in the electricity system by 1936.

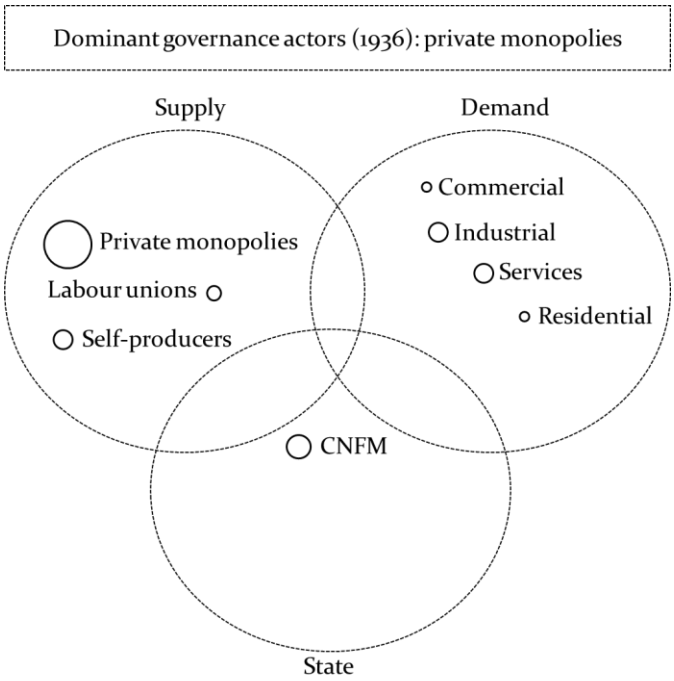


Fig. 5. Dominant governance actors by 1936. The size of the circles represents the relevance of their role within the governance system. Adapted from [29] with information from [28,33].

3.1.1. Multi-perspective summary (1879-1936)

Porfirio Díaz's (national) policy objectives were oriented towards modernisation and progress in all economic sectors. Increasing demand for electricity posed pressure to the state to

increase its participation in the governance system by promoting development of the sector. Thus, the National Electricity Code was created to regulate the use of electricity generation equipment and intervene in conflict resolutions. Based on policy mix literature [34], Fig. 6 presents the main policy objectives and instruments during this period of analysis.

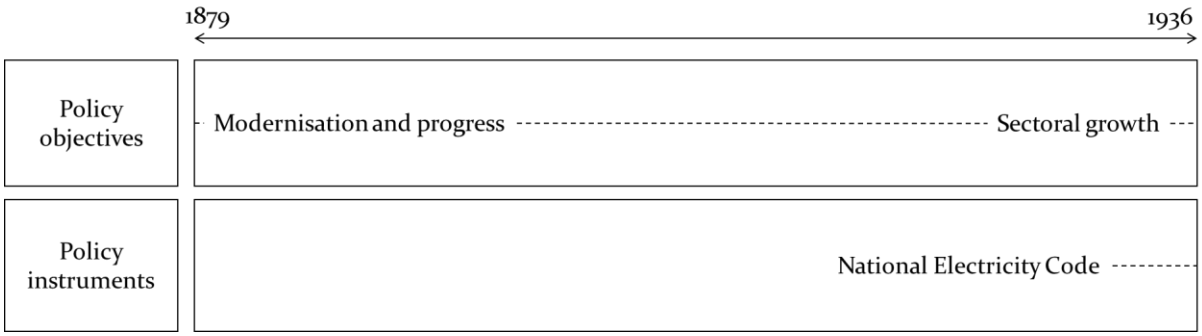


Fig. 6. Socio-political perspective snapshot (1879-1936).

Electricity services started by meeting specific local or regional needs, characterised by poor supply services. Also, the lack of regulation created great variability in electricity tariffs and coverage for specific areas only. Fig. 7 presents the main outcomes of interest for analysing the electricity system performance during this period.

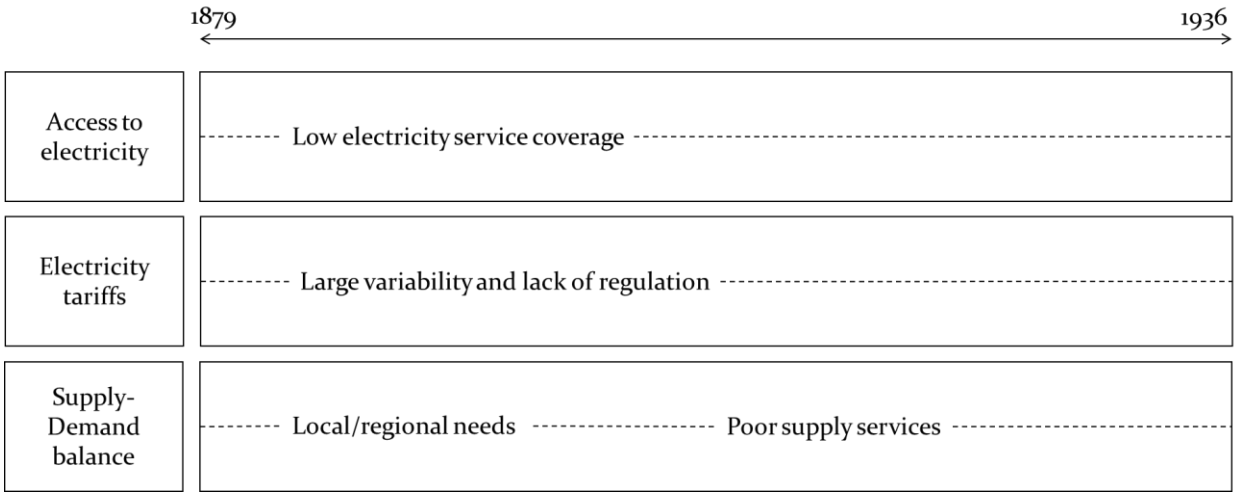


Fig. 7. Techno-economic perspective snapshot (1879-1936).

From the technological change point of view, the period was characterised by a transition from thermoelectric power plants to hydropower plants; construction of medium-size power plants (a few MW), and a transition from piston engines to turbines (horizontal turbines in the case of hydropower). However, Mexico was completely dependent on imported equipment mainly from US, Canada, and Europe. Fig. 8 depicts the main socio-technical changes the electricity system experienced during this period.

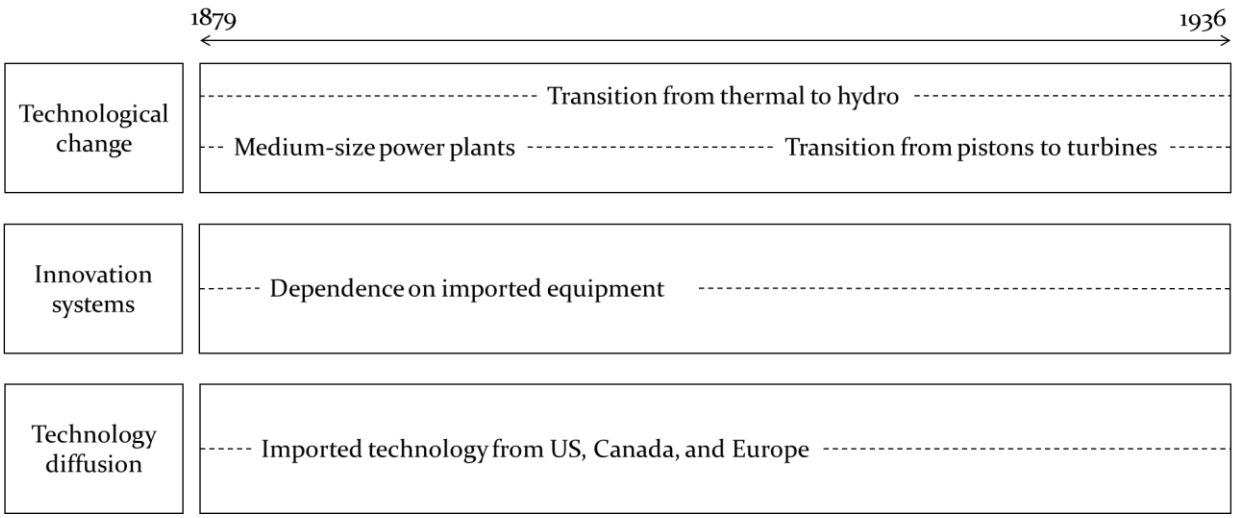


Fig. 8. Socio-technical perspective snapshot (1879-1936).

3.1.2. Energy transitions governability (1879-1936)

The period from 1879 to 1936 was characterised by weak state regulation (starting with a governance system without government [35]); a process of monopolisation; a governance system controlled by the market (mainly private monopolies); a restructuring process of the regime caused by internal tensions and external landscapes; no innovation; and a local/regional development of the electricity sector. Fig. 9 and Table 1 represent the energy transitions governability snapshot for this period.

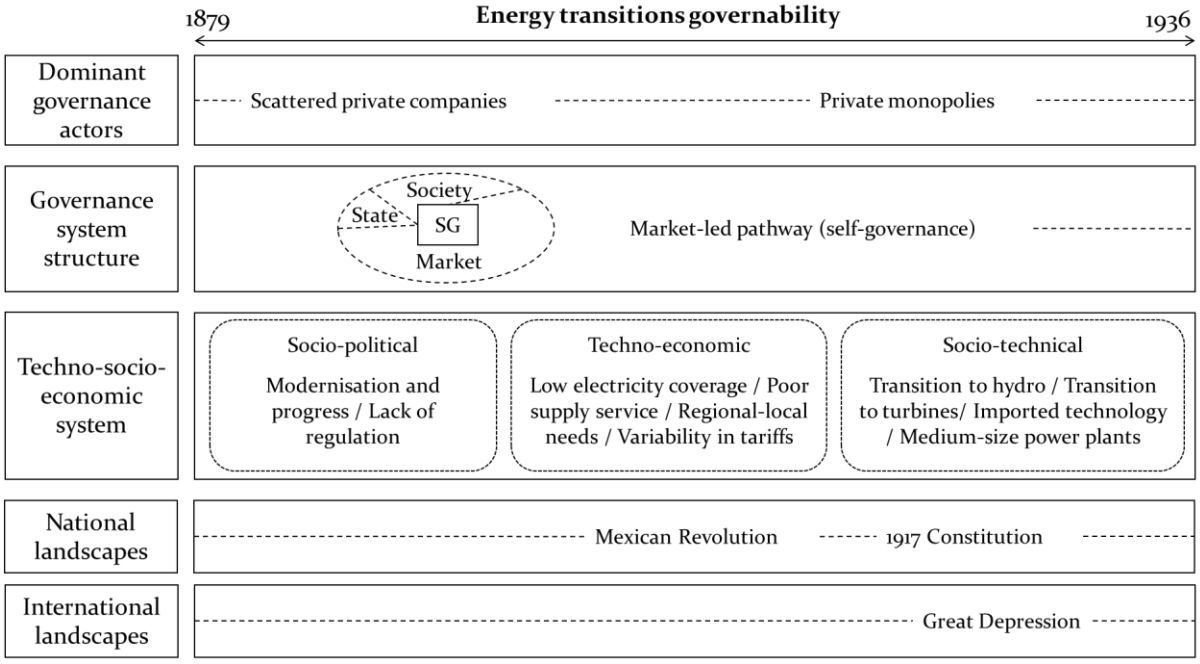


Fig. 9. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1879-1936).

Table 1
Energy transitions governability snapshot – governing interactions (1879-1936).

State -> Market
Pressure for service expansion to developing areas.
Participation on tariff regulation and conflict resolution.
Pressure for standardisation of generation equipment.
Pressure for access to financial records.
Pressure for better services (e.g. public lighting).
State -> Society
Promotion of economic growth and progress.
Society -> State
Pressure for tariff regulation.
Pressure for regulation on work conditions.
Pressure for access to electricity in developing areas.
Society -> Market
Pressure for better services and prices.
Pressure for improving working conditions.
Market -> State
Pressure for better conditions for private investments.
Pressure for more concessions.
Market -> Society
Give access to spaces where infrastructure would take place.

3.2. Co-governance: private companies and the state (1937-1959)

[Actors] Due to increasing tensions within the ***regime***, the state increased its participation within the ***governance system*** by creating in 1937 a state-owned electricity company, the Federal Electricity Commission (Comisión Federal de Electricidad, CFE) with the aim of consolidating and guiding a national electricity system including generation, transmission, and distribution at fair prices [28]. CFE started investing in small power plants mainly in the central and southern areas of Mexico. From 1940 to 1950 the ***governance system*** was dominated by the three main monopolies and CFE. Due to transmission and distribution were owned by these monopolies, the initial agreement was that CFE would provide electricity to them at reasonable prices [29]. By 1959 CFE had 38% of the total installed capacity and 49% for public service [36].

[Socio-political] The effects of the Great Depression were evident throughout the 1930s with a general decrease of exports and foreign currency shortages. To ameliorate the effects of this ***external landscape***, a process of industrialisation and an imports substitution model took place during the presidency of Lázaro Cárdenas (1934-1940). The economic development of the country required an expansion of infrastructure for electricity services towards rural areas and improving services already provided in cities under development [29]. Thus, ***policy objectives*** during this period were focused on increasing access to electricity and fostering the expansion of the sector [30]. A ***policy instrument*** to reach these objectives was the first Six Year Plan (1934-1940) where electricity supply was considered as a priority for the development of the country [28]. Also, an increase of electricity imports from US occurred during this period to secure electricity supply in line with increasing demand (see Fig. 10).

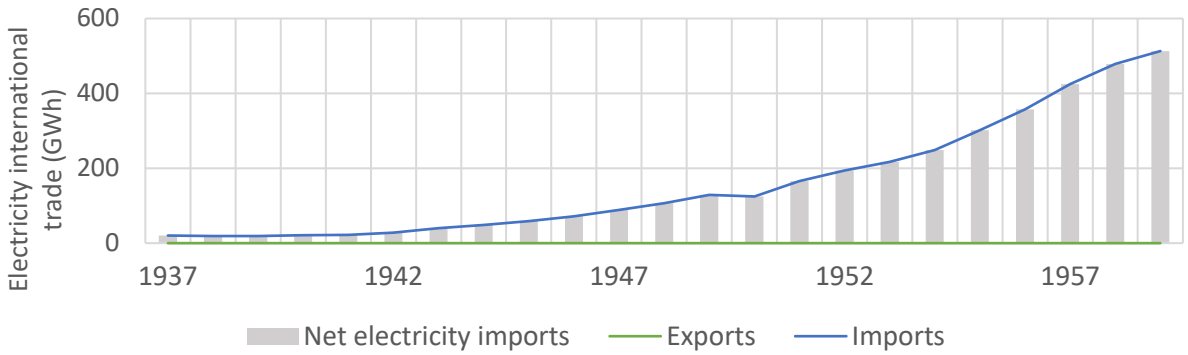


Fig. 10. Electricity imports, exports, and net imports from 1937 to 1959. Constructed with data from [37].

[External landscapes] An important domestic ***landscape*** during this period was the conflict between the state and private oil companies which ended up with their expropriation in 1938 and the creation of a state-owned oil and gas company, Mexican Petroleum (Petróleos Mexicanos, PEMEX). As a result of this ***landscape*** strong nationalistic feelings were diffused among other economic sectors (including the electricity sector); and a need for regulation and ***state intervention*** in the electricity industry was emphasised [29].

[Socio-political] After the creation of CFE, the Electricity Industry Law proposed by the Cárdenas's mandate was approved in 1939, considered as the most complex normative framework for the electricity industry at the time [28]. The law encompassed regulations on electricity generation, transformation, transmission, distribution, importation, exportation, trade, use, and consumption aiming at speeding the development of the electricity industry with a social focus. Due to the complexity of this ***policy instrument***, from 1941 to 1944 legislation and regulation adjustments were done to the law and its regulations. This highlights the dynamic aspect of ***policy instruments*** which adapt according to internal and external changes.

[Techno-economic] Regulations on concessions, tariffs, and profits included in the law were of paramount interest for private companies. According to the law, electricity tariffs were determined by the Secretariat of Economy (Secretaría de Economía, SE) and concessions were given to projects with the most efficient uses of natural resources and the major social impacts. These changes carried profit reductions for private companies and thus low investment in new capacity [29]. As a result, installed capacity did not increase at the same pace as the national economy. From 1940 to 1945 total installed capacity increased less than 6% (from 680 to 720 MW) [28]. This may be also attributable to the fear of private companies to be in the same situation as with the oil companies. Also, there was an increasing pressure from civil society actors (mainly large electricity users) for better services and lower prices.

[Socio-political] The period from 1940 to 1959 was characterised by the coexistence of public and private electricity companies with financial support from the state to both parts. The main role of CFE during this period was to close the gap arisen from what the private companies were not able to cover: electrifying rural communities and to foster national development. The Rural Electrification Program was established in 1952 and by joint efforts among the state, municipal governments and local communities, around 915 zones were provided with electricity by the end of the decade [38]. However, by 1959 less than 44% of the population had access to electricity [39].

[External landscapes] The World War II (1939-1945) was an international ***landscape*** that shaped economic and technological opportunities to the electricity industry. This is, exemptions from paying taxes when importing electrical equipment were granted to private companies if they were to provide electricity for public services (unless the equipment was

produced within the country) [28]. Thus, new equipment was imported mainly from United Kingdom (UK), US, and Canada at the beginning of the period and later from Japan and Switzerland [28,33].

[Socio-technical] Since its beginnings CFE recorded a tendency to invest in hydropower plants while private companies in thermoelectrical [28]. This may be explained as private (mainly foreign) investors were interested in short-term financial benefits by satisfying immediate needs with thermal power plants, while the state was interested more in long-term social benefits by investing in hydropower plants (higher upfront capital cost and longer construction times but relatively lower operational costs). Thus, total installed capacity from thermoelectric took over hydropower during this period. Fig. 11 shows installed capacity for public service from 1937 to 1959.

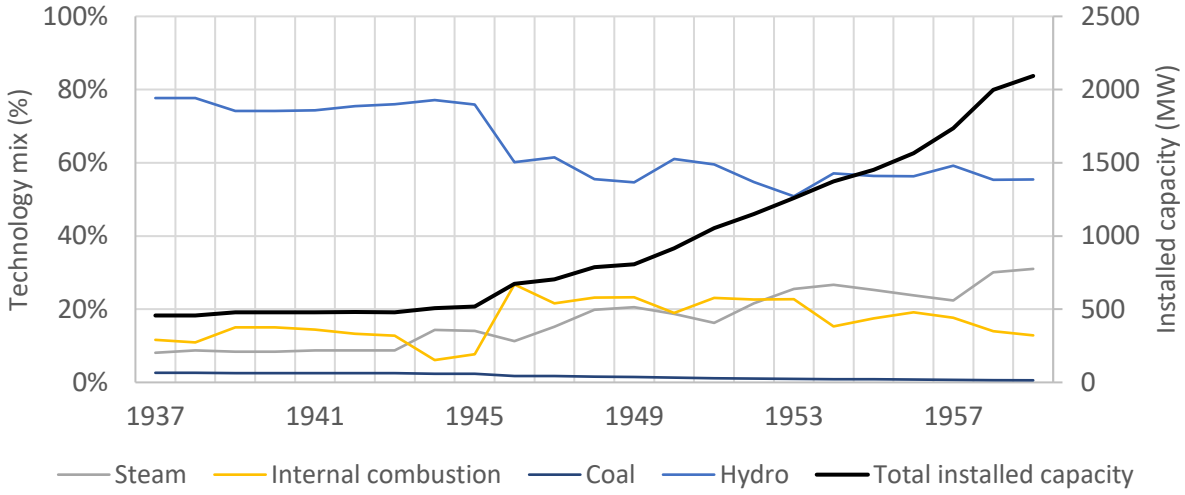


Fig. 11. Technology mix (left) and installed capacity for public service (right) from 1937 to 1959. Constructed with data from [37].

Some other relevant technological changes took place during this period. The first can be attributed to the size of power plants. For instance, the Miguel Aleman hydropower system (built from 1938 to 1944), in Ixtapantongo, was the first large-size power plant (28 MW) shifting from horizontal to vertical axis turbines. The second important technological change was on electrical equipment: technical characteristics and efficiencies were improved over time (e.g. larger capacities and higher pressure of steam boilers). Third, a ***technological learning*** process based on ***learning-by-doing*** [40] and ***learning-by-using*** [41] was performed during this period. Fourth, in 1959 the CFE installed the first geothermal (pilot) power plant in Mexico with 3 MW of capacity, aiming at exploring new ***technological niches*** by taking advantage of the geothermal potential of the country.

[Actors] Other relevant actors who increased their participation in the ***governance system*** were labour unions. At the beginning they were independent social organisations; however, from the 1940s their involvement with the state increased, creating ***socio-political interests***. Fig. 12 depicts the dominant governance actors by 1959.

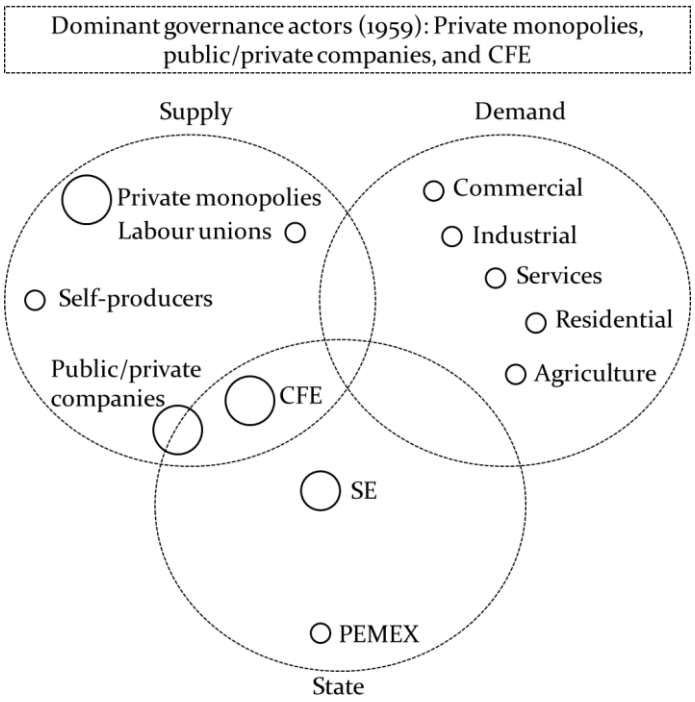


Fig. 12. Dominant governance actors by 1959. The size of the circles represents the relevance of their role within the governance system. Adapted from [29] with information from [28].

3.2.1. Multi-perspective summary (1937-1959)

State's policy objectives, in line with industrialisation and development, were directed towards meeting increasing electricity demand and expanding services to rural areas. The state increased its authority by creating a public electricity company and implementing different policy instruments to fulfil societal needs. Fig. 13 presents the policy mix changes during this period.

State regulations brought profit reductions and low investment in new capacity, limiting the expansion of the system, and creating tensions in the governance system (e.g. increasing electricity tariffs). In order to meet the increasing demand, the state opted for increasing electricity imports. Fig. 14 presents the main outcomes of interest for this period.

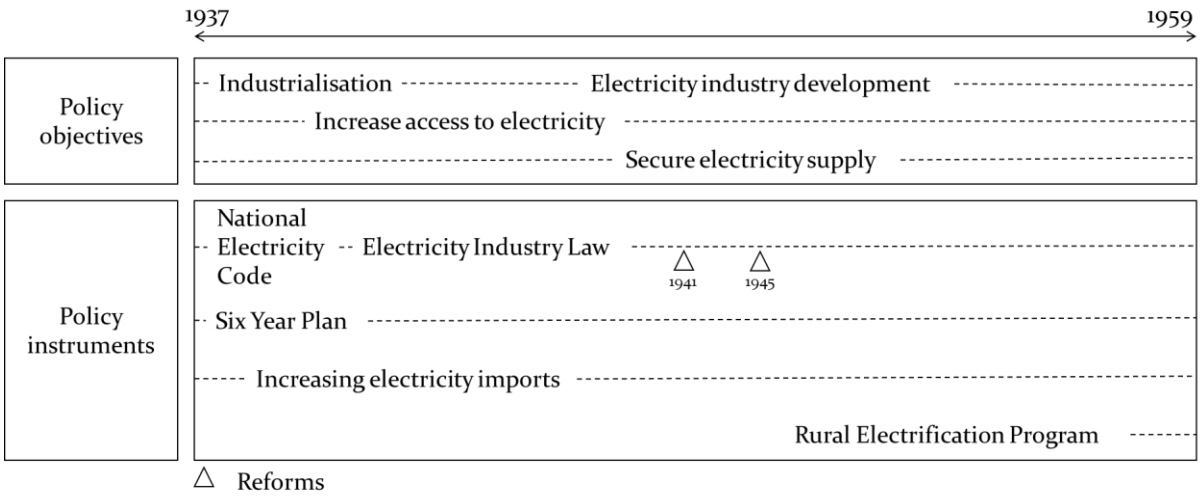


Fig. 13. Socio-political perspective snapshot (1937-1959).

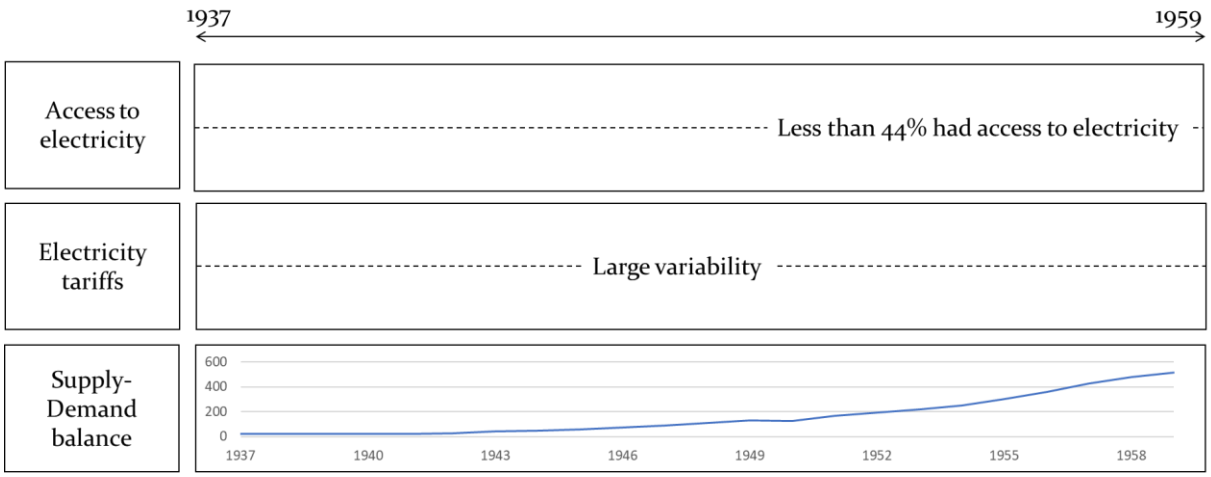


Fig. 14. Techno-economic perspective snapshot (1937-1959). Supply-Demand balance refers to the net electricity imports in GWh. Constructed with information from [28,37].

In terms of technological change, the period was characterised by a transition from hydropower to fossil-fuel based technologies (e.g. steam, internal combustion, coal); construction of large-size power plants (tens of MW); a transition from horizontal to vertical turbines for hydropower plants; new technological niches (i.e. geothermal); a process of technological learning; and diversification of electrical equipment suppliers. Fig. 15 depicts the main socio-technical changes for this period.

3.2.2. Energy transitions governability (1937-1959)

This period was characterised by the end of exclusivity from private companies to generate electricity and provide services; contested interest between the state (increase social benefits) and private companies (increase profits); increase in state regulation and intervention; a transition from a market-led (self-governance) to a co-governance system pathway; transition to fossil fuel technologies; a restructuring process of the regime caused by internal pressures and external landscapes; and expansion of the sector. Fig. 16 and Table 2 represent the energy transitions governability snapshot for the period from 1937 to 1959.

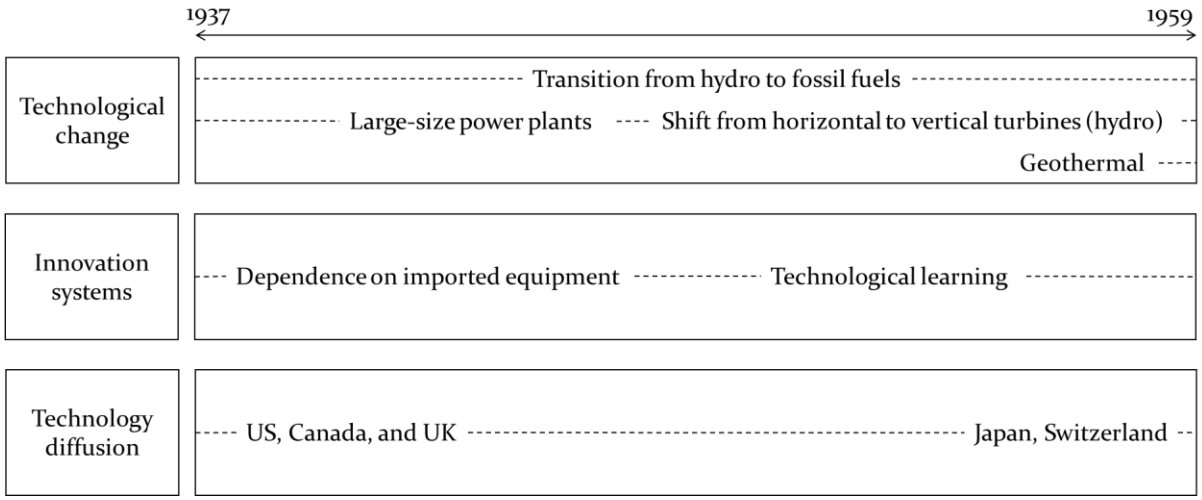


Fig. 15. Socio-technical perspective snapshot (1937-1959).

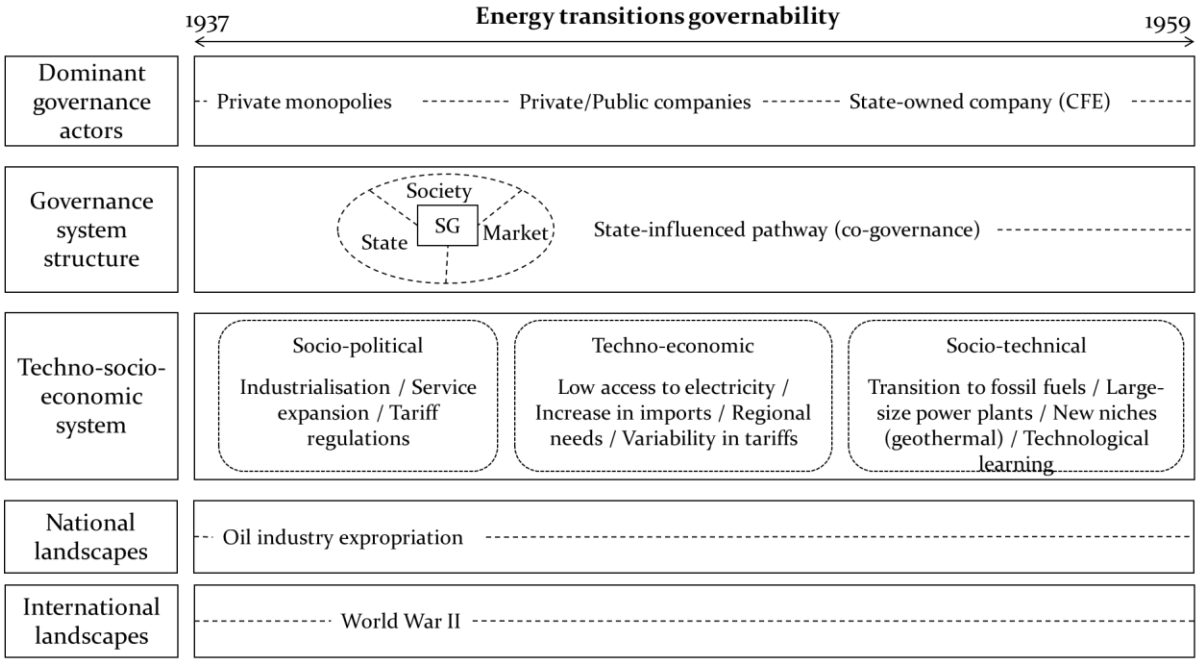


Fig. 16. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1937-1959).

Table 2
Energy transitions governability snapshot – governing interactions (1937-1959)

State -> Market
Pressure for service expansion to rural areas.
Intervention on tariff regulation and concessions.
Intervention on conflict resolution.
Pressure for access to private financial records.
State -> Society
Promotion of industrialisation.
Promotion of social benefits.
Participation on urbanisation planning.
Society -> State
Pressure for more state control (nationalisation).
Pressure for lower prices.
Pressure for access to electricity in rural areas.
Society -> Market
Pressure for better services and prices.
Pressure for improving working conditions.
Market -> State
Pressure for better investment and profit regulations.
Market -> Society
Facilitate access to infrastructure development.

3.3. State control of the sector (1960-1991)

[Actors] A need for expanding electricity services, great variability among tariffs, nationalistic feelings, and a need for transmission and distribution integration were the main factors for the nationalisation of the electricity industry in 1960. This was a complex process where the state acquired private companies by different financial means. The acquisition process lasted until 1972 when the last private company was purchased by the government [29,42]. By 1960 CFE

had a 54% share from the total installed capacity in the country (2,308 MW), while the Mexican Light and Power held 25%, the American and Foreign Company 12%, and the rest of the companies 9% [33].

[Socio-political] During this period a ***policy paradigm shift*** towards nationalism and sovereignty occurred [42]. The nationalisation process formally concluded with the publication of the Public Service Electricity Law (Ley del Servicio Público de Energía Eléctrica) in 1975 which declared CFE and Compañía de Luz y Fuerza (CLyF) (before the Mexican Light and Power Company) as the only providers for public service (including generation, transmission, and distribution) [29]. In terms of private generation, the law stated that self-producers could produce their own electricity as long as CFE were not able to cover their specific needs.

The ***governance system*** had several challenges when the nationalisation took place. First, due to electricity services were offered based on local or regional demands, around 170 tariffs coexisted before 1962 and only 44% of the population had access to electricity. Second, during the 1960s the electricity systems throughout the country (not interconnected yet) included 8 transmission voltages (from 66 to 220 kV), 29 distribution electric tensions (from 440 to 2,300 V), and 2 frequencies (50 and 60 Hz) [28]. Third, the government acquired several electricity companies with high operation costs and old equipment (some of them already above their operational lifespan). Fourth, tensions between labour unions and the government took place around the integration of these social actors within the new structure of the regime. Thus, the state addressed these technological, operational, administrative, and contractual issues by implementing different ***policy instruments*** as described below.

[Techno-economic] Following international best practices on electricity tariffs, the state led a tariff unification process from 1962 to 1964. A system of 12 tariffs were established and subsidies to agriculture, public services, and other relevant subsectors were granted by the government [36,43]. Tariffs were kept relatively constant until 1973 when they were adjusted, and subsidies for residential consumers were promoted by the state. The social focus of the ***policy paradigm*** carried with it financial constraints with increasing public debt and operational issues with low productivity levels [36]. The financial crisis of CFE and CLyF forced the state to seek new mechanisms to increase income for these energy companies. Thus, based on international prices (mainly U.S.), electricity tariffs were redefined and increased in 1990 and subsidies began to gradually be eliminated during the early 1990s. Fig. 17 depicts the electricity tariff changes from 1962 to 1991.

[Actors] Following the restructuring process of the electricity industry, labour unions were consolidated into two main unions and the state legally recognised the relevance of their role in the development of the industry. These social organisations played a key role when ***political interests*** emerged from the dynamics of the system. For instance, aiming at creating a single state-owned electricity company, the president Luis Echeverría Álvarez (1970-1976) authorised the dissolution of CLyF in 1974. However, disagreements between the state and the SME delayed this process until 2009 bringing several socio-political tensions and operational issues within the system [44].

[Socio-technical] The interconnexion of the different electricity systems was a complex process that took place in around 16 years. Although the National Electrification Program (Programa Nacional de Electrificación) was issued in 1962, the Committee for the Unification of Frequencies (Comité de Unificación de Frecuencia, CUF) was created in 1972 and was until 1976 when existing electricity systems changed to a frequency of 60 cycles per second consolidating the National Electricity System (Sistema Eléctrico Nacional, SEN). The interconnexion process brought operational, administrative, and social benefits to the system. Access to electricity increased from 44% in 1960 to 88% in 1991 (see Fig. 18).

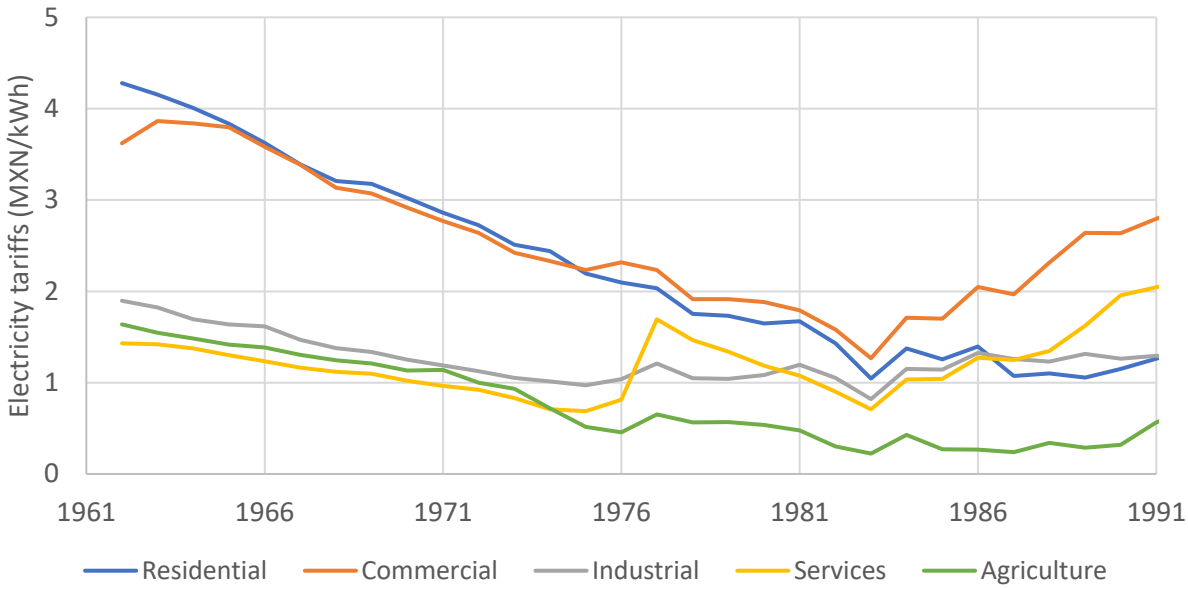


Fig. 17. Average electricity tariffs (1962-1991). (Values in real Mexican 2015 pesos). Constructed with data from [45,46].

[Socio-technical] Following energy policies from the oil and gas sectors, investments in electricity were mainly oriented towards fuel oil and natural gas. With the nationalisation of the industry, CFE started its participation in the definition and design of equipment with particular technical characteristics and started the (semi)automation process of power plants and substations. Also, the construction of larger capacity power plants (hundreds of MW) was a technological change during this period of analysis.

[External landscapes] A particular (nationwide) focus on science and technology took place during Luis Echeverría's administration (1970-1976). A national ***landscape*** was the creation of the National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología, CONACYT) in 1970 aimed at developing ***policy mixes*** on research and development (R&D), and innovation on priority topics for the Nation [47].

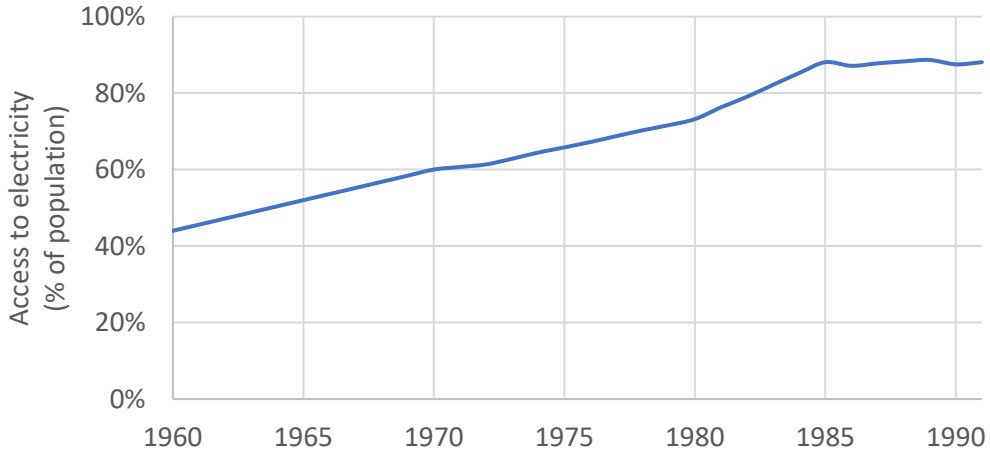


Fig. 18. Access to electricity from 1960 to 1991. Constructed with data from [36,39,48].

[Socio-technical] Although electricity production was dominated using oil as the preferred fuel, other niches received attention during this period. Fig. 19 depicts the technology mix and installed capacity for public service from 1960 to 1991. In 1966 CFE built its first 37.5 MW coal power plant. Also, the adoption of natural gas turbines (NGT) in 1965 and natural gas combined cycles (NGCC) in 1974 was possible due to international technological

improvements on gas turbines [29]. On the other hand, the first 3-MW geothermal pilot plant was dismantled in 1973. However, a new geothermal field started operations in the northern part of Mexico where the first power units (75 MW) were commissioned in 1973. Finally, a nuclear power plant (Laguna Verde) started operations in 1990. Table 3 presents the international technological leaders (countries with the highest total installed capacity) on these technological niches in 1974 and 1991. Technology (including knowledge and equipment) might be diffused from these ***core*** countries to the ***periphery*** (including Mexico) [49].

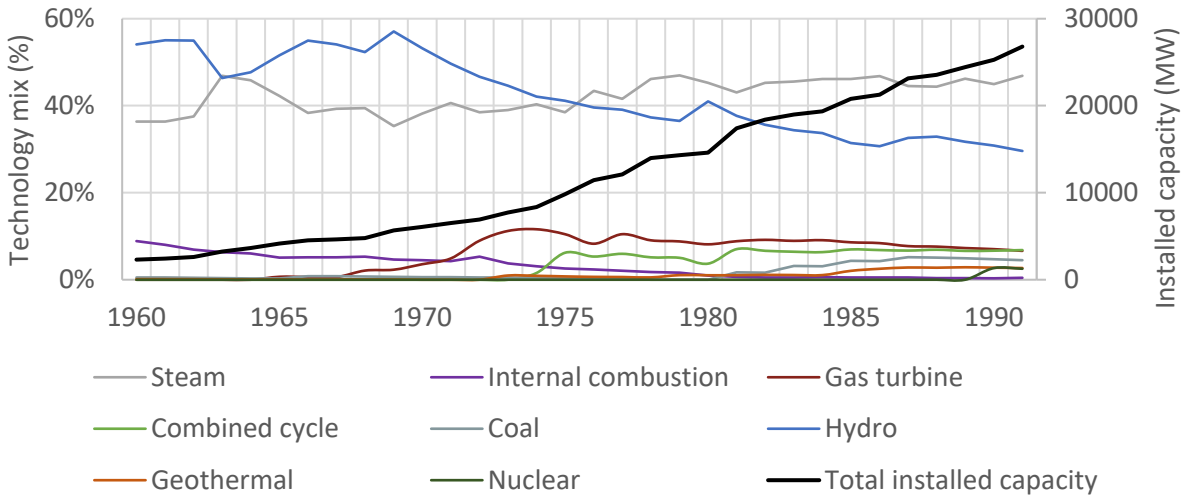


Fig. 19. Technology mix (left) and installed capacity for public service (right) from 1960 to 1991. Constructed with data from [32,37,50].

Table 3
International (core) leaders on selected electricity generation technologies in 1974 and 1991. Source: [50].

Technology	Core countries in 1974 (installed capacity in MW)	Core countries in 1991 (installed capacity in MW)
Coal	US (174,319) UK (45,118) Germany (30,843)	US (262,661) Germany (42,065) UK (33,704)
Gas turbine	Mexico (971) Finland (781) Australia (313)	US (48,815) Germany (5,948) UK (3,585)
Geothermal	Italy (382) New Zealand (160) Mexico (75)	US (2,632) Mexico (720) Italy (567)
Natural gas combined cycle	Mexico (130) Hungary (116)	US (23,762) Japan (4,715) Mexico (1,933)
Nuclear	US (31,662) Japan (3,906) Germany (3,294)	US (99,609) France (56,780) Japan (33,404)

[External landscapes] - [Actors] The international oil crisis in 1973 was an international ***landscape*** that triggered concerns around energy diversification and energy planning. The government promoted technological innovation and development for both the incumbent regime (i.e. oil-based electricity production) and emerging technological niches (i.e. coal, NGT, geothermal, NGCC, and nuclear). The National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias, INEEL[2]) was created in 1975 aiming at carrying out innovation, technological research and development in electrical generation, transmission, and distribution processes. Similarly, the National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares, ININ[3]) and the National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias, CNSNS) were created in 1979 to conduct research activities and regulate nuclear matters, respectively. Also, in 1982 the Secretariat of Energy (Secretaría de Energía, SENER[4]) was created aiming at coordinating, planning, developing, and implementing energy ***policy mixes*** nationwide. Fig. 20 shows the dominant actors of the governance system by 1991.

[External landscapes] - [Actors] Since the early 1970s the government had been borrowing large amount of foreign currencies (mostly U.S. dollars). Thus, the external debt of the public sector had drastically grown by the end of the decade. The Mexican electricity sector faced financial difficulties due to unstainable foreign debt, lack of management autonomy of CFE, subsidised tariffs, and lower export revenues caused by the fall of international oil prices [29,51]. The 1982 economic crisis in Mexico forced the government to focus on energy savings and energy mix diversification. Thus, the National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía, CONUEE[5]) was created in 1989 aiming at developing energy efficiency strategies. Also, CFE created diverse ***policy instruments*** focused on electricity savings such as Energy Saving Program for the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico, PAESE) in 1989 and the Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica, FIDE[6]) in 1990 [52]. Fig. 21 shows the electricity intensity (total electricity consumption per unit of GDP) for this period. Also, environmental concerns arisen during this period and the General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente, LGEEPA) was published in 1988 (affecting the electricity sector in later years).

[External landscapes] The Mexican oil boom was a national ***landscape*** that affected electricity generation and consumption [53]. With vast fossil fuel resources available within the country, during the second half of the 1980s an increase in electricity exports to US took place and imports were kept relatively constant to meet regional needs (see Fig. 22). Another important ***landscape*** during this period was the North American Free Trade Agreement (NAFTA) signed between Mexico, United States, and Canada, started negotiations in 1991, with a major focus on liberalising trade in key sectors between the three countries.

[2] Before (Mexican) Electricity Research Institute (Instituto de Investigaciones Eléctricas, IIE).
[3] Before the National Nuclear Energy Commission (Comisión Nacional de Energía Nuclear, CNEN).
[4] Before Secretaría de Energía, Minas e Industria Paraestatal (SEMIP).
[5] Before National Energy Saving Commission (Comisión Nacional para el Ahorro de Energía, CONAE).
[6] Originally named Fund in Support of PAESE.

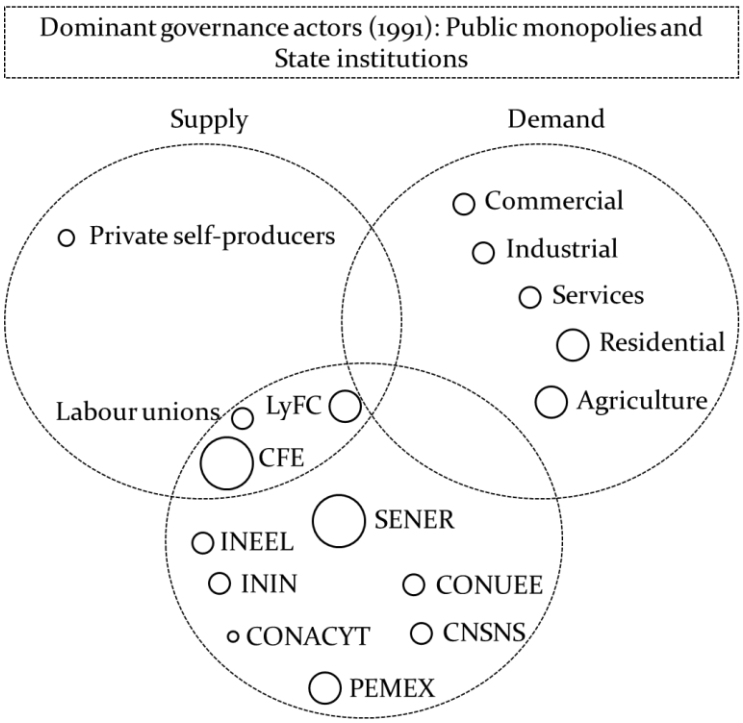


Fig. 20. Dominant governance actors by 1991. The size of the circles represents the relevance of their role within the governance system. Adapted from [29] with information from [28,47,49,51].

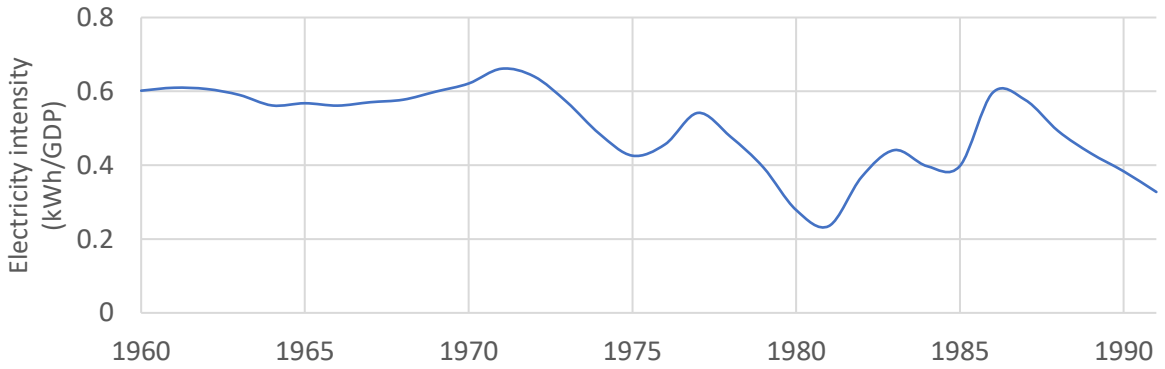


Fig. 21. Electricity intensity from 1992 to 2012. Constructed with data from [37,54,55].

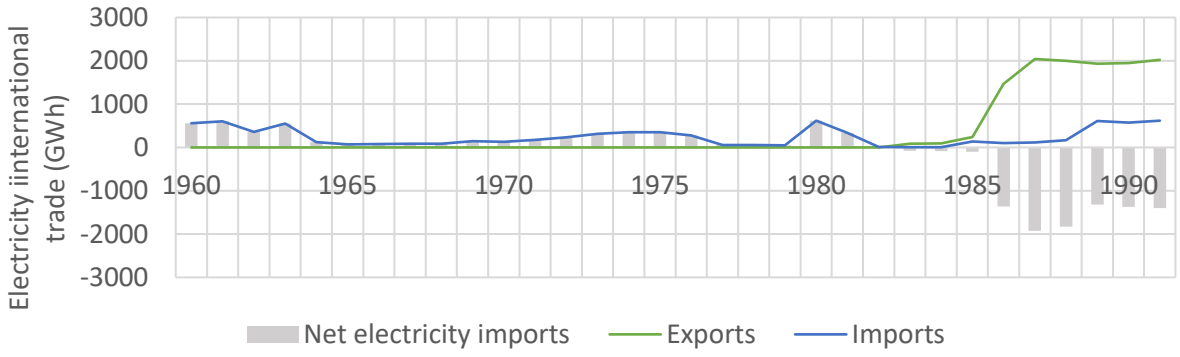


Fig. 22. Electricity imports, exports, and net imports from 1960 to 1990. Constructed with data from [32,37].

3.3.1. Multi-perspective summary (1960-1991)

The nationalisation of the electricity sector brought several challenges to the governance system including the unification of tariffs, interconnexion of the national system, expanding access to electricity, diversification of energy sources, integration of relevant actors to the new structure, reduction of energy consumption, and environmental concerns. Policy mixes during this period were oriented towards addressing these challenges as shown in Fig. 23.

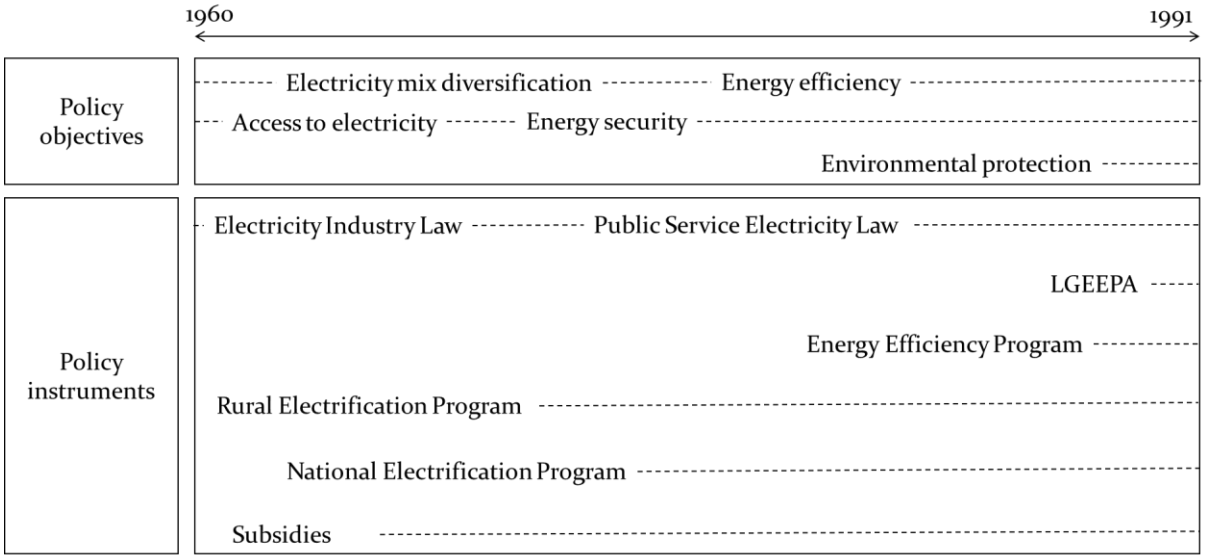


Fig. 23. Socio-political perspective snapshot (1960-1991).

In line with policy objectives, electricity access increased from 44% to 88%; electricity tariffs changed according to the state's (social) policy paradigm (including subsidies for agriculture and residential in tariff structures); electricity demand was met with almost national generation and surplus was exported to US; and electricity intensity fluctuated based on diverse internal and external events with a decreasing trend over time. Fig. 24 presents the main outcomes of interest for this period of analysis.

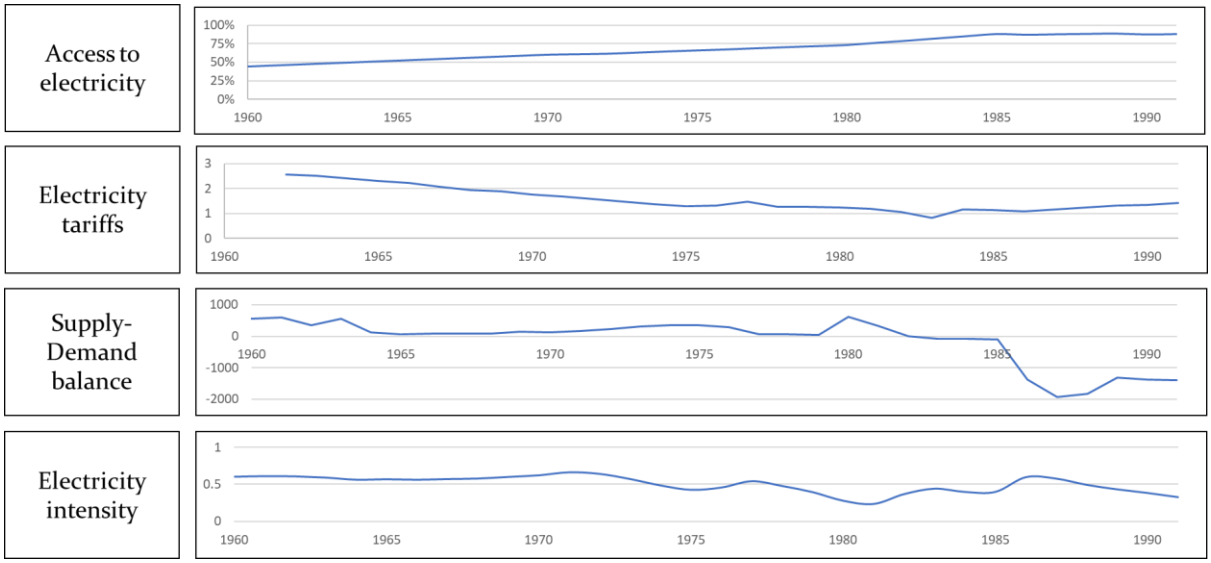


Fig. 24. Techno-economic perspective snapshot (1960-1991). Access to electricity refers to the percentage of population with access to electricity. Electricity tariff represents the changes in total average tariff considering the main consumer sectors (i.e. residential, commercial, industrial, services, and agriculture). Supply-Demand balance refers to the net electricity imports in GWh. Constructed with data from [32,36,37,39,45,46,48,54,55].

From a socio-technical perspective, the period was characterised by the inclusion of automation processes; construction of larger-size power plants (hundreds of MW); new technological niches (i.e. NGT, coal, geothermal, NGCC, and nuclear); a focus on fostering the creation of innovation systems; and technology diffusion from different core countries. Fig. 25 depicts the main socio-technical changes for this period.

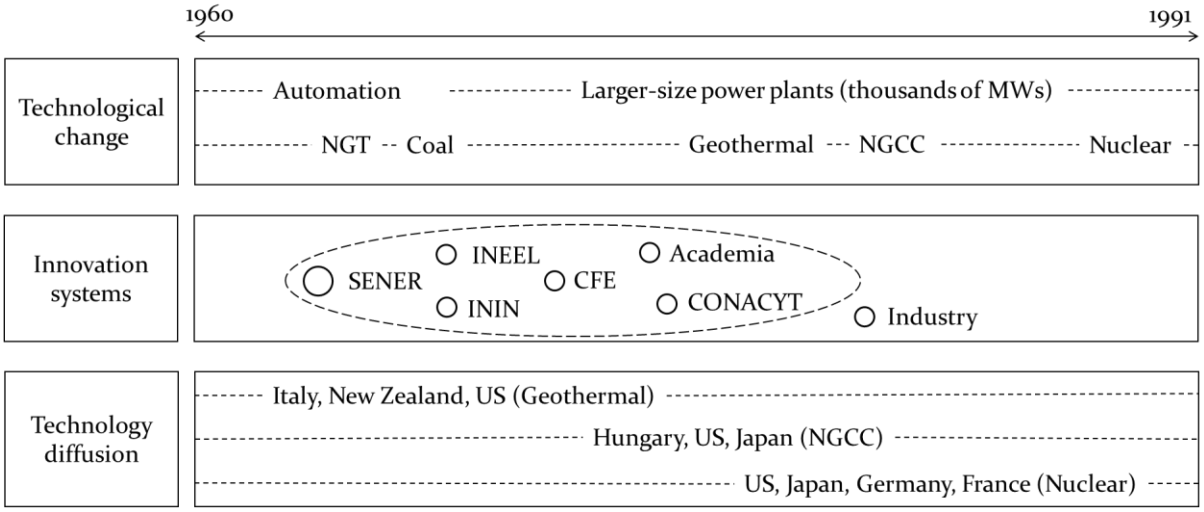


Fig. 25. Socio-technical perspective snapshot (1960-1991).

3.3.2. Energy transitions governability (1960-1991)

This period was characterised by the control of the state in generation, transmission, and distribution following a hierarchical governance model with a social approach; a remarkable increase in access to electricity with rural and national electrification programs; a transition from a co-governance to a state-led (hierarchical governance) system pathway; expansion of the sector; a focus on innovation and support to technological niches. Fig. 26 and Table 4 represent the energy transitions governability snapshot for this period.

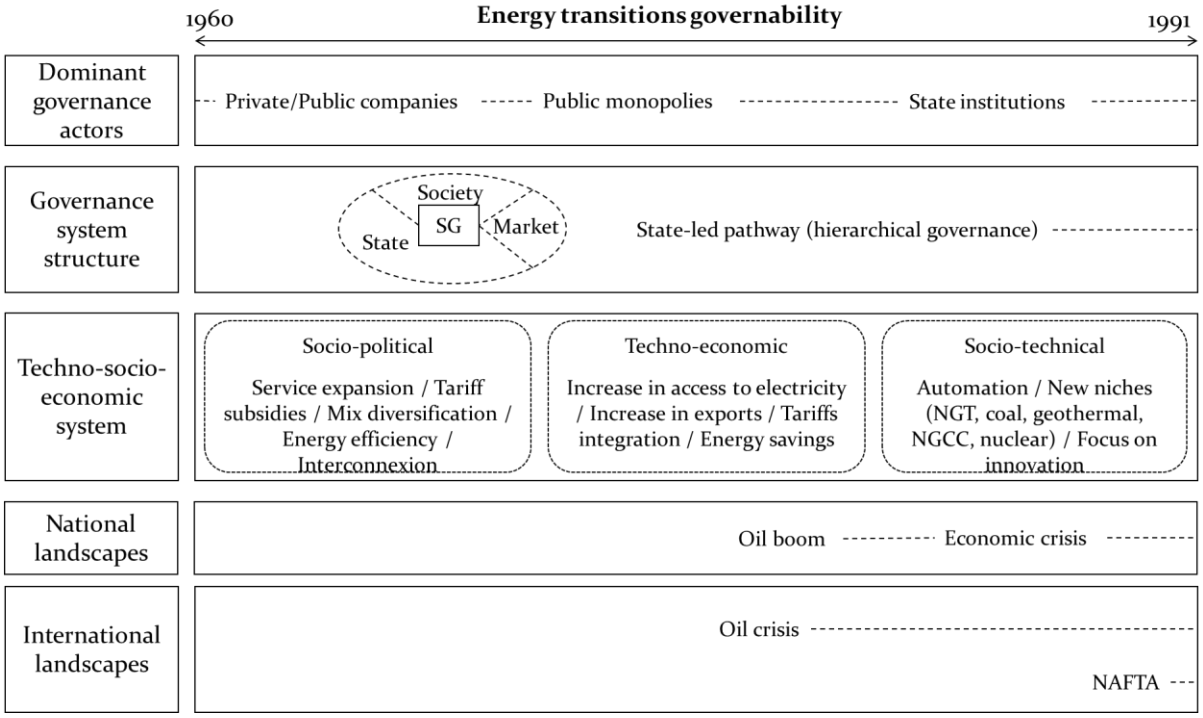


Fig. 26. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1960-1991).

Table 4
Energy transitions governability snapshot – governing interactions (1960-1991).

State -> Market
Pressure for service expansion to rural areas.
Intervention on tariff regulation and subsidies.
Intervention on expansion planning.
State -> Society
Promotion of lower electricity tariffs (subsidies).
Society -> State
Pressure for lower prices.
Pressure for access to electricity in rural areas.
Society -> Market
Pressure for better services and prices.
Market -> State
Pressure for better expansion planning.
Pressure for financial support.
Pressure for fostering innovation systems.
Market -> Society
Pressure for reducing electricity intensity.

3.4. Partial liberalisation of the sector (1992-2012)

[Actors] A ***policy paradigm shift*** towards free markets occurred during the 1980s. Following the neoliberal ideology of 'less state intervention' the administration of Carlos Salinas de Gortari (1988-1994) started a process of liberalisation in the electricity sector. CFE and CLyF remained the owners of transmission and distribution lines, but private actors were allowed to participate in electricity generation under six new modalities. The independent power producer (IPP) scheme allowed private companies to produce and sell electricity to CFE under power purchase agreements (PPAs). Small power producer (SPP) mode included isolated rural communities generating less than 1 MW for self-supply, generation coming from small power plants with no more than 30 MW and sold to CFE, and electricity exported up to 30 MW. Power self-supply (PSS) and cogeneration power producer (CPP) schemes encompassed electricity and heat generation for fulfilling their needs and electricity surplus were sold to CFE. Power imports (PI) and exports (PE) were only allowed for covering specific needs (e.g. self-supply). Additionally, permits for self-supply granted before 1992 remained active for private producers under the continuous self-supply (CSS) scheme [29,56]. With new potential participants within the system, new regulations were needed. Thus, the Energy Regulatory Commission (Comisión Reguladora de Energía, CRE) was created in 1993 to foster an appropriate and efficient development of the electricity and natural gas industries and to protect users' interests.

[Socio-political] The rapid growing demand and the inability of state-owned electricity companies to continue expanding the system (mainly due to financial constraints) posed potential challenges to keep the ***supply-demand balance***. Some of the energy ***policy objectives*** during this regime were to secure electricity supply by different mechanisms (e.g. allowing private investment in generation and importing electricity from US) and to increase access to electricity in rural areas. Fig. 27 depicts electricity international trade from 1992 to 2012. An increasing trend in imports can be observed during the first years of this period and until 1997 when they decreased. Also, by 1992 around 93% of the population had access to electricity services. However, the state continued efforts to expand the system and reached 99% of coverage by 2012 (see Fig. 28). To allow participation of private actors, a major reform to the Public Service Electricity Law took place in 1992.

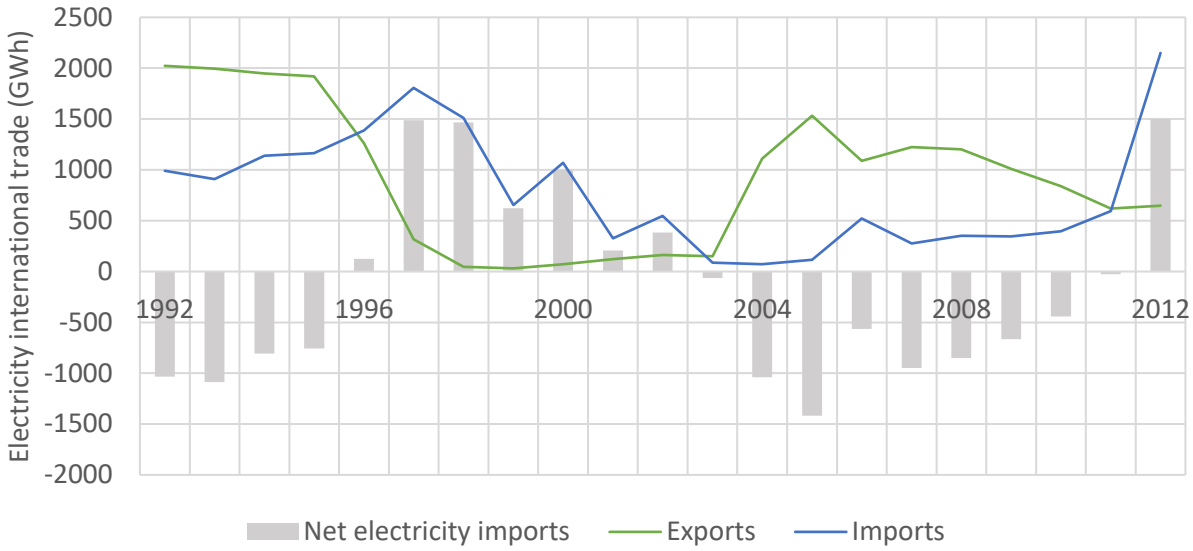


Fig. 27. Electricity imports, exports, and net imports from 1992 to 2012. Constructed with data from [32,57,58].

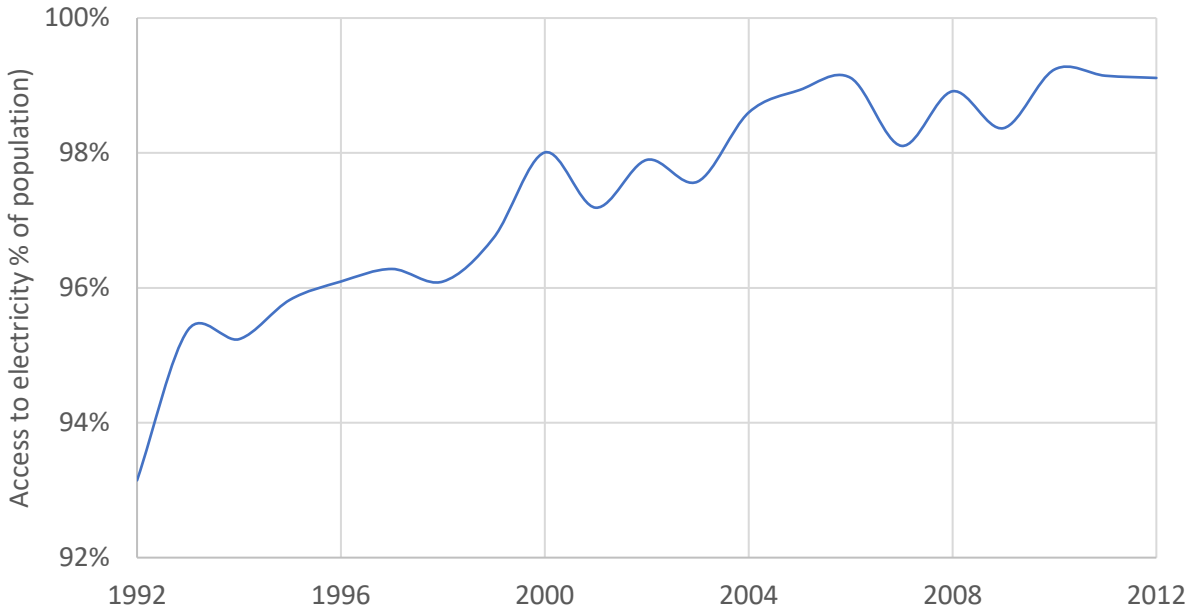


Fig. 28. Access to electricity from 1992 to 2012. Constructed with data from [59].

[External landscapes] Mexico became a member of the Organisation for Economic Co-operation and Development (OECD) in 1994, bringing opportunities for international cooperation. However, Mexico's economy experienced a severe recession after the Mexican peso crisis in 1994, affecting several economic sectors. This ***external landscape*** accelerated the privatisation process in the electricity sector. Although the Public Service Electricity Law was reformed during Carlos Salinas' administration, the first permit to an IPP was granted in 1997 and generation from private producers began in 2000.

[Socio-political] The next three administrations (Ernesto Zedillo, 1994-2000; Vicente Fox, 2000-2006; and Felipe Calderón, 2006-2012) proposed energy reforms oriented towards increasing private participation in the energy system. Even though the initial proposals were rejected by the Mexican Congress some changes to the electricity system took place during this period. First, the electricity tariff structure was revised and modified during 2002,

increasing tariffs and reducing subsidies for some consumer sectors (and eliminated for higher-tier residential consumers) [29]. Fig. 29 shows the average electricity tariffs for the main consumption sectors during this period. Second, to promote a transition to a low-carbon economy by means of renewable energy and energy efficiency, the Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía, LASE) and Use of Renewable Energy and the Financing of the Energy Transition Law (Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética, LAERFTE) were published in 2008. In terms of energy efficiency, although the use of electricity per unit of GDP increased just after the Mexican peso crisis, a decreasing trend in electricity intensity from 1995 to 2012 can be observed in Fig. 30 Third, by a presidential decree the LyFC state-owned electricity company was dissolved in 2009 due to its administrative and operational inefficiency, transferring their responsibilities to CFE.

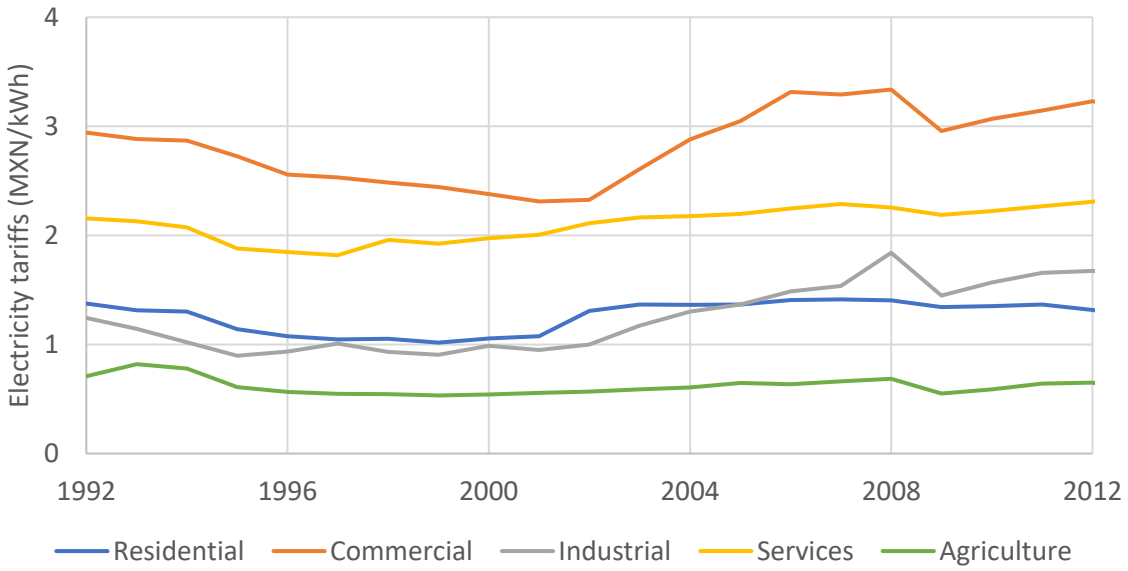


Fig. 29. Average electricity tariffs (1992-2012). (Values in real Mexican pesos of 2015). Constructed with data from [46,60,61].

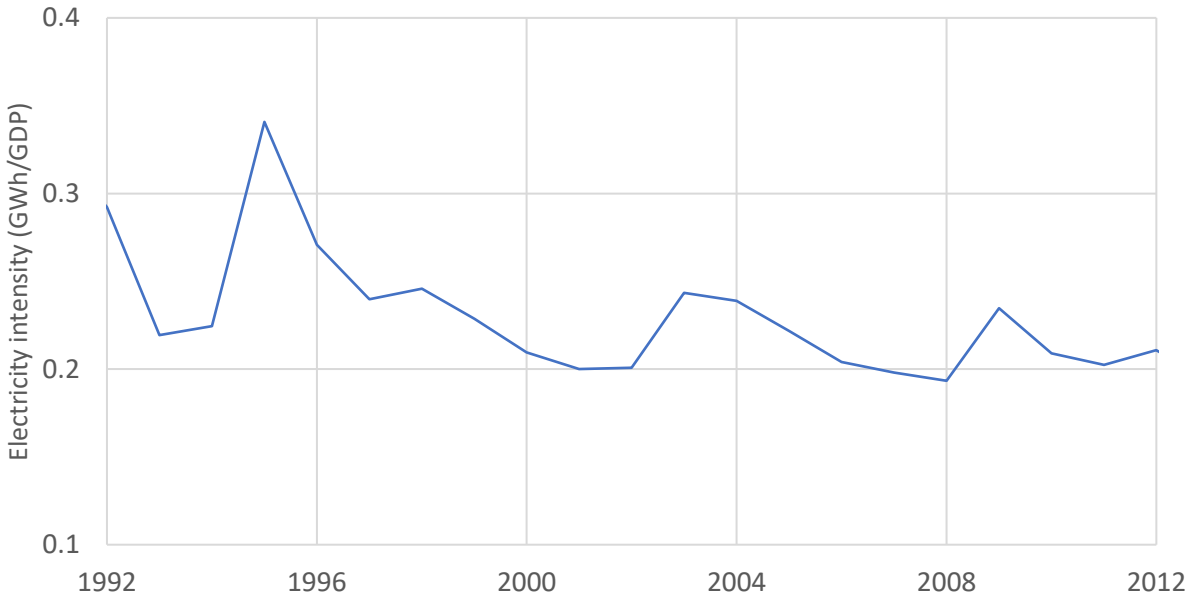


Fig. 30. Electricity intensity from 1992 to 2012. Constructed with data from [54,55].

[External landscapes] - [Socio-political] International concerns regarding climate change and environmental protection influenced ***policy energy objectives*** towards a more sustainable economy. Thus, based on the LGEEPA law, new regulations on environmental standards for SO_x and NO_x emissions in environmentally critical areas were established in 1994. These environmental regulations limited CFE on the use of high-sulphur fuel oil for power generation in important metropolitan and industrial areas [62], thus promoting the use of natural gas [29].

After the United Nations Framework Convention on Climate Change (UNFCCC) entered into force in 1994, Mexico stated its commitment on climate change by signing the Kyoto Protocol in 1998. However, Mexico's climate change policy started in 2007 with the publication of the National Climate Change Strategy aiming at guiding policies on climate change. Regarding electricity production and use, the strategy focused on promoting energy efficiency and technology mix diversification in order to reduce GHG emissions. In 2012 the Congress approved the General Climate Change Law (Ley General sobre Cambio Climático, LGCC) establishing the institutional and programmatic framework for national policy on climate change [63]. Fig. 31 shows total GHG emissions (excluding land use change and forestry (LUCF)) and emissions by source within the energy sector. Total emission increased from 455.13 Mt CO_2-e in 1992 to 673.72 Mt CO_2-e in 2012 (an increase of 48%). Similarly, emission from electricity generation increased from 66 Mt CO_2-e to 124.9 Mt CO_2-e in the same period (representing 19% of the total GHG emissions and 27% of the energy-sector GHG emissions) [64].

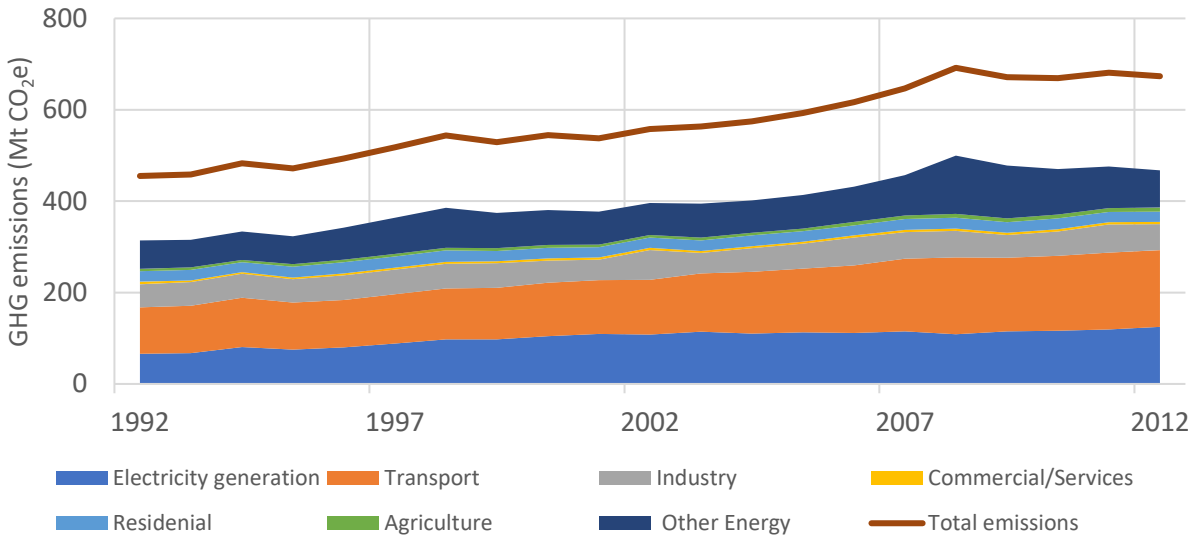


Fig. 31. Total GHG emissions, total emissions from main energy activities, and emissions by source within the energy sector. Constructed with data from [64].

A relevant national ***landscape*** within the energy sector was the decline of oil and gas production since the mid-2000s. Oil production declined around 34% from the peak of 3.8 million barrels per day (mb/d) in 2004 to 2.5 mb/d in 2016. Similarly, domestic production of natural gas started falling since 2009, resulting in an increase in imports (mainly from US) to meet national demand [9]. Another important international ***landscape*** was the global financial crisis in 2008. In order to ameliorate the effects of the crisis, the state adopted different measures including freezing household energy prices, decreasing industrial and commercial electricity tariffs (see Fig. 29), and increasing public expenditures on infrastructure and innovation-oriented activities [65].

[Actors] - [Socio-technical] In line with ***policy objectives*** towards a more sustainable economy, multiple academic institutions carried out research activities on clean energy and energy efficiency. Apart from INEEL, relevant institutions include the Institute of Engineering (Instituto de Ingeniería, IINGEN) at the National Autonomous University of Mexico (Universidad Nacional Autónoma de México, UNAM), the Centre for Economic Research and Teaching (Centro de Investigación y Docencia Económicas, CIDE), the Metropolitan Autonomous University (Universidad Autónoma Metropolitana, UAM), the Institute of Renewable Energy (Instituto de Energías Renovables, IER) at UNAM, among many others. Also, the government created the Energy R&D Funds in 2008. The main objective of the Hydrocarbons Fund (FH) and the Energy Sustainability Fund (FSE) is to support innovation, scientific research, technology development and deployment, human capital development, and sustainable energy development nationwide. These funds are jointly led by SENER and CONACYT, aiming at coordinating innovation efforts made by academia, industry, and public institutions [66–70]. Thus, ***innovation systems*** were strengthened with (public and private) research centres, universities, and other organisations working collaboratively across the country. Fig. 32 depicts the dominant governance actors by 2012.

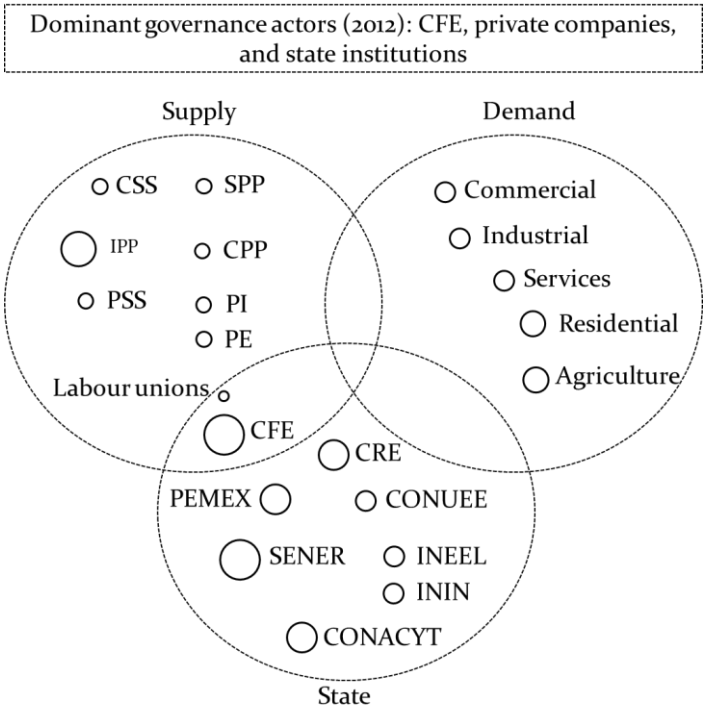


Fig. 32. Dominant governance actors by 2012. The size of the circles represents the relevance of their role within the governance system. Source: adapted from [29] with information from [47,49,56].

[Socio-technical] During this period, a technology transition from fuel oil to natural gas occurred, becoming natural gas combine cycle (NGCC) the dominant technology in the ***technological regime*** (see Fig. 33). The IPPs' NGCC installed capacity increased from 484 MW in 2000 to 11,907 MW in 2012 (an increase of 2360%) while CFE increased its NGCC capacity by 110% in the same period (from 2,914 to 6,122 MW). On the other hand, the first 1.57 MW wind project was set up in 1994 in La Venta, Oaxaca by CFE. Wind installed capacity grew from 1.57 to 598 MW from 1994 to 2012, with 511 MW owned by IPPs. Similarly, the first 5 MW solar photovoltaic (PV) project started operations in 2012 (owned by CFE). In terms of technology diffusion, Table 5 depicts the main technological leaders for different technologies selected.

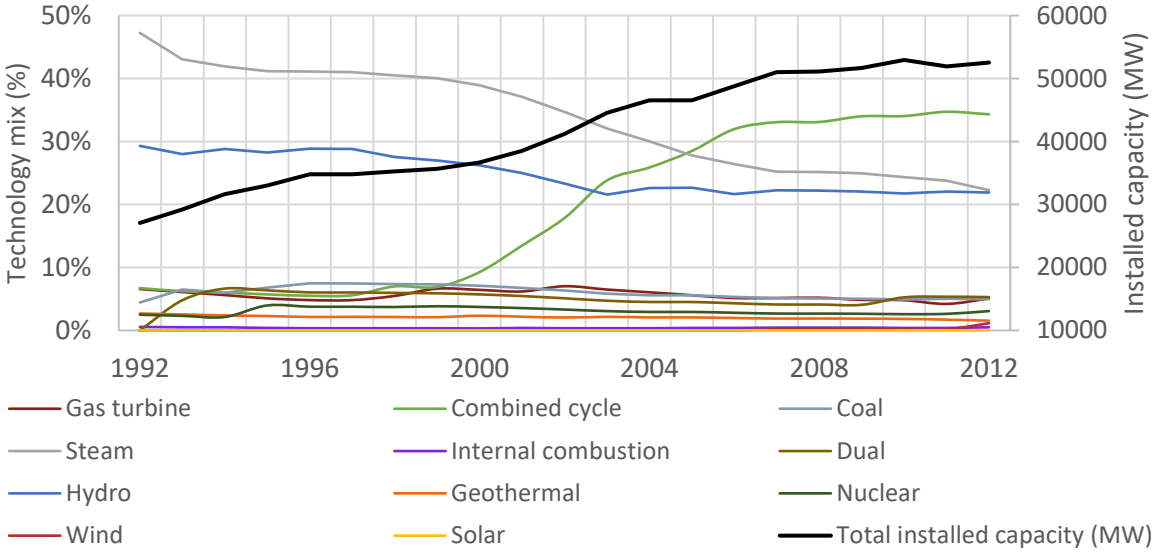


Fig. 33. Shares of technology mix (left) and total installed capacity (right) for public service (1992-2012). Constructed with data from [71–83].

Table 5
International (core) leaders on selected electricity generation technologies in 1992 and 2012. Source: [50].

Technology	Core countries in 1992 (MW)	Core countries in 2012 (MW)
Natural gas combined cycle	US (27,458) Japan (5,040) Mexico (1,933) Netherlands (1,819)	US (221,952) Italy (42,486) UK (35,150) Mexico (22,504)
Gas turbine	US (51,161) Germany (6,051) Japan (4,103)	US (139,738) Canada (11,759) Japan (11,297)
Wind	US (1,823) Denmark (436) Germany (183)	US (59,075) Germany (30,979) Spain (22,789)
Solar PV	US (44) Japan (19) Italy (8)	Germany (34,075) Italy (16,785) US (8,137)
Nuclear	US (99,005) France (57,675) Japan (34,584)	US (101,885) France (63,130) Japan (46,148)
Hydro	US (96,059) Canada (61,668) Japan (39,523)	US (101,106) Canada (75,537) Japan (48,934)
Geothermal	US (2,910) Mexico (730) Italy (471)	US (2,592) Mexico (824) Italy (728)

3.4.1. Multi-perspective summary (1992-2012)

Due to diverse internal and external pressures, a policy paradigm shift towards (partial) liberalisation of the market took place during this period. The main policy objectives were

promoting energy efficiency and technology mix diversification; expand electricity services to rural areas; energy security; environmental protection; and climate change mitigation. Fig. 34 presents the main policy mixes adopted during this period.

During this period the system reached a 99% coverage nationwide; electricity tariffs varied based on different internal and external events; supply-demand balance also fluctuated based on diverse landscapes (e.g. a decline in hydrocarbons production); GHG emissions increased in 48%; and electricity intensity showed a decreasing trend over time. Fig. 35 depicts the main outcomes of interest to show the overall performance of the system.

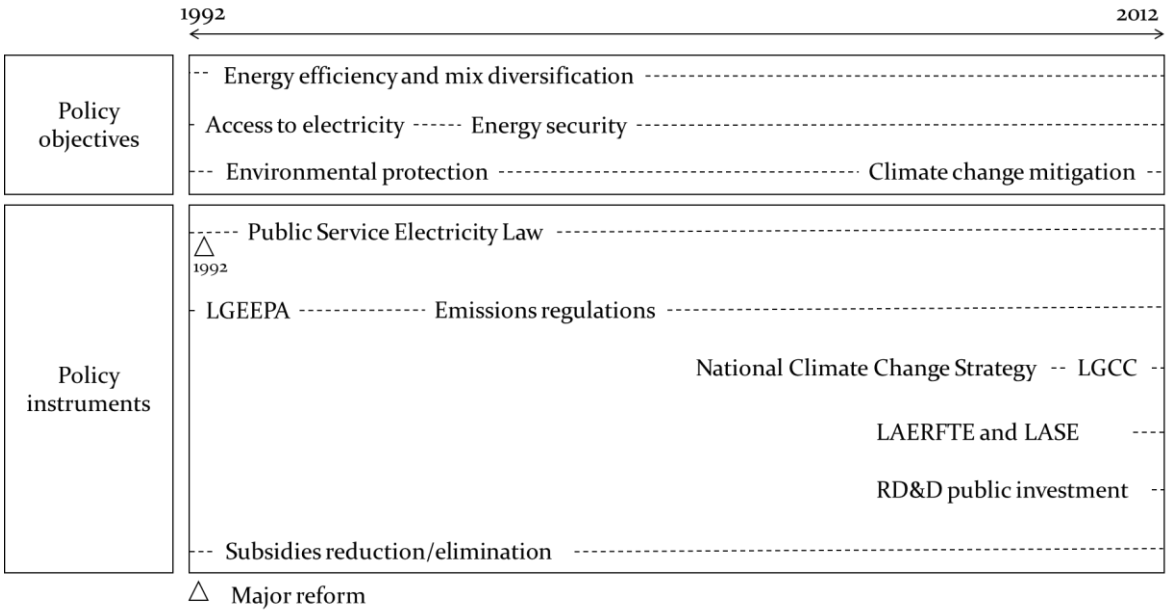


Fig. 34. Socio-political perspective snapshot (1992-2012).

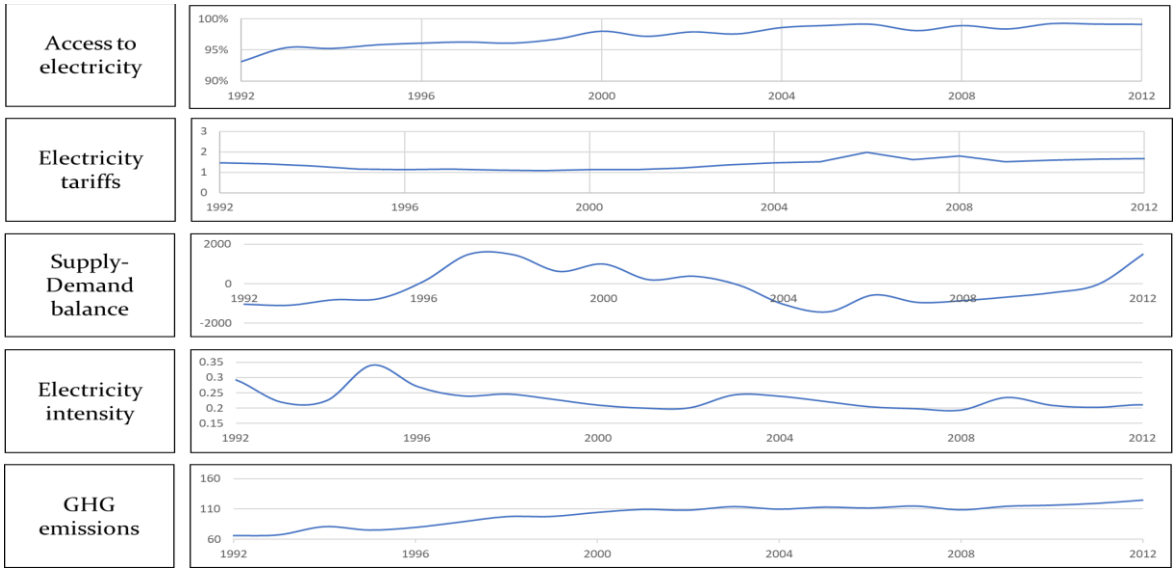


Fig. 35. Techno-economic perspective snapshot (1992-2012). Access to electricity refers to the percentage of population with access to electricity. Electricity tariff represents changes in the total tariff considering the main consumer sectors (i.e. residential, commercial, industrial, services, and agriculture). Supply-Demand balance refers to the net electricity imports in GWh. GHG emissions depicts emissions from electricity generation in Mt CO_2-e. Electricity intensity refers to electricity needed to generate one unit of GDP (in current US$). Constructed with data from [46,54,55,57–59,61,64].

The system experienced a transition to natural gas combined cycle; the first onshore wind and solar PV projects started operations; innovation systems were strengthened with new policy instruments (i.e. creation of the RD&D energy funds); technology diffusion came mainly from US, Japan, and Europe where the largest technology deployment of NGCC, wind, and solar PV took place. Fig. 36 depicts the main socio-technical changes during this period.

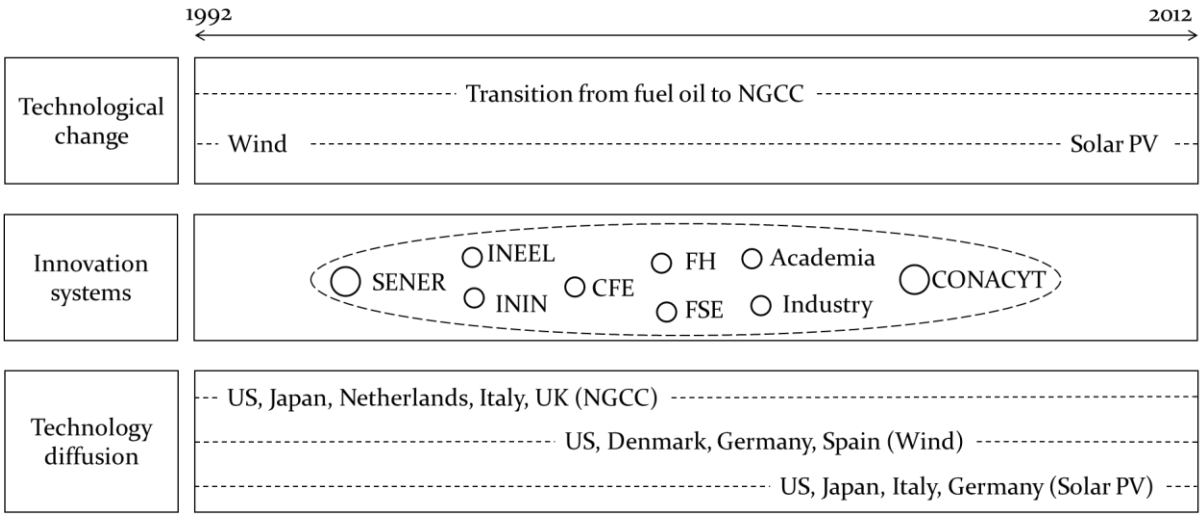


Fig. 36. Socio-technical perspective snapshot (1992-2012).

3.4.2. Energy transitions governability (1992-2012)

During this period, the governance system expanded to include less homogenous actors and institutions, creating diverging standpoints and more complex interactions. Governability during this period was characterised by a shift from 'command-and-control' state interventions to a more participative (and coordinated) interactions with non-state organisations (i.e. market actors and civil society) [11]. Fig. 37 and Table 6 depict the energy transitions governability snapshot for the period from 1992 to 2012.

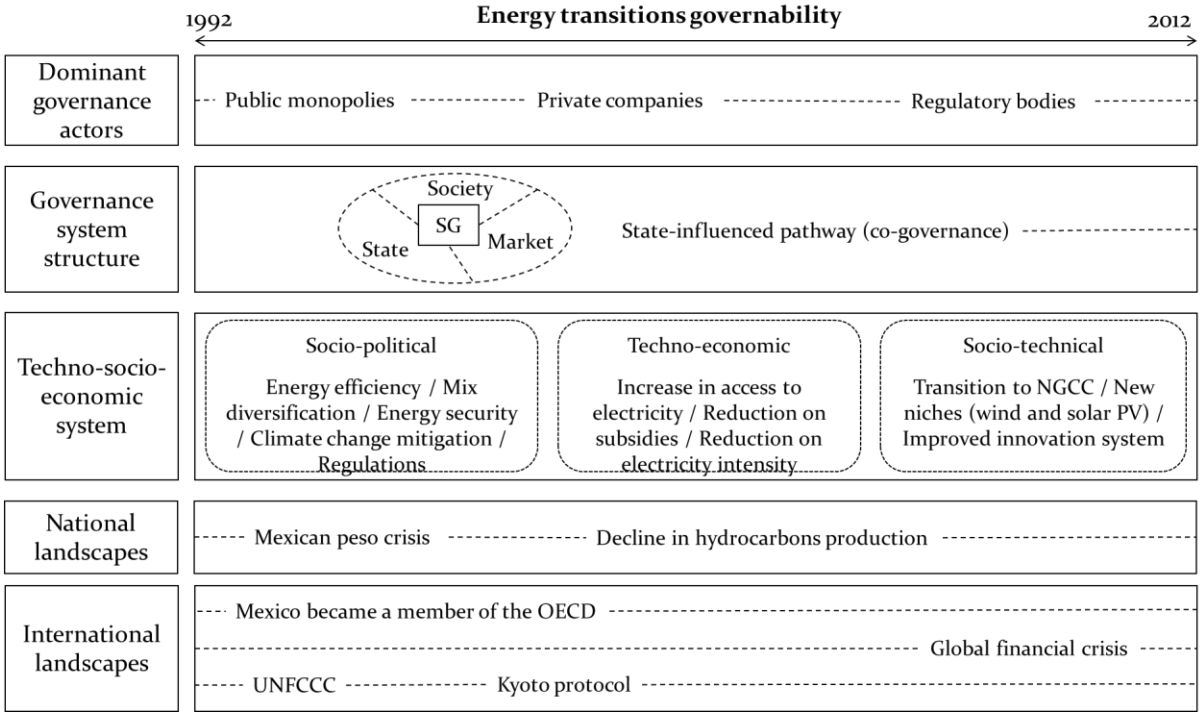


Fig. 37. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1992-2012).

Table 6
Energy transitions governability snapshot – governing interactions (1992-2012).

State -> Market	
	Intervention on energy efficiency and mix diversification.
	Regulation of tariffs.
	Regulation on power generation.
	Intervention on environmental protection and climate change mitigation.
State -> Society	
	Intervention on subsidies.
	Promotion on expansion of services.
	Intervention on energy efficiency.
Society -> State	
	Pressure for access to electricity in rural areas.
	Pressure for lower prices.
Society -> Market	
	Pressure for better services and prices.
	Pressure for use of clean energy technologies.
Market -> State	
	Pressure for tariff increase.
	Pressure for financial support.
	Pressure for improving innovation systems.
Market -> Society	
	Pressure for reducing electricity intensity (e.g. demand side management).

4. Discussion and future research

The energy transitions governability framework was developed and applied in this article as a multi-perspective analytical framework to describe the evolution of electricity transitions in Mexico from 1879 to 2012. Based on the structural configuration of governance systems (at an actor level), four periods were explored in this article. First, a market-led pathway took place from 1879 (when the electricity industry in Mexico originated) to 1936, dominated by informal interactions between the state, private monopolies, and key actors within the society (mainly industrial consumers) with little state regulation (i.e. self-governance). After multiple tensions within the regime, a transformation process towards a state-influenced pathway occurred between 1937 and 1959 with an increasing state participation in the expansion of the electricity industry to meet societal needs (i.e. co-governance). Mainly derived from nationalistic spirits, a state-led pathway took place from 1960 to 1991 resulting in the creation of diverse public institutions to guide the development of the industry (i.e. hierarchical governance). Finally, the electricity system transitioned to a state-influenced pathway from 1992 to 2012 with a partial liberalisation of the sector coordinated by public regulatory bodies. Based on the historical evolution of the electricity sector, different drivers have been identified in shaping electricity transitions in Mexico.

First, governance decisions have depended on specific paradigms that relevant actors have adopted. For instance, informal social relations between the state and (mainly) transnational electricity companies benefited private interests (i.e. clientelism) during the early stages of the electricity industry in Mexico, allowing monopolistic practices [84]. On the other hand, a nationalistic paradigm shaped the evolution of the industry from 1960 to the 1990s, when the state recognised the need for reliance on private capital and liberal markets to meet societal needs (e.g. increase in electricity demand). Even if it is likely that future transitions follow a market-led with state regulation pathway (directed co-governance) a policy paradigm shift may change the direction (or pace) of these structural changes. Also, the electricity tariff

policy has followed different pathways throughout the periods analysed. At the beginning of the electricity sector, tariffs were set by private companies based on economic interests (increase profit) and were mainly based on (variable) operational costs. Then, a policy paradigm shift towards nationalisation and sovereignty set tariffs below real generation costs promoting social benefits to the Nation (following oil development and cross-sectoral subsidies). The social aspect of nationalisation brought financial constraints to state-owned companies, resulting in an increase in electricity prices since the late 1980s but subsidising some key subsectors. One plausible explanation for setting subsidies for agriculture and residential subsectors under the socio-political perspective is the relevance of acquiring low/middle income class voters by decreasing the price paid by these sectors [42]. Although subsidies have been falling throughout the years, this state intervention represents (socio-political) challenges in the future (e.g. regressive effects, tensions between governance actors with high political costs).

Second, available (indigenous) resources have played a key role in directing the path and pace of electricity production technologies. When multiple changes in the system reinforce each other, inertia and path dependency emerge. In the case of Mexico, electricity generation has followed a path-dependent pathway ruled by available energy resources in the country (e.g. fuel oil or natural gas production). Fossil fuels are geologically finite, geographically fixed, and unevenly distributed around the world. Thus, when countries, such as Mexico, have had access to (indigenous) fossil fuels tend to privilege long-standing incumbent regimes (e.g. by supporting aging fossil-fuel incumbent power plants) creating a technological lock-in effect for new technological niches (e.g. wind, solar, geothermal) [85]. However, the ever-growing electricity demand in the country has called for the utilisation of different (complementary) technologies for power generation (sometimes referred as energy additions [5]). The decline in hydrocarbons production in the country since the mid-2000s has accelerated the promotion of clean energy development and diffusion. Thus, a transition away from fossil fuels (i.e. technology-based energy transition) is likely to take place in the future due to the geologically finite nature of these fossil fuel resources. However, constraints on clean energy technologies (e.g. limited steam extraction for geothermal power generation or extended use of land for solar farms) may pose challenges to the diffusion of these technologies. Although efforts on supporting the development of clean energy technologies have been made (public energy R&D, promoting innovation systems), technological lock-in has been (a will remain) a key challenge for new niches if fossil-fuel incumbent regimes are promoted by the state due to operational and socio-political interest (e.g. clientelism). Thus, the integration of coordinated energy innovation policy mixes towards clean energy transitions are needed (technology-push and market-pull mechanisms) to overcome technical and market barriers.

Third, increasing environmental and climate change concerns have modified the way electricity is produced and used (nationally and internationally). International agreements on climate change mitigation may gain further weight in deploying clean technologies and adopting energy efficiency measures (e.g. demand response management) even if socio-political interests exist within the governance system. However, a transition to a low-carbon economy in Mexico may pose significant challenges such as increasing inequality or exacerbating vulnerability of particular communities if key (ecological, economic, political, and social) aspects such as inclusivity, mineral extraction, land utilisation, and population management are not included in the political agenda [86,87]. A first step to better understand transitions at different scales could be to adopt a more holistic approach by including the potential negative effects of a clean energy transition (e.g. political conflict, degradation of the environment, economic inequality) as opposed to simply focus on emissions reduction (i.e. mitigation strategies).

To comply with international agreements on climate change mitigation and to meet electricity demand, Mexico has facilitated the adoption of neoliberal models towards private investments

in low carbon energy technologies since the 1990s. However, the economic approach of private companies has led to adverse social effects on vulnerable communities whose traditional lifestyles and economic livelihoods are threaten by such investments (e.g. land acquisitions through unfair land-lease contracts) [88]. The socio-economic effects of renewable energy developments on vulnerable communities in Mexico have been extensively discussed in recent years [86,88–94]. It has been argued that a 'just' energy transition that prioritise safe, affordable, and sustainable energy for all individuals and across all areas (including local communities) is needed [88–90]. A transition towards a more sustainable energy system may be problematic if specific variables of the local context (e.g. land tenure, human rights) are not considered within energy planning [92]. To facilitate a fair energy transition in Mexico the definition of more democratic and participatory mechanisms for energy planning should be considered by policymakers (e.g. by combining top-down and bottom-up approaches for energy planning) [92–94]. Thus, energy transitions governability may be improved by fostering (local and international) communication and cooperation among actors and institutions to define policy mixes in line with national societal needs while complying with international agreements.

The structural transformations occurred during the last period (1992-2012) derived in a broad energy reform approved by the Mexican Congress in 2013 (affecting both the power and the oil and gas sectors). The reform and its ongoing effects are beyond the scope of this article due to three main reasons. First, the impacts of new (or reformed) energy policy mixes are usually not observed immediately after their implementation due to the long-term, evolving nature of processes of structural change within electricity transitions. Instead, adaptations to these policy mixes frequently take place derived from internal and external tensions within the system (e.g. policy paradigm shifts, opposition to change, international agreements). Second, data availability for some of the key variables used in this work (i.e. sustainability concepts) presents a significant limitation for describing the ongoing electricity transition. For instance, the latest data on GHG emissions from the energy sector published by the National Institute of Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático, INECC) corresponds to 2015. Third, the energy reform encompasses several complex structural changes at different scales (e.g. modifications to the Mexican constitution, enactment of new laws, new legislation, new actors, a different governance structure, and the development and implementation of several strategies and programs) aimed at accelerating the transition to a low-carbon economy. The analysis of a fifth period (e.g. 2013-2020) using the proposed analytical framework may significantly increase the length of the article. Thus, the application of energy transitions governability as an analytical framework to explore the complex structural transformations derived from the 2013 energy reform merits special attention and it is proposed as future research.

The empirical application of the proposed analytical framework to the Mexican case has identified drivers (and challenges) in electricity transitions at different structural levels that may be applicable to other developing countries. For instance, developing countries share some common characteristics affecting their electricity systems such as the increasing electricity demand and thus the need for infrastructure expansion [1]. However, the framework may be also applied to other countries (or regions) by explicitly establishing the key energy/sustainability concepts and periods of analysis to be used for the investigation. Also, its application may be extended to different societal systems (e.g. oil and gas sector, clean energy technologies, transport sector with a focus on deploying electric mobility) by identifying the relevant concepts for each perspective (socio-political, techno-economic, and socio-technical) to describe structural system transformations over time. Similarly, the framework proposed may be used as an analytical tool to conduct comparative research between countries or regions to extend its applicability and improve the generalisability of the findings.

Although the analytical framework has demonstrated its applicability to (qualitatively) describe historical electricity transitions in Mexico, it presents some limitations. First, we have used concepts from literature on policy mixes for sustainability transitions, energy/sustainability transitions, and interactive governance theory to describe changes in socio-techno-economic systems. However, complementary concepts may be used to explain transformation processes not covered here. These may include concepts found within the same disciplinary roots (e.g. technology costs, voters' preference, international competition, public opinion, corporatism) or relevant concepts/processes derived from complementary literature (e.g. geography, political ecology, energy justice). Second, according to systems thinking, any societal system (e.g. oil and gas) is interrelated with other systems (e.g. electricity), influencing them and providing context for future changes. An analysis of the oil and gas sector using the analytical framework presented here, may aid to better understand the interactions between these two sectors and get a broader picture of energy transitions in developing countries. Similarly, the analytical framework may be applied to electricity subsystems (e.g. renewable energy technologies) to propose energy strategies to meet specific policy objectives (e.g. 50% of total electricity production from clean energy sources by 2050). Third, data availability and reliability have been identified as important limitations for the applicability of the proposed analytical framework for developing countries (e.g. outdated information available from public organisations or data inconsistency from different sources). Although a more robust research method was sought by following the systematic review process described in Appendix A, it should not be interpreted as the coverage of the full collection of sources on the history of the electricity industry in Mexico. The procedures involved in conducting research or collecting data (i.e. methods) usually exclude and privileges diverse social actors [95,96]. In the case of Mexico, for instance, illegal activities (fuel theft, violent confrontation, organized crime, and cartels) may play a role in socio-political processes [97]. However, the lack of reliable information makes hard to research their specific role in societal transitions. Being conscious of these caveats, the research method applied in this work may be improved by diversifying sources, comparing findings with other studies, and triangulating research methods (e.g. on-site interviews or expert elicitation) [10]. Also, complementary sources (not covered here) may provide additional information regarding structural transformations in the electricity system in Mexico (e.g. including sources in other languages or using different keywords).

5. Conclusions

The electricity sector is a complex system that has been under continuous change since its creation. The aim of this article was to explore the evolution of historical electricity transitions in Mexico (1879-2012) from the perspective of the interactive governance approach. Four periods of analysis were proposed based on the structural configuration of governance systems. Interactive governance theory and governability enable an analytical framework for exploring the role of social actors, technological change, policy mixes, and the interactions among them in national energy transitions. We conceptualised the system-to-be-governed as a co-evolving socio-techno-economic system by using a meta-perspective framework for national energy transitions. Structural changes in energy systems at their diversity, complexity, dynamics, and scale pose challenges to governance systems and have highlighted the role of these in guiding energy transitions. In the case of Mexico, it started as self-governance system led by the market (mainly private monopolies) without government regulation. Then, a co-governance mode was adopted with coordination among the government, private companies, and civil society to guide the development of the industry. After a policy paradigm shift towards nationalism and sovereignty took place, a hierarchical governance mode was adopted to meet societal needs (e.g. access to electricity, expansion of the system, tariff reduction). Finally, a liberal market paradigm adopted by the state transitioned to a co-governance system where private participation in electricity generation

was allowed to meet increasing demand and overcome financial, technological, and operational challenges in the regime.

This article is a complementary analytical exercise to previous work focused on explaining historical electricity transitions in Mexico. The multi-perspective approach used in this work overcomes some of the limitations of analytical frameworks applied before (e.g. socio-technical change) by making a distinction between the economic, political, and technological aspects of the system and their interactions (as opposite as a 'seamless-web' approach). The use of concepts from energy transitions and policy mixes for sustainability transitions were useful to understand the role of policy mixes, social actors, technological change, and the system's performance in different episodes of electricity transitions. The interactive governance perspective assumes that different modes of governing may be more appropriate depending on contextual characteristics of the societal system to be analysed. By using interactive governance theory, we have attempted to synthetise these 'micro-logics' into a broader theoretical construct as suggested by [2]. This may help at understanding why different countries have adopted different policy mixes to tackle similar issues like climate change mitigation or energy security (e.g. different policy paradigms tend to influence governance decisions and thus the pathway of energy transitions).

As the case study presented here revealed, governability of national energy transitions has varied considerably from one episode to another depending on how governance systems have handled societal needs. Different factors have influenced how the electricity system in Mexico has transitioned from one configuration to another. First, governance decisions have been influenced by (policy) paradigms adopted by relevant actors. Second, available (indigenous) resources have played a key role in guiding the pace and pathway of electricity production technologies. Third, increasing environmental and climate change concerns have modified the electricity sector development. We have suggested that energy transitions governability may be improved by fostering (local and international) communication and cooperation among actors and institutions to define policy mixes which meet the societal needs.

CRediT authorship contribution statement

Omar Castrejon-Campos: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualisation. **Lu Aye**: Validation, Resources, Writing - review & editing, Visualisation, Supervision, Project administration, Funding acquisition. **Felix Kin Peng Hui**: Supervision, Writing - review.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Description on the research method adopted to describe the governability of historical electricity transitions in Mexico

This article focuses on answering the following research questions: how governing structures in the electricity sector have evolved over time? What role have these governing structures played in shaping electricity transitions? What have been the main drivers for structural change within the Mexican electricity system?

The aim of this article is to explore the evolution of historical electricity transitions in Mexico from 1879 to 2012 by applying the analytical framework described in Section 2. Thus, a systematic review process was conducted in this work with the objective of describing structural changes within the Mexican electricity system following a theoretical heuristic approach. A comprehensive literature search was initially developed in November 2019 and updated in August 2021. To facilitate replicability, the process followed a series of steps (i.e. research design) to identify, screen, and select relevant documents for analysis as described as followed.

Step 1. Identification of sources.

Two main tools were used to conduct a preliminary search on historical electricity transitions in Mexico: broad disciplinary databases and grey literature searching (e.g. reports, working papers, government documents). Scopus (https://www.scopus.com) and Google Scholar (https://scholar.google.com) were the two databases chosen to locate relevant studies for the purpose of the analysis. In the case of grey literature, different web pages were selected for a preliminary search of relevant documents. These include the Mexican Secretariat of Energy (Secretaría de Energía, SENER) website (https://www.gob.mx/sener), the Federal Electricity Commission (Comisión Federal de Electricidad, CFE) website (https://www.cfe.mx), the Mexican government website (https://www.gob.mx/), and the International Energy Agency website (https://www.iea.org/).

At first, a search was conducted on Scopus using a combination of English-language keywords such as “Mexico”, “electricity”, “transition”, “history”. The preliminary search resulted in 71 documents (including articles, conference papers, books chapters, reviews, and books) using the following string: TITLE-ABS-KEY (“Mexico” AND “electricity” AND (“transition” OR “history”)). We also searched relevant literature using a combination of keywords in Spanish-language on Google Scholar. Keywords used include “México”, “electricidad”, “historia”, “industria eléctrica”, “sector eléctrico”, and “sistema eléctrico”. The preliminary search resulted in 39,900 results (including citations). From these, only the first 300 results sorted by relevance were selected for screening due to time limitation. No publication date or publication status restrictions were imposed.

The grey literature search included targeted, iterative hand searching of government and/or research organisation websites. A total of 50 additional records were added to the review from the grey literature search, including annual reports, working papers, laws, regulatory frameworks, datasets, manuals, theses, critical analyses, among others.

Step 2. Title/abstract screening.

A preliminary screening process of 421 documents was conducted on the criteria of title and abstract/summary (if available) to verify their relevance to the review. From these, 309 records were excluded due to three main reasons: (1) the studies focused on different regions (e.g. United States) and/or broader regions (e.g. Latin America) with no (or not enough) relevant information on Mexico; (2) the studies were out of scope (i.e. covering broader topics such as population, democracy processes, general history of Mexico, etc.); and (3) no apparent relevance was found (e.g. analysis of historical temperatures in specific regions of Mexico) and/or did not match the research aim (i.e. describe historical electricity transitions in Mexico).

Step 3. Full-text screening and eligibility.

During this step we reviewed 112 documents. They were filtered based on their relevance on contributing to a critical analysis according to the analytical framework proposed. A total of 76 records were excluded due to four main reasons: (1) content of the studies were partially or completely covered by other records (e.g. books or reports describing in detail the history of the electricity sector in Mexico for different periods); (2) the documents covered periods of time not contemplated within this analysis (e.g. after 2012) or were out of scope in terms of the research aim (e.g. historical analysis of specific government institutions); (3) the same data were included in multiple publications (e.g. description of the structure and objectives of the Mexican energy funds were included in several annual reports); and (4) national laws, their corresponding reforms, and regulatory frameworks were not cited due to word limitation and to avoid misperceptions (i.e. reforms modify both previous laws and published related documents such as regulatory frameworks).

On the other hand, reference lists of included records (e.g. articles, reports, thesis) were manually screened to identify additional relevant studies. A total of 19 additional studies were included to the review going through the (iterative) literature review process. After this step, the number of relevant documents was reduced to 55.

Step 4. Records included.

A total of 55 records were accordingly cited within this article to describe historical electricity transitions in Mexico under the interactive governance approach. The review process followed by this article was updated in August 2021.

Evolution of clean energy technologies in Mexico: A multi-perspective analysis

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ABSTRACT

Electricity is fundamental for supporting economic development in emerging economies. Power generation from clean energy sources may help to meet societal needs such as increasing electricity demand while complying with contemporary global challenges (e.g. climate change). This paper aims at qualitatively describing the development of clean energy technologies in Mexico by using a multi-perspective analytical framework. By integrating a meta-theoretical framework for national energy transitions and core concepts from policy mixes for sustainability transitions literature, a series of stylised facts are developed to qualitatively describe the evolution of clean energy technologies in Mexico from 1879 to 2021. Interactive governance theory is used as an analytical framework to synthesise these storylines by highlighting the role and interactions among technologies, actors, and policy instruments in governance processes. The case study revealed that the ever-growing electricity demand in Mexico have called for exploring different available energy sources and technologies over time. Diminishing oil and gas domestic reserves, increasing concerns around environmental issues, and worldwide agreements on greenhouse gas emission reductions have been the main drivers for clean energy and energy efficiency development in Mexico. However, different barriers to a clean energy transition in Mexico have been identified and discussed in this study: (1) access to a vast oil and gas resources in the past reinforced the position of fossil-fuel incumbent regimes, displacing clean energy technological niches; (2) lack of investment in clean energy research, development, and innovation; (3) policy paradigms have shifted based on (dynamic) societal needs and socio-political interests in favour of fossil fuel power generation. To overcome these barriers and allow a transition towards a clean energy electricity system in Mexico, multiple policy instruments have been identified and discussed.

***Keywords*:** Clean energy technologies, Electricity sector, Interactive governance, Multi-perspective analysis, Mexico, Energy policy mix.

Abbreviations

BAU	business as usual
CCS	carbon capture and storage
CEC	clean energy certificate
CEMIE	Mexican Energy Innovation Centre (Centro Mexicano de Innovación en Energía)
CENACE	National Centre of Energy Control (Centro Nacional de Control de Energía)
CFE	Federal Electricity Commission (Comisión Federal de Electricidad)
CNEG	Geothermal Energy National Commission (Comisión Nacional de Energía Geotérmica)
CNSNS	National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias)
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CONACYT	National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología)
CONAE	National Commission for Energy Saving (Comisión Nacional para el Ahorro del Energía)
CONUEE	National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía)
CPP	cogeneration power producer
CRE	Energy Regulatory Commission (Comisión Reguladora de Energía)
CSS	continuous self-supply
ENCC	National Climate Change Strategy (Estrategia Nacional de Cambio Climático)
ENE	National Energy Strategy (Estrategia Nacional de Energía)
FCC	Climate Change Fund (Fondo para el Cambio Climático)
FIDE	Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica)
FIRCO	Shared Risk Fiduciary Fund (Fideicomiso de Riesgo Compartido)
FOTEASE	Energy Transition Fund (Fondo para la Transición Energética y el Aprovechamiento Sustentable de la Energía)
FSE	Energy Sustainability Fund (Fondo de Sustentabilidad Energética)
GDP	gross domestic product
GHG	greenhouse gas
GI	governing interactions
GS	governance system
GW	gigawatt
GWh	gigawatt-hour
IEA	International Energy Agency
IIE	Electricity Research Institute (Instituto de Investigaciones Eléctricas)
INDC	Intended Nationally Determined Contribution
INEEL	National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias)
ININ	National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares)
IPP	independent power producer

IRENA	International Renewable Energy Agency
kW	kilowatts
kWh	kilowatt-hour
LAERFTE	Law for the Use of Renewable Energy and the Financing of the Energy Transition (Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética)
LASE	Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía)
LCFE	Federal Electricity Commission Law Ley de la Comisión Federal de Electricidad)
LGCC	General Climate Change Law (Ley General sobre Cambio Climático)
LGEEPA	General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente)
LIE	Electricity Industry Law (Ley de la Industria Eléctrica)
LPDB	Bioenergy Law (Ley de Promoción y Desarrollo de los Bioenergéticos)
LTPA	long-term power auction
LUCF	land use change and forestry
LyFC	Compañía de Luz y Fuerza
MLP	Multi-level perspective
$MtCO_2e$	million tonnes of carbon dioxide equivalent
MTPA	medium-term power auction
MW	megawatts
MWh	megawatt-hour
NAFINSA	Nacional Financiera
NAFTA	North American Free Trade Agreement
NAMA	Nationally Appropriate Mitigation Actions
NEI	National Emissions Inventory
NGCC	natural gas combined cycle
NO_x	nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
PAER	Speacial Program for the Use of Renewable Energy (Programa Especial para el Aprovechamiento de Energías Renovables)
PAESE	Program of Energy Savings in the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico)
PE	power exports
PECC	Special Program for Climate Change (Programa Especial de Cambio Climático)
PEMEX	Mexican Petroleum (Petróleos Mexicanos)
PETE	Special Program for the Energy Transition (Programa Especial de la Transición Energética)
PI	power imports
PJ	Petajoules
PPA	power purchase agreement
PPP	purchase power parity
PROCER	Mexico-US Renewable Energy Cooperation Program (Programa de Cooperación en Energía Renovable)

PRODESEN	National Electricity System Development Program (Programa de Desarrollo del Sistema Eléctrico Nacional)
PRONASE	National Program for Sustainable Use of Energy (Programa Nacional para el Aprovechamiento Sustentable de la Energía)
PRONASOL	National Solidarity Program (Programa Nacional de Solidaridad)
PROSENER	Energy Sectoral Program (Programa Sectorial de Energía)
PSS	power self-supply
PV	photovoltaic
R&D	research and development
RD&D	research, development, and demonstration
REC	Renewable Energy Cooperatives
SE	Secretariat of Economy (Secretaría de Economía)
SEMARNAP	Secretariat of the Environment, Natural Resources and Fisheries (Secretaría de Medio Ambiente, Recursos Naturales y Pesca)
SEMARNAT	Secretariat of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales)
SEMIP	Secretaría de Energía, Minas e Industria Paraestatal
SENER	Secretariat of Energy (Secretaría de Energía)
SG	system-to-be-governed
SIE	Energy Information System (Sistema de Información Energética)
SLCPs	short-lived climate pollutants
SO_x	sulfur oxides
SPP	small power producer
T&D	transmission and distribution
TCP	Technology Collaboration Program
toe	tonnes of oil equivalent
TWh	terawatt-hour
US	United States

1. Introduction

There is a broad consensus that to put the world on a path to a reasonable climate future, significant reductions in greenhouse gas (GHG) emissions are necessary [1]. The vast majority of GHG emissions come from a small set of countries where the energy sector represents the main source of these emissions. Although Mexico has one of the lowest levels of carbon dioxide (CO_2) emissions per capita among the Organisation for Economic Co-operation and Development (OECD) countries [2], it is the world's 11th largest GHG emitter due to its fossil fuel-intensive energy mix [1,3]. In 2018, CO_2 emission from power and heat generation in Mexico accounted for 34.5% of total emissions from fuel combustion, being the highest pollutant activity nationwide [3].

Mexico is the eleventh-largest global economy by purchase power parity (PPP), and the second-largest in Latin America [4]. It is expected to become the seventh-largest economy worldwide by 2050 [5]. However, Mexico's growth has been achieved at the expense of its environment and society, exposing the country to severe climate change risks [2–4]. Mexico is endowed with abundant (fossil and renewable) energy resources. Given the right mix of policy instruments, Mexico has the potential to develop clean energy and thus diversify its energy mix and significantly reduce its GHG emissions [6]. To meet international climate pledges, Mexico has set ambitious national GHG emissions reduction targets (22% by 2030 from business as usual and 50% versus 2000 levels) [7,8]. The largest contribution to GHG emissions reduction is expected from the electricity sector [4]. Thus, targets for power generation from clean energy sources were established aimed at reaching a share of 35.1% in total electricity generation by 2024, 38.2% by 2030, and 50% by 2050 [9]. According to the (new) Electricity Industry Law (2014), clean energy technologies include renewable energy sources (geothermal, wind, solar, hydropower, biomass), as well as electricity generation through nuclear power, hydrogen, fossil-fired generation with carbon capture and storage (CCS), and efficient cogeneration [10].

Mexico has a fast-growing electricity sector, with annual demand increasing 2.8% since 2000 (on average) and it is projected to increase by more than half by the end of the decade [4]. Expediting the speed of Mexico's clean energy diffusion may result in annual net savings of up to USD 11.6 billion in the national energy system costs by 2030 (accounting for externalities such as health effects and carbon emission reductions) [6]. However, limited progress has been made to date. As of 2019, electricity generation from clean energy technologies (not including cogeneration) was 65.1 TWh (20% of the total generation). The mix was composed mainly of hydropower (7%), followed by onshore wind (5%), nuclear (3%), geothermal (2%), and solar photovoltaic (PV) (2%) [11]. Also, Mexico reached 448.5 million tons of CO_2 emissions from fuel combustion in 2018 (24% more than in 2000) [12]. Structural transformations in the Mexican electricity system have changed the way electricity is produced and used over time. A deeper understanding of the barriers (and drivers) of clean energy development in Mexico is needed to explore different pathways to achieve national energy and climate objectives.

The aim of this paper is to qualitatively describe the development of clean energy technologies in Mexico by using a multi-perspective analytical framework. By integrating a meta-theoretical framework for national energy transitions and relevant concepts from policy mixes for sustainability transitions literature, a series of stylised facts are developed to describe the evolution of clean energy technologies in Mexico from 1879 to 2021. Then these storylines are synthesised using an interactive governance approach to highlight the relative role of energy technologies, actors, and policy instruments (and the interactions among them) in governance processes. Although different analytical frameworks have been used to describe economic, technological, and socio-political changes in the Mexican electricity system at different periods in time (see, for instance, [8,13,14]), the detailed evolution of clean energy technologies

has received little attention and their development has been marginally described within a broader scope (i.e. electricity systems). Thus, the contributions of this paper are three-fold. First, this paper builds on previous studies on energy transitions by thoroughly describing the evolution of clean energy technologies in national electricity transitions, highlighting advances and setbacks in their diffusion. Second, the period of analysis covers the national clean energy development since the first use of electricity in Mexico (1879) to date (2021), providing an updated comprehensive historical analysis. Third, the application of an integrative multi-perspective analytical framework contributes to the discussion on the design and development of national policy mixes towards a clean energy transition in Mexico by making a distinction between the economic, social, political, and technological aspects of the system and their interactions (opposite to a 'seamless-web' approach). The findings of the study contribute to the existing literature in the following ways. Drivers and barriers for deploying clean energy technologies in Mexico are identified and discussed. Also, potential policy instruments towards a clean energy transition in Mexico (based on current policy objectives, specific targets, and performance indicators) are discussed. The work is intended for energy policymakers, researchers, energy analysts, and energy practitioners.

The rest of paper is organised as follows. Section 2 presents the integrated analytical framework for describing the evolution of clean energy technologies in the electricity sector. Section 3 illustrates an empirical application of the framework to the Mexican case (1879-2021). The current (2021) policy objectives, specific targets, and performance indicators towards a clean energy transition in Mexico are presented in Section 4. In addition, potential policy instruments towards a clean energy transition in Mexico are discussed in this section. Drivers and barriers for a clean energy transition in Mexico are discussed in Section 5. Also, potential future research and conclusions are exhibited within this section.

2. Integrative analytical framework for techno-socio-economic systems in energy transitions

2.1. Multi-perspective analysis for national energy transitions

Energy (or electricity) transitions have been conceived as complex, long-term, multi-actor, dynamic, co-evolutionary processes of structural transformations regarding energy (or electricity) production and consumption [15]. A single transition theory can be used to gain insights on these complex structural changes. However, by using multiple complementary theoretical approaches (e.g. political science, social studies, economics) energy transitions may be better explained and analysed (see, for instance, [16,17]). Cherp et al. [16] proposed a multi-perspective analytical framework to explain the long-term structural changes that occur in national energy systems through the analysis of three main co-evolving subsystems: (1) socio-technical subsystem, characterised by the interaction of different energy technologies; (2) techno-economic subsystem, defined by the energy that is supplied and used through the coordination of energy markets; and (3) socio-political subsystem, explained by the development and implementation of energy policy instruments that influence energy systems [15,16]. Within this meta-theoretical framework, multiple (complementary) concepts in the sustainability transitions literature are adopted to explain national energy transitions as co-evolving techno-socio-economic systems (see, for instance, [18]). Similarly, Castrejon-Campos et al. [15] suggested the integration of core concepts from the policy mixes literature to investigate the role of policy mixes in historical energy transitions. Concepts from the three perspectives (i.e. socio-technical, socio-political, and techno-economic) and policy mixes for sustainability transitions literature are used in this paper to gain insights on the role of clean energy technologies in historical electricity transitions, and to identify potential drivers (and barries) towards a clean energy transition in Mexico (see Fig. 1). Transitions in energy systems may occur derived from the interactions of diverse contextual drivers and barriers, with different relative influence from one phase to another. Thus, a more comprehensive

explanation of these structural changes is sought by using multiple (yet complementary) sustainability and energy transitions concepts [15,16].

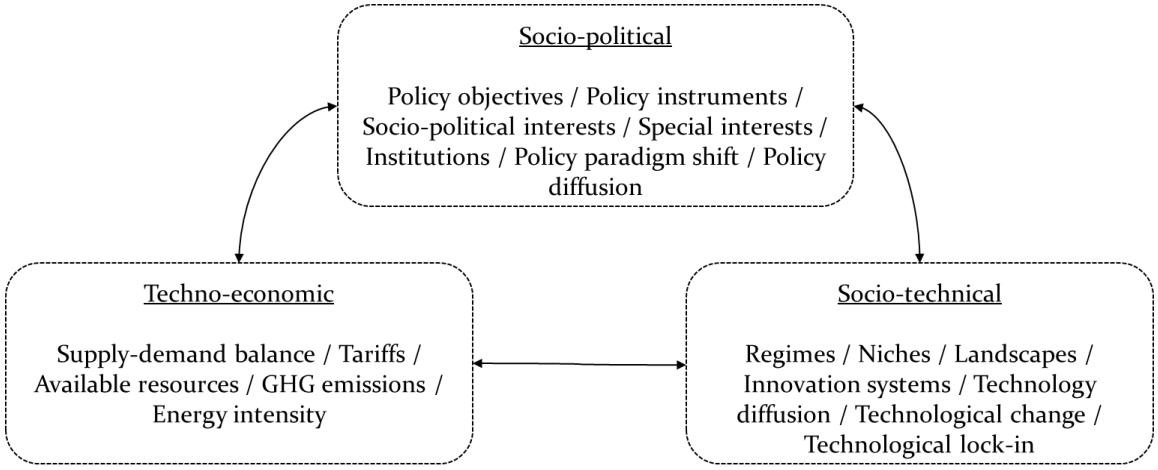


Fig. 1. Energy and sustainability transitions concepts used to explain national energy transitions. Source: adapted from [15] with information from [16,19].

In the socio-political perspective, the state is the focus of the analysis [16]. The adoption and implementation of policy instruments by the government include different (social, political, or special) interests based on the conceptualisation of 'state'. Policy objectives (e.g. economic growth, energy security, climate change mitigation, technological leadership, reliable access to electricity) are the main focus on state-centric approaches. Competing socio-political interests (e.g. voters' preference, political parties, social movements) and special interests (e.g. industrial lobbies) are the main factors that influence policy mixes within state-structural approaches [16,20]. Policy mixes for energy transitions comprise a strategic element (encompassing policy strategies, objectives, and specific plans/programs), the analysis of dynamic policy processes, and the examination of the role that institutions and relevant actors play in the design and implementation of policy instruments and the interactions among them [19,21]. Institutions are defined as "structures and rules that enable and constrain state and other political actors" [16]. The role of institutions has been explored following different neo-institutionalism (e.g. sociological, historical, and rational choice) and discursive institutionalism approaches [20]. Within the latter a key concept is policy paradigm shift. A policy paradigm is "a pattern of framing policy problems and searching for solutions" [16]. A policy paradigm shift takes place when relevant social actors and the state agree on an alternative solution to or a different definition of a problem, highlighting the role of learning within this dynamic process [20]. International relations theories aid to explain the phenomenon when countries with different characteristics adopt similar policies to deal with energy issues (e.g. energy crises). Pressures from international institutions, international harmonisation, best practices from other countries or international policy promotion may encourage the adoption of new or alternative energy policy instruments (i.e. policy diffusion). However, policies adopted from other countries may be not suitable/compatible with domestic structures (i.e. institutions and capacities).

According to the techno-economic perspective, the notion of supply-demand balance in electricity systems refers to the idea that any change in electricity supply or demand should be counterbalanced by analogous adjustments in other aspects of the electricity systems [16]. For instance, if domestic electricity demand is increasing it must be met by expanding electricity generation or imports. On the other hand, if electricity generation is expanded using clean energy technologies, it must be accompanied by phasing out fossil-fuel sources of generation. Also, the idea of market equilibrium used within this perspective states that energy supply and demand are in a stable equilibrium if producers and consumers agree on prices/tariffs for

electricity services. This is production, consumption, and trade in markets are in equilibrium under competitive markets [16]. Resources available for electricity production is another relevant aspect to be included within the analysis (e.g. fossil fuel deposits, uranium deposits, flows of water, solar radiation, average wind speed, heat flows from Earth). For instance, it may not be worth investing in building several geothermal power plants in countries like Australia, Brazil, or Russia, while in other places like New Zealand, Italy, or Mexico is worth doing it due to their geothermal potential (considering several environmental factors) [22]. Increasing concerns on climate change mitigation and thus designing policy mixes aimed at reducing GHG emissions have posed special interest in understanding the evolution of energy systems. Mitigation strategies should be directed towards both energy generation and consumption. Thus, energy efficiency (e.g. through energy intensity analysis) has also become a relevant variable to be included within (quantitative) models to explore energy system pathways. Energy efficiency technologies may play a greater role in energy transitions due to their potential benefits: pollution reduction, public health improvement, and financial savings. Also, it has been argued that energy savings may be the fastest, cheapest, and most environmentally friendly mitigation strategy to meet energy needs in developing countries [23,24].

Within the socio-technical perspective, two main streams of research for transition studies have been used to explain energy transitions: technological innovation systems [25] (combination of innovation systems and technological systems) and socio-technical transition analysis (which includes frameworks such as transition management [26], strategic niche management [27], and multi-level perspective [28]). These strands share the concepts of a socio-technical system, a (incumbent) socio-technical regime, and (technological) niches [16]. A socio-technical system is defined as a configuration of technologies, regulations and actors, services and infrastructure that fulfils a societal function (e.g. energy provision) [29]. A socio-technical regime is defined as a shared set of routines and rules enclosed in a socio-technical system to assure they are able to meet relevant societal needs. Niches are socio-technical subsystems with less stable and more fluid boundaries, rules, practices, and actors [8,16,30]. Within the multi-level perspective (MLP) framework [28], the regime must be destabilised by external pressures (i.e. landscapes) in order to give place to niches to fulfil the relevant function [8]. Innovations can be fostered by regimes to survive or expand, but they may hinder them if they represent a treat for their stability [16]. When the latter takes place, it is known as technological lock-in. Thus, industrial economies may "become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale" (also known as carbon lock-in) [31]. Contrarily, a regime shift may take place when incumbent regimes make room to newcomers emerging from previously protected niches (e.g. renewable energy technologies) [18,27]. Regime shifts may enable technology transitions where a change in the proportion of energy produced by emerging energy sources (or technologies) occur (sometimes called energy additions [32]). Also, multiple explanations for technological change can be used within the socio-technical perspective by using concepts from technological innovation systems literature. For instance, learning processes focused on gaining knowledge and experience of a particular technology may occur through various channels. When the focus is on experience gained through production processes (i.e. technology deployment) learning may increase through learning-by-doing [33], learning-by-using [34], and/or learning-by-interacting [35]. On the other hand, when the focus is on increasing learning through innovation activities within the early stages of the innovation chain, learning may increase through learning-by-researching [36]. Huenteler et al. [37] found quantitative support to the argument that improving national learning conditions (e.g. suitable organisational processes, skilled workforce) may have a significant impact on technology costs reductions and thus increase technology diffusion in

developing countries. This highlights the important role of technological learning and innovation systems in energy transitions.

By using concepts from the three perspectives and policy mixes for sustainability transitions an inventory of 'micro-logics' is formulated to explain specific elements or episodes of energy transitions (e.g. the role of clean energy technologies in electricity transitions). Interactive governance theory is proposed in this study to synthesise these micro-logics into a broader theoretical construct, as suggested in previous studies (see, for instance, [16]).

2.2 Energy transitions and the interactive governance approach

Within the interactive governance approach, societal systems (e.g. energy systems) are the result of synergies between three main interrelated components: a governance system (GS), a system-to-be-governed (SG), and the governing interactions (GI) among these systems [38]. A governance system includes the different mechanisms and processes for control, guidance, and steerage of the system-to-be-governed. The conceptualisation of the system-to-be-governed can take place under distinct analytical paradigms and at diverse scale levels depending on the nature and scope of the research inquiry [39,40]. How to conceptualise the SG has been identified as a relevant analytical limitation in the interactive governance perspective [41]. To overcome this caveat, this study proposes the meta-theoretical framework described in Section 2.1 to explore the role of clean energy technologies in national energy transitions as a co-evolving techno-socio-economic system (see Fig. 2.) under the interactive governance approach. Governing interactions involves relevant relationships and influences between the main actors or social units in a specific governance setting [39,40]. External forces (outside the control of the system of interest) may affect or influence the behaviour of societal systems and their interactions due to mutually influencing interactions with their external environment [42,43].

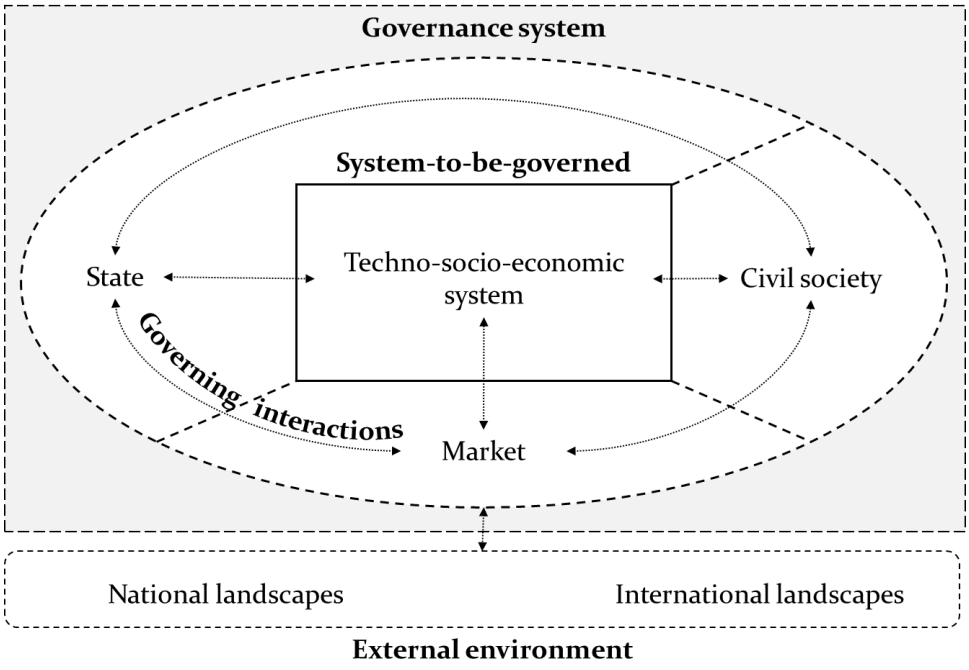


Fig. 2. Conceptualisation of societal systems under the interactive governance approach. Source: Adapted from [38,44].

Although interactive governance has been applied mainly to one particular societal field (i.e. fisheries and aquaculture issues) (see, for instance, [38,39]), due to its broad scope and systematic analysis it is gaining interest in other disciplines such as energy. For instance, interactive governance frameworks have been used to investigate the role of organisational governance and decision-making in Renewable Energy Cooperatives (REC) in Germany [45].

Di Lucia [43] employed the concept of system governability to analyse the problems facing the governance of biofuels in the European Union. García Lázaro [14] applied interactive governance theory to analyse the role of the state, private companies, and civil society in the public service of electric lighting in Mexico City (from 1881 to 1938). Similarly, Hernández Ibarzábal [44] examined the governability of Mexico's natural gas sector under the Mexican constitutional energy reform approved in 2013 by applying an interactive governance approach. Also, governance of societal transitions has been gaining interest in social-ecological and environmental modelling [46], sustainable innovations [47,48], and energy systems [8,49].

The interactive governance approach is used in this article to analyse governance processes focusing on the relative role of the market, the state, and the civil society in promoting clean energy development over time. The review of several documents and relevant datasets under a theoretical heuristic approach has been applied in this study as the principal analytical method used to describe the development of clean energy technologies in the electricity sector in Mexico. The review process derives in micro-logics that are presented as stylised facts and described in a qualitative manner [50]. Then these qualitative storylines are synthesised under the interactive governance approach using the analytical framework proposed in this section (see Fig. 3).

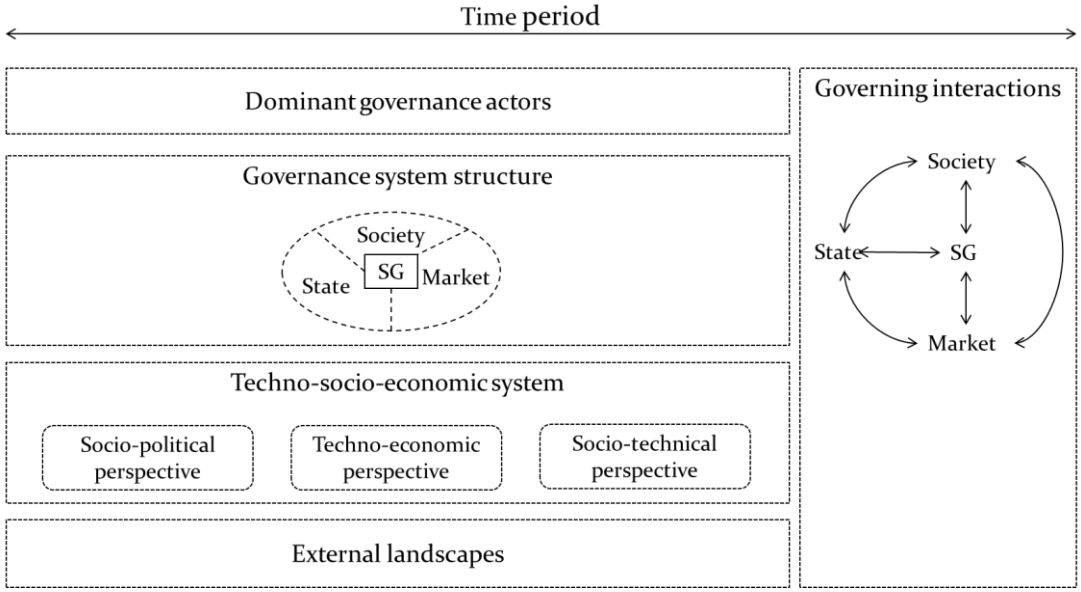


Fig. 3. Analytical framework for describing the development of clean energy technologies in electricity transitions.

3. Clean energy development in Mexico

3.1. The early stages of the electricity sector in Mexico (1879-1949)

The first equipment used for electricity generation in Mexico was a 1.8 kW (coal-fired) thermal plant installed in a textile factory for lighting purposes in the city of León, Guanajuato in 1879 [8,14,51]. During the following ten years from the origin of the power sector in Mexico, electricity was completely generated from conventional thermal technologies (e.g. coal/oil-fired). The first recorded use of hydroelectric power in Mexico dated from 1889 in the state of Chihuahua [51]. Clean energy technologies have had different development time frames due to diverse drivers and barriers over time as described in the following sections.

During the early stages of the electricity sector in Mexico, national ***policy objectives*** set by the government of Porfirio Díaz (1884-1911) were focused mainly on economic growth and progress. Thus, different economic ***policy instruments*** were implemented aimed at modernising the country through foreign investment and the adoption of technological

developments in other parts of the world (i.e. cross-border ***technology diffusion***). For instance, technology diffusion from Europe and the United States (US) was promoted by the administration of Díaz by offering exemptions from paying taxes when electrical equipment was imported and installed in Mexico. Also, national progress was sought through the exploitation of domestic natural resources. Although electricity generation was dominated by conventional thermal technologies, the extensive ***water resources available*** in Mexico allowed the rapid development of hydropower (see Fig. 4), resulting in a ***technology transition*** from thermal to hydro.

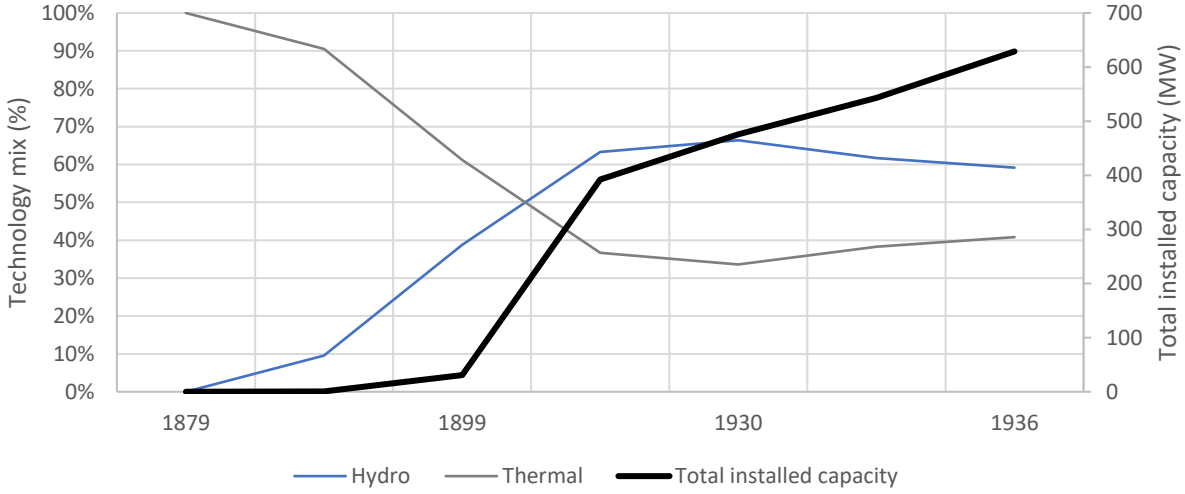


Fig. 4. Shares of technology mix (left) and total installed capacity (right) from 1879 to 1936. Source: elaborated with data from [51–53].

From 1879 to 1936 the ***governance system*** was controlled mostly by the market (mainly private monopolies) with little ***state intervention*** in relevant decision-making processes such as expansion planning. Thus, private companies focused on increasing profits by supplying services to certain regions and/or customers. This mode of ***self-governance*** was not in line with ***policy objectives*** of national economic development, bringing multiple socio-political tensions to the regime (e.g. different electricity tariffs for different regions and customers, poor labour conditions, lack of service in rural areas). Acknowledging the ***societal needs*** of increasing access to electricity nationwide and improving services supplied by private companies [54], the government of Lázaro Cárdenas (1934-1940) created the Federal Electricity Commission (Comisión Federal de Electricidad, CFE) aimed at increasing state's participation in governing processes through a state-owned electricity company and consolidating a national electricity system [51]. In line with the creation CFE, the Electricity Industry Law was approved by the Mexican Congress in 1939. This ***policy instrument*** established a set of regulations for the whole electricity supply chain with a particular focus on meeting ***societal needs*** (e.g. expanding electricity services at fair prices) [51]. For instance, concessions for new power generation projects were awarded based on higher social benefits with the most efficient use of natural resources. Also, the state extended its presence within the ***governance system*** by regulating and defining electricity tariffs through the Secretariat of Economy (Secretaría de Economía, SE).

Within the energy sector, the creation of Mexican Petroleum (Petróleos Mexicanos, PEMEX) as a state-owned oil company and the expropriation of private oil companies in 1938 were relevant domestic ***landscapes*** that affected the electricity sector in later years [8]. Fig. 5 depicts the principal actors and institutions in the electricity sector by 1950. The size of the circles illustrates the relative importance of their role in governance processes. Based on the sources reviewed and presented in this paper, the values for the size of the circles were subjectively determined.

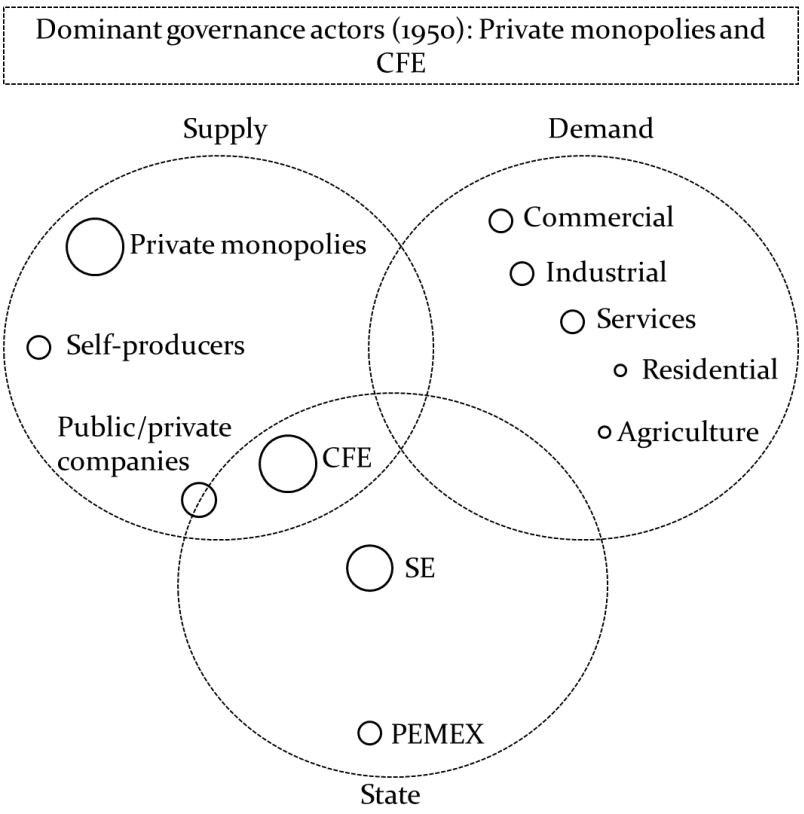


Fig. 5. Main actors within the governance system by 1950. Source: adapted from [8] with information from [51].

The most important ***technological changes*** occurred towards the development of clean energy technologies during this period were the construction of the fist large-size (28 MW) hydropower system (Miguel Alemán) and the ***technology transition*** from horizontal to vertical axis turbines [51]. Fig. 6 and Table 1 depict the snapshot for the early stages of the electricity sector under the interactive governance approach.

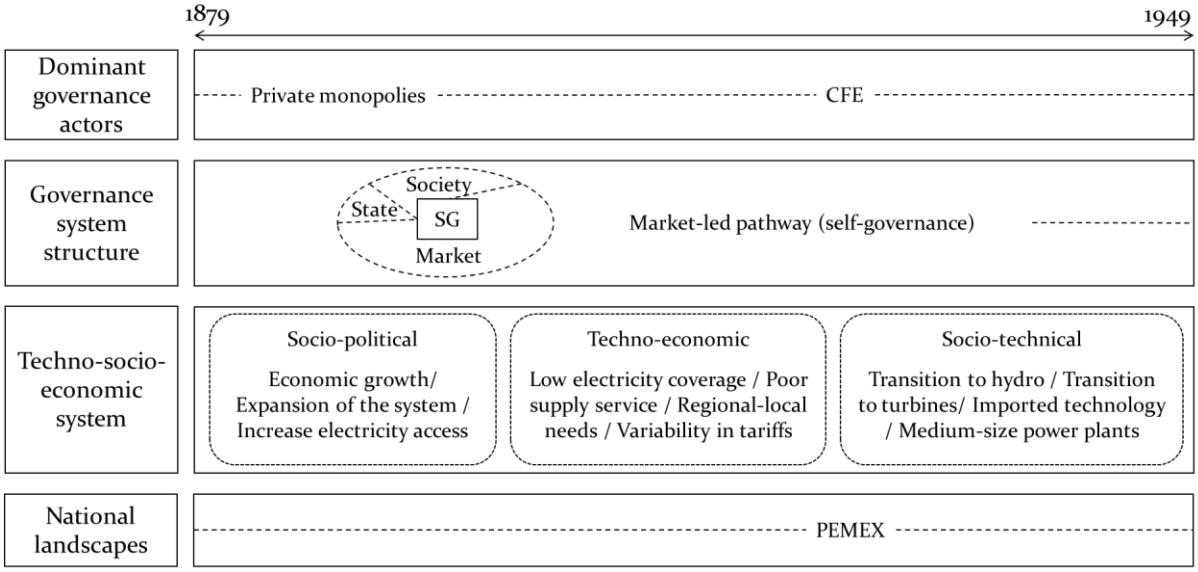


Fig. 6. Electricity system snapshot under the interactive governance approach (1879-1949) –system-to-be-governed, governance system, and external landscapes.

Table 1
Electricity system snapshot under the interactive governance approach (1879-1949) – governing interactions (actor level). Source: elaborated with information from [8,51].

From	Interactions	To
Market	Pressure for increasing service concessions.	State
	Pressure for better investment conditions.	
Market	Promotion of productivity improvement through electricity services.	Society
State	Promotion of technology diffusion through economic incentives.	Market
	Intervention in conflict resolution.	
	Pressure for improving supply services.	
	Pressure for expanding services to rural areas.	
State	Intervention in conflict resolution.	Society
	Promotion of increasing access to electricity nationwide.	
	Promotion of development and modernisation of the sector.	
Society	Pressure for electricity access in rural areas.	State
	Pressure for intervention in work rights.	
	Pressure for intervention in tariff regulation and control.	
Society	Pressure for competitive tariffs.	Market
	Pressure for improving work conditions (e.g. workload, salaries).	
	Pressure for improving services.	

3.2. The beginning of alternative energy technologies in Mexico (1950-1972)

Policy objectives within the electricity sector from 1937 to 1959 focused on the development of the sector by providing financial support to both private and public electricity companies [51]. Thus, the Rural Electrification Program was introduced in 1952 as a ***policy instrument*** aimed at expanding access to electricity to rural areas (a relevant social gap arisen from market dynamics) and fostering national development [8]. The primary role of CFE during its beginnings was to design and implement solutions to meet these ***societal needs***. Although electricity production was dominated by hydropower and fossil fuel technologies (mainly steam) in similar proportions from 1950 to 1972 (see Fig. 7), other ***technological niches*** received attention during this period such as geothermal energy.

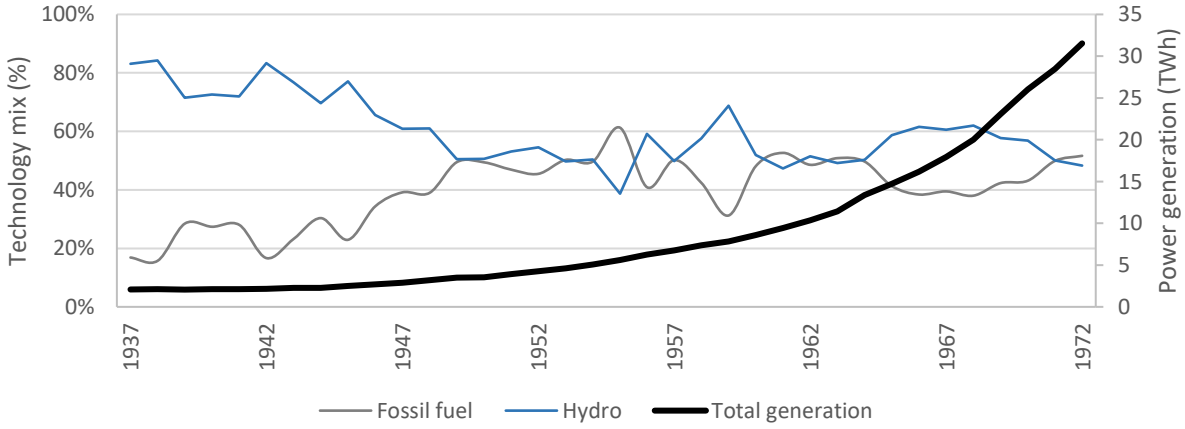


Fig. 7. Shares of technology mix (left) and total electricity generation (right) for public service (1937-1972). Elaborated with data from [55].

In 1955 the Geothermal Energy National Commission (Comisión Nacional de Energía Geotérmica, CNEG)[7] was created to study possibilities and developments of geothermal energy in Mexico (before 1955 several places with hydrothermal springs were known in the country – mainly used for recreation and bathing– underlining the national potential for electricity generation). Thus, the first 3.5-MW geothermal (demonstrative) power plant was installed in 1959 in the Pathé geothermal field, in the state of Hidalgo [8]. The plant was a CFE's acquisition from the Larderello geothermal field in Italy, where installed capacity had reached almost 300 MW by 1950 [56]. The power plant never operated at full capacity in Mexico due to insufficient steam, however it remained operating until 1973 [57]. A ***technological learning*** process based on *learning-by-using* [34], *learning-by-doing* [33], and *learning-by-researching* [36] took place over the following years. This is, knowledge may flow across countries in two main forms: embodied in traded intermediate or final goods (e.g. pilot plants, solar panels, wind turbines) or disembodied in patents, blueprints, exchange of ideas among researchers or scientific bodies, and imitation [58]. In order to increase (disembodied) technological knowledge, in the 1960's personnel from CFE were commissioned to study the development of geothermal energy reached in New Zealand [59]. This highlights the relevant role that international spillovers play in the process of ***technology diffusion*** for nascent technologies (e.g. geothermal in this case) from ***core countries*** (e.g. Italy or New Zealand) to ***periphery*** countries (such as Mexico). Also, CFE started geological, geochemical, and geophysical studies in the state of Baja California since 1958 [59]. Exploration, drilling, and exploitation activities progressed during the 1960's and early 1970's until the first large-scale geothermal field started commercial production in 1973 in Cerro Prieto (Baja California) with a 37.5-MW unit [8].

A ***policy paradigm shift*** focused on autonomy and nationalism arose during this period due to different tensions within the ***regime*** (e.g. dissimilar electricity prices along the country, the need for national access to electricity, and the existence of several electricity systems not interconnected) [60]. For instance, despite efforts by CFE in expanding electricity services to rural areas, only 44% of the population had access to electricity by 1960. Following the nationalistic feelings derived from the oil and gas sector, the nationalisation of the electricity industry occurred in 1960 during López Mateos' administration (1958-1964). Thus, the state carried out a complex acquisition process until the last private corporation was acquired in 1973 [8,60]. With a state-owned energy system, investment decisions in the electricity sector were significantly influenced by PEMEX as the dominant player in the oil and gas sector, promoting the use of fuel oil for power generation [8].

During Luis Echeverría's government (1970-1976) a particular interest on science and technology emerged, resulting in the creation of the National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología, CONACYT) in 1970. CONACYT's aim was to design, develop, and implement ***policy mixes*** on innovation activities (including research and development (R&D)) on strategic sectors (e.g. the energy sector) [59]. Although this was an important national ***landscape***, CONACYT's role in promoting clean energy technologies was limited until 2008. Fig. 8 depicts the key actors in the electricity sector by 1972. Fig. 9 and Table 2 represent the electricity system snapshot for the period from 1950 to 1972.

[7] The CNEG was sponsored by CFE, Mexico's central bank, and Nacional Financiera (NAFINSA). The CNEG was dissolved in 1971 and the CFE's Geothermal Division took charge of geothermal development in Mexico.

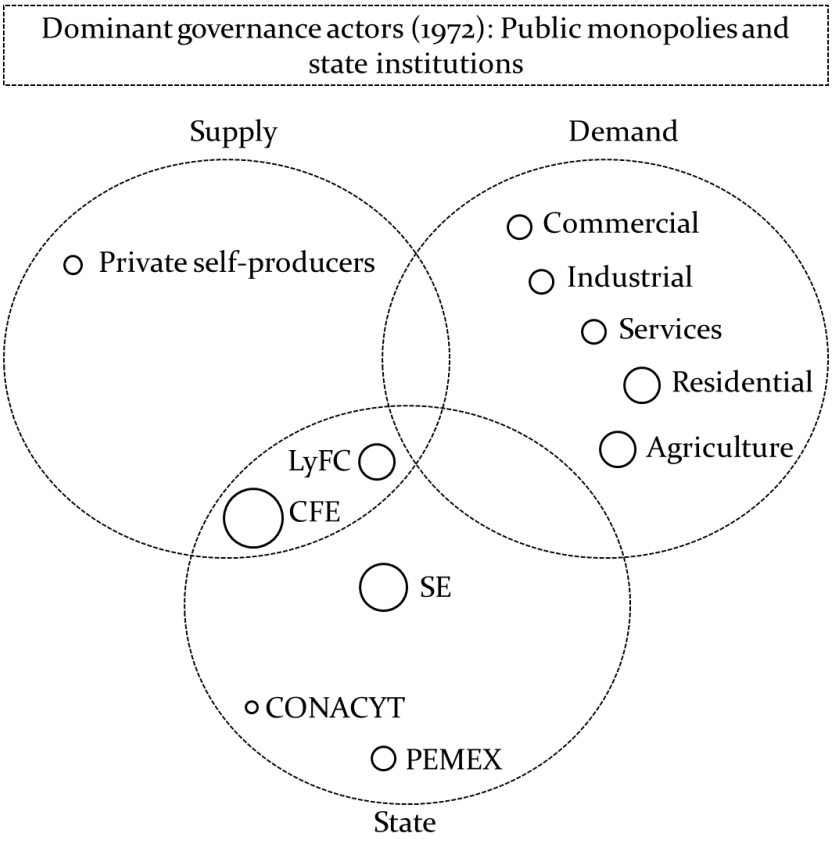


Fig. 8. Main actors within the governance system by 1972. Source: adapted from [8] with information from [51,59]. LyFC: Compañía de Luz y Fuerza.

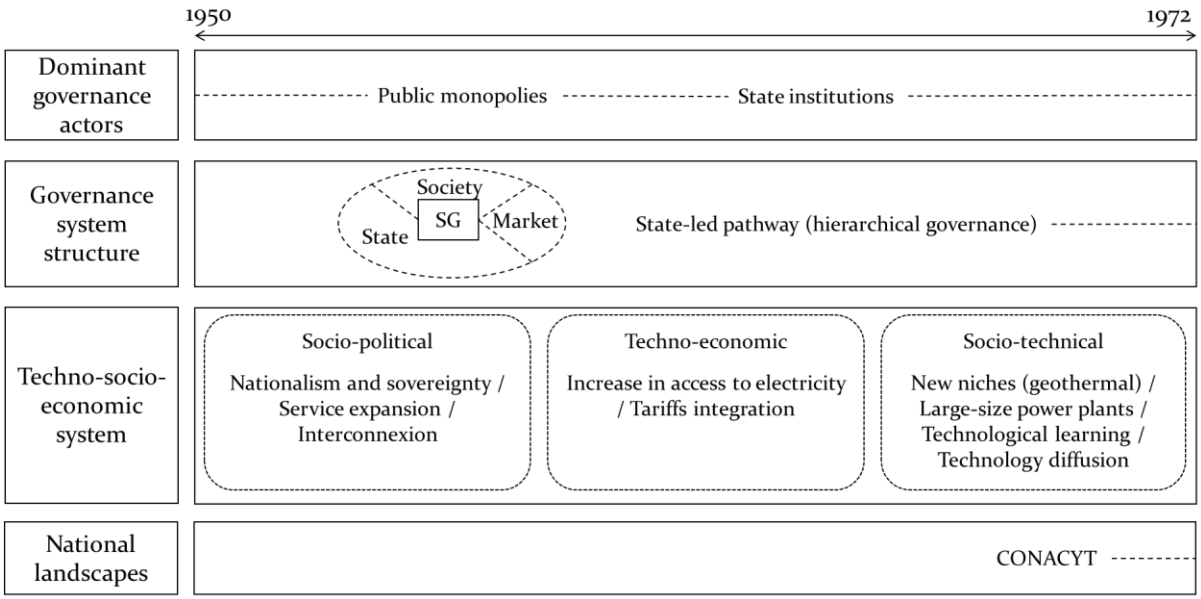


Fig. 9. Electricity system snapshot under the interactive governance approach (1950-1972) – system-to-be-governed, governance system, and external landscapes.

Table 2
Electricity system snapshot under the interactive governance approach (1950-1972) – governing interactions (actor level). Source: elaborated with information from [8,51,61].

From	Interactions	To
Market	Pressure for increasing financial support.	State
	Pressure for promoting technological development and innovation.	
Market	Promotion of competitive tariffs (social benefits).	Society
	Promotion of service expansion towards rural areas.	
State	Pressure for improving supply services.	Market
	Intervention on planning processes (e.g. expansion of the system).	
	Pressure for system interconnexion nationwide.	
	Intervention on tariff regulation (including subsidies).	
	Pressure for expanding services to rural areas.	
State	Promotion of increasing access to electricity.	Society
	Promotion of tariff reduction for some sectors (subsidies).	
	Promotion of better electricity supply services.	
Society	Pressure for increasing government incentives (e.g. subsidies).	State
	Pressure for expanding electricity services.	
Society	Pressure for reducing electricity tariffs.	Market
	Pressure for enhancing supply services.	

3.3. The early stages of clean energy technologies in Mexico (1973-2007)

The nationalisation process formally ended up in 1975 when the Public Service Electricity Law (Ley del Servicio Público de Energía Eléctrica) was published. According to this new law (which derogated the previous Electricity Industry Law), the only electricity suppliers for public service in Mexico were CFE and Compañía de Luz y Fuerza (LyFC) (including generation, transmission, distribution, and commercialisation) [8]. Electricity production for private companies was allowed under the self-producers scheme only if state-owned electricity companies were unable to provide the service to them (e.g. due to technical issues). Thus, private generation accounted for around 7% of the total electricity generated annually from 1975 to 1999 (see Fig. 10).

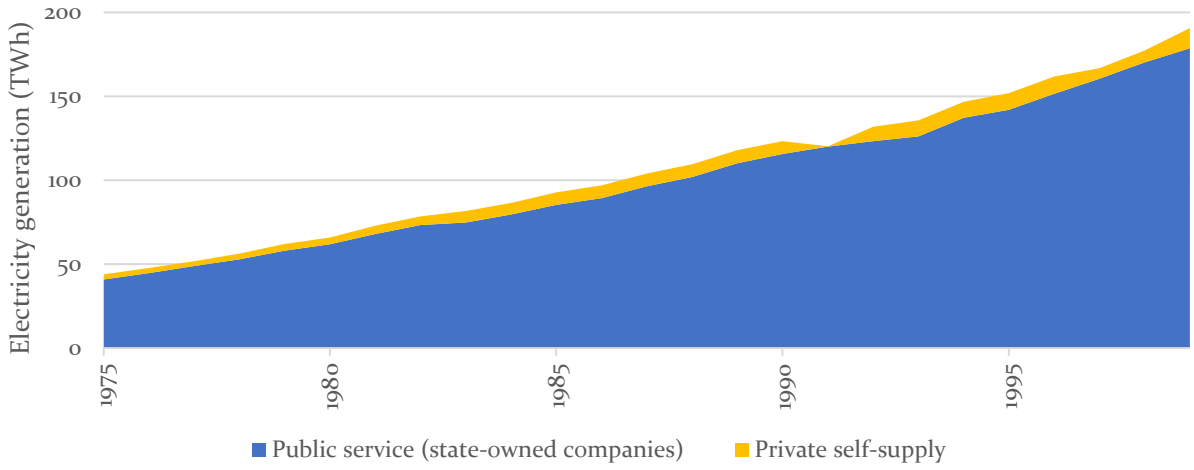


Fig. 10. National electricity generation (1975-1999). Elaborated with data from [11].

A relevant external ***landscape*** that affected several energy systems worldwide in 1973 was the international oil crisis[8]. The oil supply disruptions around the world highlighted the importance of energy planning with a particular focus on technology diversification. In Mexico, following the efforts on science and technology, the state supported innovation activities and technology development for both the ***incumbent regime*** (i.e. hydropower and fossil-fuel technologies) and new ***technological niches*** (e.g. coal, natural gas-fired technologies, geothermal, wind, solar, and nuclear). With the objective of performing R&D activities, as well as technological innovation on electricity production from alternative energy sources (including wind, solar, geothermal, and biomass), a new state-owned institution was created in 1975, the National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias, INEEL[9]) [59,62]. INEEL's R&D activities on clean energy technologies started by mapping the potential for electricity generation based on the availability of these sources (including data gathering and analysis) [62]. Similarly, two public institutions were established in 1979 to regulate and conduct R&D activities on nuclear matters: the National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias, CNSNS) and the National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares, ININ). Even though several energy-related activities were carried out by different public organisations, the Secretariat of Energy (Secretaría de Energía, SENER[10]) was created in 1982 to coordinate these efforts and to design, develop and implement ***energy policy mixes*** at a national level.

Although an (international) interest in alternative energy sources emerged after the oil crisis, electricity supply and demand in Mexico were significantly affected by a national ***landscape*** known as the Mexican oil boom [63]. With substantial ***oil resources available*** for Mexico after the discovery of the Cantarell Complex in 1976 and aiming at exploiting the rising oil prices at the time, electricity production was led by fossil fuel technologies displacing alternative technologies (hydropower and geothermal). However, the 1982 economic crisis in Mexico was another national ***landscape*** that changed the direction of energy production and consumption. Thus, energy efficiency, technology mix diversification, and environmental protection gained interest in the energy policy agenda. The General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente, LGEEPA) was enacted in 1988 as a ***policy instrument*** to cope with environmental concerns in different strategic sectors (with an impact on the electricity generation in subsequent years) [8]. Also, aimed at designing and implementing ***policy instruments*** on energy efficiency, the National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía, CONUEE[11]) was created in 1989. Similarly, CFE developed in 1989 the Program of Energy Savings in the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico, PAESE) aimed at identifying and designing ***policy instruments*** to save electricity withing the power sector. Due to PAESE's limited budget, CFE created in 1990 the Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica, FIDE) to support and implement electric-efficiency programs (e.g. replacement programs for refrigerators, air conditioning, and fluorescent lights, minimum energy efficiency standards for appliances, energy consumption labelling/sealing, and training programs) [23,64,65]. Fig. 11 shows the total electricity consumption per unit of GDP (i.e. electricity intensity) for this period, highlighting the role of these programs in

[8] As a result, the International Energy Agency (IEA) was created in 1974 (initially) aimed at helping with the co-ordination of a collective response to major disruptions in oil supply.
[9] Before Electricity Research Institute (Instituto de Investigaciones Eléctricas, IIE).
[10] Before Secretariat of Energy, Mining and Semi-Public Industries (Secretaría de Energía, Minas e Industria Paraestatal, SEMIP).
[11] Before National Commission for Energy Saving (Comisión Nacional para el Ahorro del Energía, CONAE).

electricity efficiency improvements (complementary to technological improvements in power generation). Mexico's electricity intensity declined by 34% from 1973 to 2007.

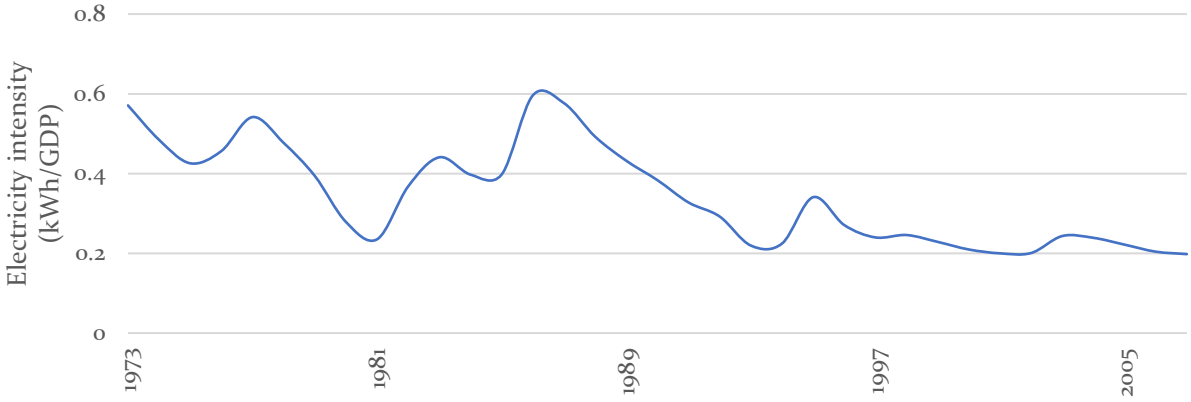


Fig. 11. Electricity intensity from 1973 to 2007. Source: Constructed with information from [66,67].

The first efforts on renewable energy development (additional to hydropower and geothermal) in Mexico focused on rural areas (i.e. off-grid applications such as small wind turbines for water pumping, solar kitchens, solar heaters, and biogas production) [62]. The Mexican government included small-scale off-grid renewable energy systems for rural electrification as an important component of the National Solidarity Program (Programa Nacional de Solidaridad, PRONASOL) launched in 1989 [68]. Hybrid systems (solar and wind) were initially thought as a solution to supply electricity to rural areas when expansion of the grid was considered costly and technically challenging (e.g. difficulties to build transmission and distribution lines) [62].

The development of (pilot) wind projects in Mexico started in the late-1970's. For instance, a 1.5-kW horizontal-axis wind turbine was installed in INEEL's experimental station named El Gavillero (State of Mexico) in 1979 with the objective of charging electric batteries and bringing lighting to the station. However, mainly due to financial constrains the development of wind turbines within the institute stopped for almost 15 years [62], resulting in ***knowledge obsolescence*** (i.e. knowledge created was lost over time). From the mid-1980s other small-scale wind projects (a few kW) were developed with public and private participation (mainly decentralised projects) [8,69].

Although interest from the government on building a nuclear facility started after the nationalisation of the sector, due to internal and external issues its construction was delayed several years until the first nuclear power plant (Laguna Verde) commenced functions in 1990 [8]. Also, geothermal exploration and drilling activities continued in different parts of the country, which led to the opening of different large-scale geothermal fields: Los Azufres (Michoacán) with 5 MW in 1982, Los Humeros (Puebla) with 6 MW in 1990, and Las Tres Virgenes (Baja California Sur) with 10 MW in 2002 [8,57,70].

The North American Free Trade Agreement (NAFTA) signed by the US, Canada, and Mexico, which negotiations started in 1991, was another relevant ***landscape*** that increased international cooperation and trade in strategic sectors (including the energy sector) between the three countries. Thus, the Mexico-US Renewable Energy Cooperation Program (Programa de Cooperación en Energía Renovable, PROCER) was established in 1991 aimed at working on technical, financial, and institutional issues on renewable energy development in Mexico [68]. The same year CFE created the Office for New Energy Sources, aimed at coordinating projects related to solar, wind, biomass, and hybrid systems [69]. Similarly, the Mexico Renewable

Energy Program was launched in 1994[12]. The goals of the program were to increase the use of renewable energy technologies in Mexico, increase the economic, social, and health standards in rural communities, and increase quality and reduce costs of renewable energy technologies by expanding markets for the US industry [69]. Around 400 renewable energy systems were installed in different states within Mexico derived from this program by 2000 [71]. It has been suggested that the main beneficiary of the activities promoting solar energy in Mexico was the PV industry in US aimed at creating a captive market for its products [69]. Also, the Shared Risk Fiduciary Fund (Fideicomiso de Riesgo Compartido, FIRCO) was created in 1994 to help with the installation of photovoltaic systems in the agriculture sector by providing financial aid [8].

After the nationalisation of the electricity industry, the electricity sector was mainly financed by loans from the World Bank, loans from the Inter-American Development Bank, bilateral loans, supplier credits, and federal resources [13]. However, during Salinas de Gortari's administration (1988-1994) the Mexican energy sector faced several economic and financial issues: the state's lower export revenues due to the fall in oil prices in the international oil market; the increasing debt of state-owned electricity companies due to a fee-structure policy focused on granting subsidies for some sectors (not adjusted for inflation) and new credit conditions set by international organisations (unsustainable foreign debt); the lack of management autonomy of CFE; and the inability of the state to invest in new (high-capital) projects to meet the rapid growing demand (jeopardising the ***supply-demand balance***). These factors motivated Salinas de Gortari to adopt a ***policy paradigm*** towards liberalisation and free markets aimed at reducing public expenditure on new infrastructure for sectoral development [13].

Relying on a neoliberal thought of 'less state intervention' seen in other parts of the world (i.e. ***policy diffusion***), Salinas' administration started a process of liberalisation in the electricity sector. In 1992 the Mexican Congress approved President Salinas' proposal to reform the Public Electricity Service Law aimed at incorporating private investment into electricity generation activities. State-owned electricity companies kept the ownership of transmission and distribution lines, however private companies could generate power under six new schemes: (1) independent power producer (IPP), (2) cogeneration power producer (CPP), (3) power self-supplier (PSS), (4) small power producer (SPP), (5) power imports (PI), and (6) power exports (PE). In addition, private electricity generation for self-supply, approved before the new law entered into force, maintained their validity under the continuous self-supply (CSS) modality (for a description of these modalities see [8,13]). The Energy Regulatory Commission (Comisión Reguladora de Energía, CRE) was established in 1993 to regulate the development of the electricity sector considering these new participants in the market[13] [8]. Fig. 12 shows the key actors in the electricity system by 1993.

[12] The program was sponsored by the US Department of Energy (USDOE) and the US Agency for International Development (USAID), in partnership with Mexican state and federal organisations and international environmental groups. The program was managed by the Sandia National Laboratories.
[13] After the deregulation of natural gas in 1995, regulation on activities related to natural gas and transport of liquified natural gas through pipelines were included in CRE's responsibilities [13].

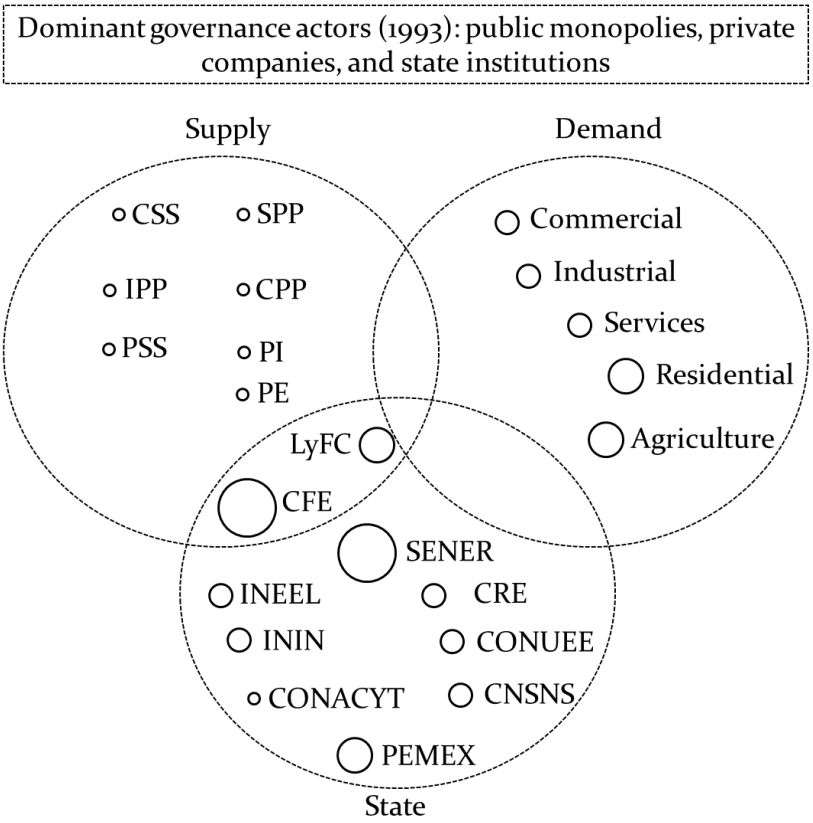


Fig. 12. Main actors within the governance system by 1993. Source: adapted from [8] with information from [13,51,62].

A relevant international ***landscape*** in this period was the incorporation of Mexico as an OECD member in 1994, opening access to information exchange (e.g. best practices) and fostering international cooperation on energy matters. Yet, the Mexican economic crisis of 1994 resulted in an acute recession that affected different strategic sectors. This national ***landscape*** had a positive effect on the speed of liberalisation processes in the electricity sector. While the reform to the Public Service Electricity Law was passed in 1992, due to the complexity of several administrative processes the first permit for electricity generation to an IPP was approved in 1997 (to Applied Energy Services) and commercial production started in 2000 [8]. State-owned companies generated 58% (178.8 TWh) of the total electricity produced within the country in 2012 (see Fig. 13), and the rest was generated by private companies (27% by IPPs for public service and 15% for self-supply). This highlights the role of private companies to meet societal needs such as increasing electricity demand.

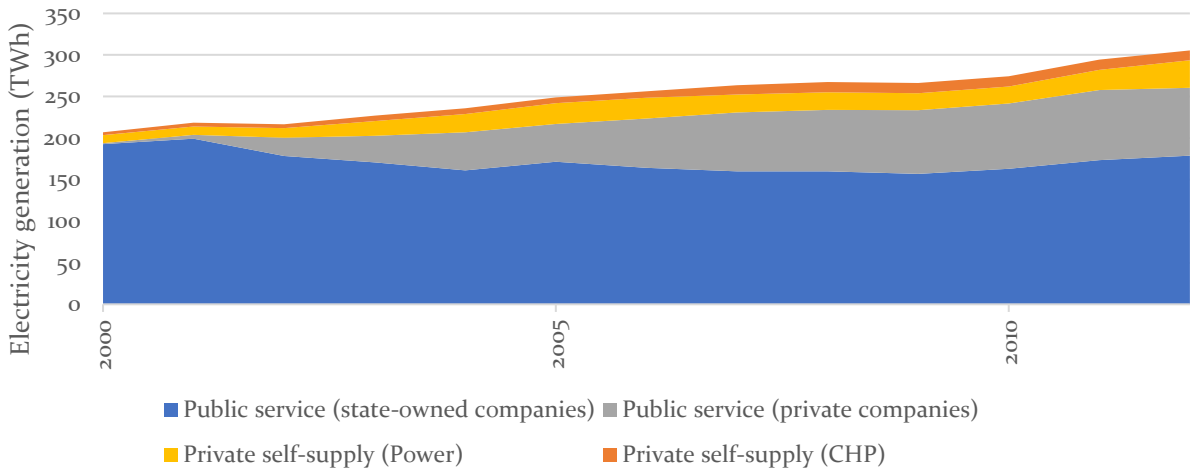


Fig. 13. National electricity generation (2000-2012). Elaborated with data from [11].

Diversification of energy technologies within the electricity sector was led by natural gas-fired technologies (mainly natural gas combined cycle (NGCC)), transitioning from fuel oil to natural gas. This may be explained by multiple factors: the liberalisation process across other countries (i.e. ***policy diffusion***), the deregulation of the natural gas sector in Mexico in 1995, the technological progress in natural gas burning technologies (i.e. ***technology diffusion***), environmental regulations, and the low prices of natural gas. For instance, new regulations on highly pollutant greenhouse gases such as sulphur oxides (SO_x) and nitrogen oxides (NO_x) were set in 1994 by the Secretariat of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT[14]) in line with the LGEEPA law. These new environmental standards posed a significant limitation in electricity production from burning high-sulphur fuel oil within main industrial and metropolitan zones [72], resulting in the promotion of natural gas as a substitute [8]. Also, the decrease in natural gas prices in the US (mainly derived from the production from unconventional sources) has reinforced the use of this fuel for electricity generation in Mexico since the 2000's creating a ***technological lock-in*** effect as investments in new infrastructure tend to favour large-scale fossil fuel-based power plants due to economies of scale [31].

Although power generation from wind and solar PV started in 1990[15] (mainly small-scale off-grid projects in rural areas), the first medium-scale (1.57 MW) wind power plant was installed in 1994 in La Venta, Oaxaca (owned by CFE) and the first large-scale (5 MW) solar PV development commenced operations in 2012 (also a project developed by CFE) [8]. Fig. 14 depicts the total electricity generation nationwide as well as the shares of fossil fuel and clean energy technologies from 1974 to 2007.

[14] Before Secretariat of the Environment, Natural Resources and Fisheries (Secretaría de Medio Ambiente, Recursos Naturales y Pesca, SEMARNAP).

[15] The annual average power generation from wind technologies was 1 GWh/year from 1990 to 1993 (less than 0.001% of total generation). Similarly, the annual average electricity generated from solar PV was 10 GWh/year from 1990 to 2011 (less than 0.005% of total generation).

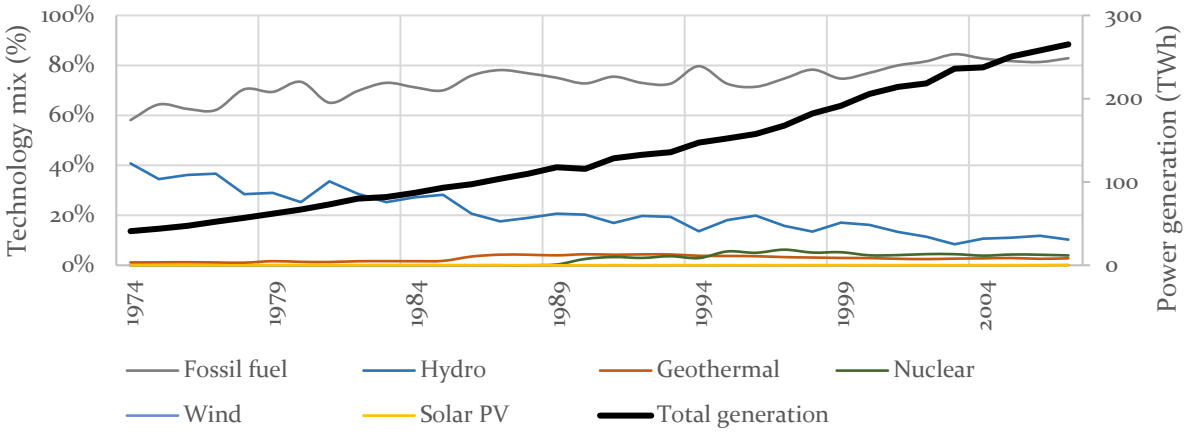


Fig. 14. Shares of technology mix (left) and total electricity generation (right) (1974-2007). Elaborated with data from [11,55,73–80].

Starting in 2001, a series of measures were established aimed at improving grid access for renewable energy technologies (see Table 3). These measures were contemplated through the 'grid interconnection contract' [6,81].

Table 3
Measures for grid connection for clean energy technologies from 2001 to 2007. Source: adapted from [81] with information from [82–85].

Measure	Year	Goal
Grid interconnection contract	2001	To allow grid interconnection for renewable energy plants over 500 kW.
Stamp system (estampilla postal)	2003	To establish a system of transmission fees per kWh.
Wheeling agreement	2004	To establish the regulations for producers under the self-supply scheme to use the grid to transport electricity from off-site plants to load centres.
Self-supplied power (Potencia Autoabastecida)	2006	To offer capacity credit for renewable energy that provides firm capacity during the hour of maximum demand. It included energy banking and transmission cost discounts in the range of 50-70%.
Open season (temporada abierta)	2006	To set an open bid system in which IPPs and companies under the self-supply scheme would bid privately for transmission capacity, in addition to the generation project. 2.6 GW of wind capacity were successfully assigned in 2006.
Solar grid connection	2007	To set grid connection rules for small-scale solar producers (<30kW).

The signature of the Kyoto Protocol from the Mexican government in 1998 (and its ratification in 2000) confirmed its international commitment on climate change mitigation. However, the first national ***policy instrument*** focused on combating climate change was the National Climate Change Strategy published in 2007. The strategy aimed at reducing GHG emissions by fostering energy production from alternative sources (i.e. mix diversification) and promoting savings in energy consumption (i.e. energy efficiency) [8]. Fig. 15 and Table 4 represent the electricity system snapshot for this period.

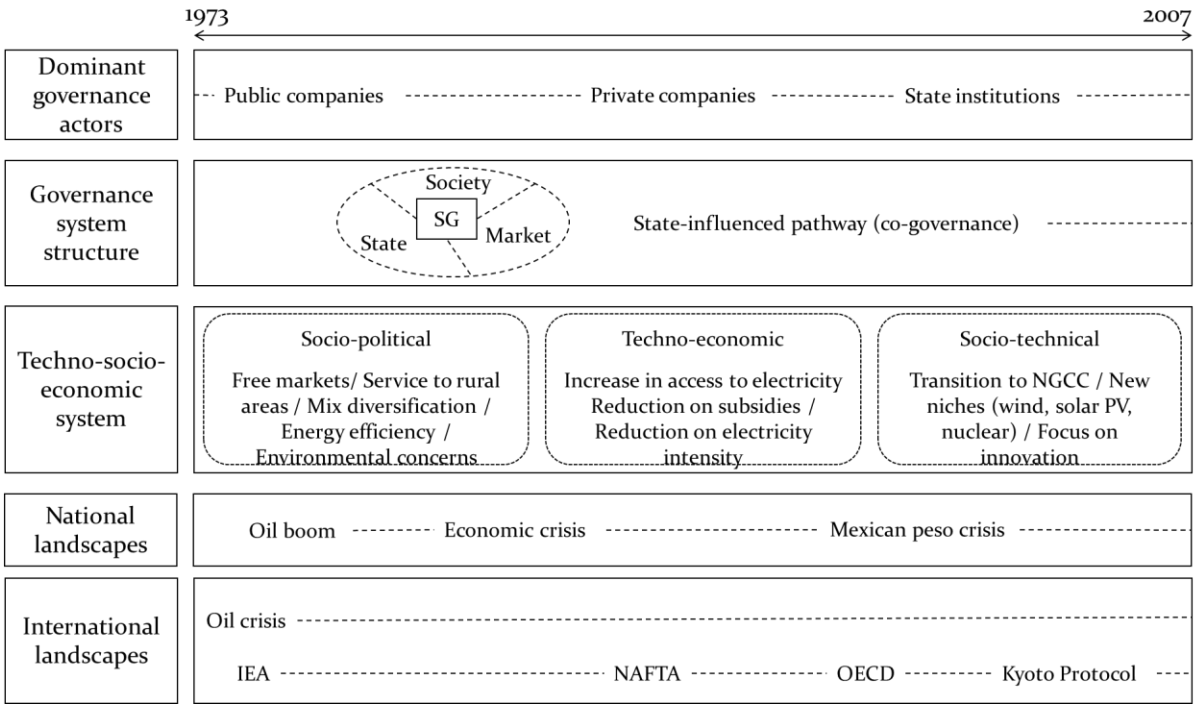


Fig. 15. Electricity system snapshot under the interactive governance approach (1973-2007) – system-to-be-governed, governance system, and external landscapes.

Table 4
Electricity system snapshot under the interactive governance approach (1973-2007) – governing interactions (actor level). Source: elaborated with information from [8,13,59–62].

From	Interactions	To
Market	Pressure for increasing investment in new capacity to meet demand.	State
	Pressure for increasing financial support.	
	Pressure for increasing electricity tariffs.	
	Pressure for supporting (national) technological development.	
Market	Promotion of reduced tariffs for specific sectors (subsidies).	Society
	Pressure for reducing electricity intensity.	
State	Intervention on partial liberalisation of the sector.	Market
	Regulation on environmental standards.	
	Regulation on electricity generation with new actors.	
	Intervention on technology diversification.	
	Regulation on electricity tariffs (reduction of subsidies).	
State	Promotion of increasing access to electricity to rural areas.	Society
	Promotion of tariff reduction for some sectors (subsidies).	
	Intervention on energy efficiency measures.	
Society	Pressure for increasing government incentives (e.g. subsidies).	State
	Pressure for expanding electricity services.	
Society	Pressure for reducing electricity tariffs.	Market
	Pressure for enhancing supply services.	

3.4. Promoting clean energy development (2008-2018)

The recent development of clean energy for power generation in Mexico started in 2008 with the Law for the Use of Renewable Energy and the Financing for the Energy Transition (Ley

para el Aprovechamiento de las Energías Renovables y el Financiamiento de la Transición Energética, LAERFTE). LAERFTE's objectives were to regulate the use of clean energy technologies for non-public service (i.e. self-supply) and set an energy transition national strategy. As a result, a remarkable interest from private sector to develop renewable energy projects (mainly wind) was evident in the system (see Fig. 16) [6]. Thus, additional measures for grid connection were established since 2010 (see Table 5). Also, as part of Mexico's low-carbon strategy, the Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía, LASE), and the Bioenergy Law (Ley de Promoción y Desarrollo de los Bioenergéticos, LPDB) were published in 2008.

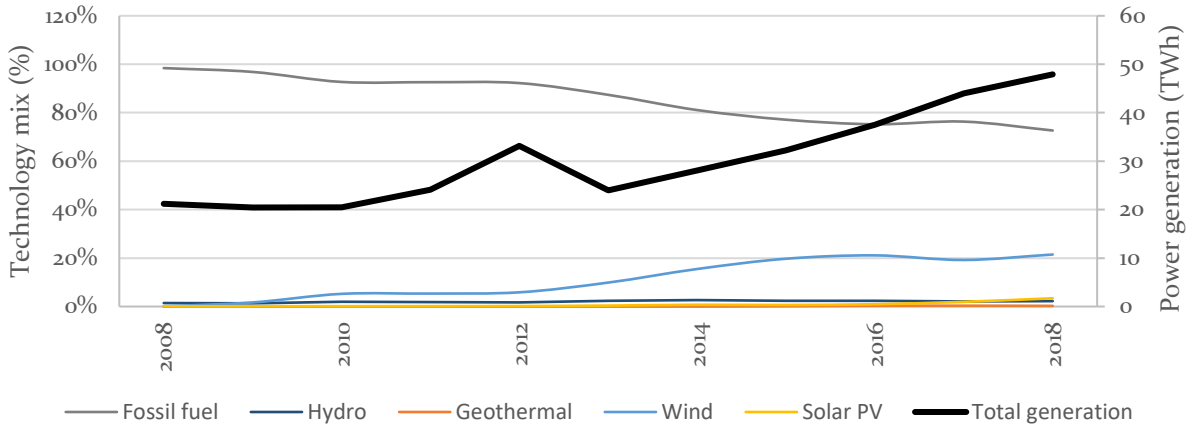


Fig. 16. Shares of technology mix (left) and total electricity generation (right) for self-supply (2008-2018). Elaborated with data from [11].

Table 5
Measures for grid connection for clean energy technologies from 2010 to 2012. Source: adapted from [70] with information from [86–89].

Measure	Year	Goal
Stamp system revised	2010	To revise and amend transmission charges for renewables under the stamp system.
Net-metering scheme	2010	To establish net metering for small-scale and medium-scale generators.
Large-hydro interconnection	2010	To set the interconnection rules for large hydropower plants (>30MW).
Self-supply interconnection	2012	To regulate collective generation for small scale self-supply.

The 2008 global economic crisis was an international ***landscape*** that affected most financial and economic markets worldwide. In Mexico, multiple ***policy instruments*** were implemented by the state with the objective of reducing the impacts of the recession and fostering economic progress through strategic sectors. Within the electricity sector, electricity tariffs were reduced for some sectors (e.g. industry) and frozen for residential consumers [90]. Also, public expenditures were allocated to develop technological R&D activities to overcome technical issues on electricity generation, improve technology performance, and support technology niche markets (e.g. wind, solar, and geothermal). In line with the ***policy objective*** of strengthening and improving innovation systems, the state created the Energy Sustainability Fund (Fondo de Sustentabilidad Energética, FSE) in 2008, jointly led by CONACYT and SENER. The main objective of the fund is to support research, development, and demonstration (RD&D), technological innovation, sustainable energy development, and

human capital training in key areas [91,92]. An important initiative derived from public investment in RD&D for clean energy technologies was the creation of the first Mexican Energy Innovation Centres (Centros Mexicanos de Innovación en Energía, CEMIEs) in 2013 (Geothermal, Solar, and Wind). As of 2018, around USD 172 million had been allocated to clean energy technology projects (see Fig. 17). Also, direct funding for (mainly) energy efficiency programs was provided by the Energy Transition Fund (Fondo para la Transición Energética y el Aprovechamiento Sustentable de la Energía, FOTEASE) established in 2009 [93]. Since its creation and until 2019 the FOTEASE fund has received around USD 465 million from the federal budget and has financed 53 projects (with 9.4% of the resources allocated to renewable energy projects and the rest used for projects with an energy efficiency component). Funded projects include the development of a renewable energy National Inventory, the publication of a Renewable Energy Atlas, and multiple projects on distributed generation, public lighting, and electromobility [81,93]. Electricity intensity kept relatively constant during this period (see Fig. 18).

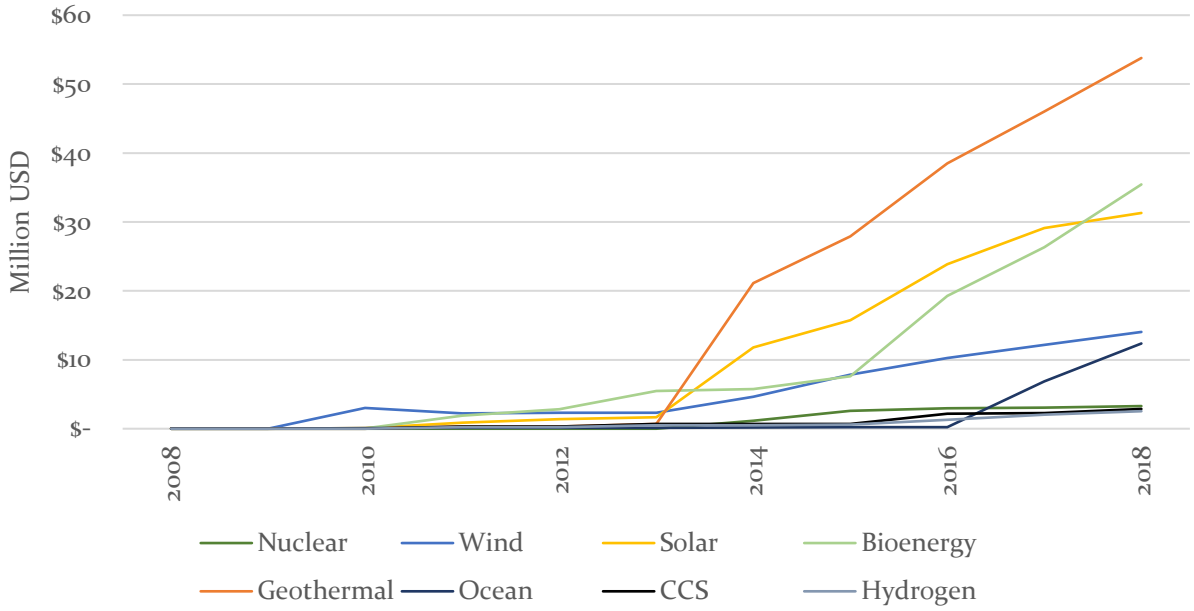


Fig. 17. Cumulative public investment in RD&D for clean energy technologies from the Sustainability Energy Fund. Source: Elaborated with information from [91,92,94–97].

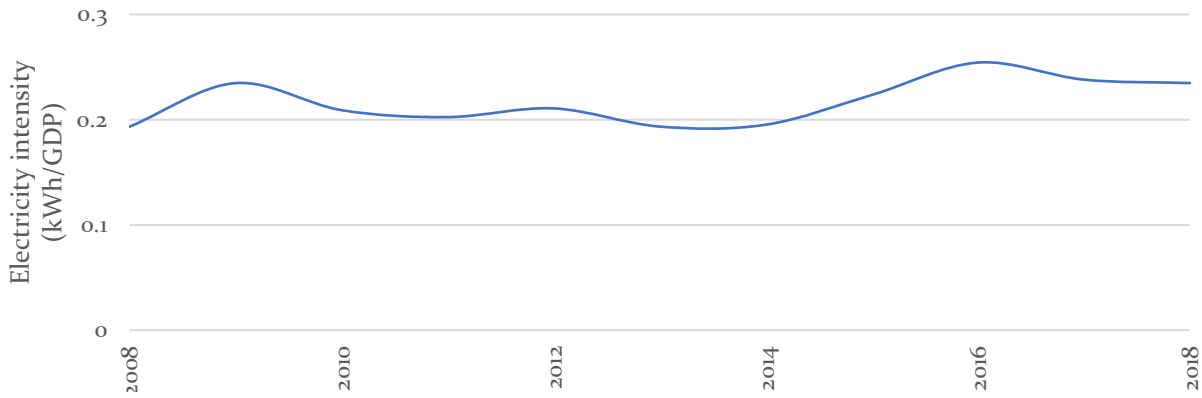


Fig. 18. Electricity intensity from 2008 to 2018. Source: Constructed with information from [66,67].

Another relevant national ***landscape*** in 2009 was the dissolution of the public power company LyFC (which operated in Mexico's central region). This decision was made based on the evident lack of operational and administrative efficiency from the state-owned company;

thus, all activities and responsibilities were transferred to CFE [8]. An international ***landscape*** was the creation of the International Renewable Energy Agency (IRENA), being Mexico a member since its creation in 2011[16]. Seeking to promote low-carbon development in line with international commitments, the General Climate Change Law (Ley General sobre Cambio Climático, LGCC) was passed in 2012. This ***policy instrument*** established the national policy framework on GHG emission reductions and climate change mitigation [7]. Fig. 19 depicts domestic GHG emissions from main energy activities (e.g. electricity generation, transport, industry) and total emissions from 1990 to 2017 (excluding land use change and forestry (LUCF)). Total GHG emission climbed from 444.74 $MtCO_2e$ in 1990 to 733.82 $MtCO_2e$ in 2017 (a growth of 65%). In the same way, emission from electricity generation rose from 66.6 $MtCO_2e$ to 162.6 $MtCO_2e$ in the same period (accounting for 31% of the energy-sector emissions and 22% of the total GHG emissions) [98].

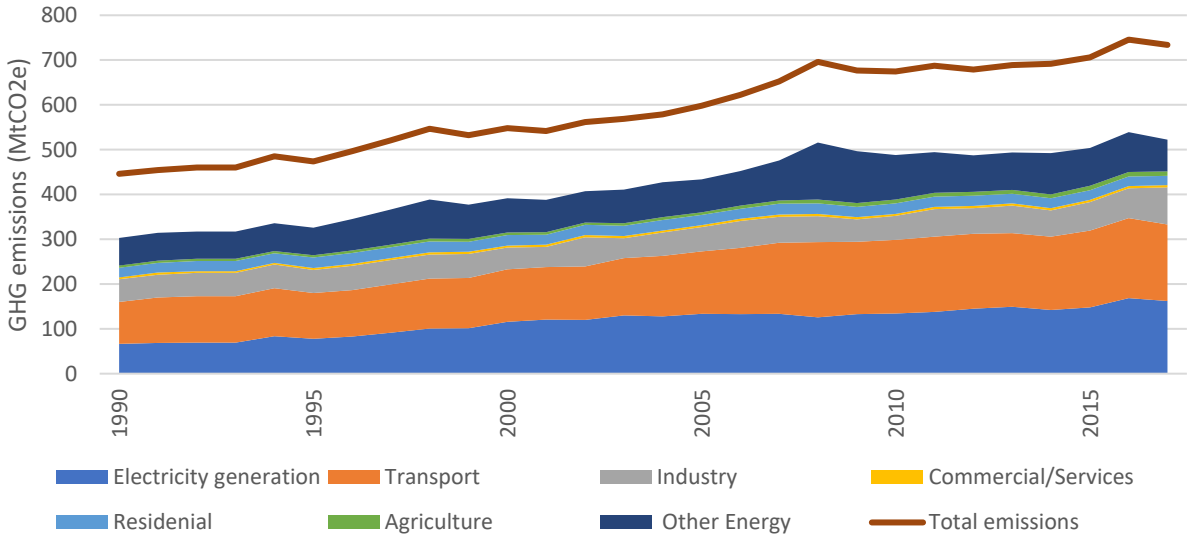


Fig. 19. GHG emissions from main energy activities and total GHG national emissions from 1990 to 2015. The gap in the figure corresponds to non-energy related emissions (e.g. domestic livestock, waste management, and processes in manufacturing industries and construction without fossil fuel combustion). Source: Elaborated with data from [98].

Mexico was lacking investment and productivity growth in both the oil and gas sector, as well as in the power sector. Mexico's oil and gas production started to decline during the mid-2000's[17], power generation costs were going up due to inefficiency in electricity supply (increasing subsidies to supply electricity at low costs), and GHG emissions were advancing towards a direction not compatible with long-term ***climate policy objectives*** [4]. Thus, the Mexican Congress approved in 2013 the energy reform proposed by the administration of Enrique Peña Nieto (2012-2018). The reform opened to competition the long-closed oil, gas, and power sectors with the aim of boosting oil and gas production, increasing the share of clean energy sources in electricity generation, increasing energy efficiency, and reducing GHG emissions [4]. The reform required modifications to the Mexican Constitution (Articles 25, 27, and 28) and several secondary laws were enacted by the Mexican Congress (10 new laws and 12 modified ones) to achieve the reform's objectives. This reform was considered as "the most ambitious energy system transformation worldwide" since the 1990's [4]. Within the electricity

[16] IRENA was officially founded in 2009, however it took around 2 years to set the institutional structure and ensure efficient internal and external communications (https://www.irena.org/history).
[17] Oil production declined from the peak of 3.8 million barrels per day (mb/d) in 2004 to 1.9 mb/d in 2019.

sector, the energy reform opened to competition generation (except nuclear) and retailing, while transmission and distribution prevailed as state-controlled activities (although private companies were allowed to invest, operate, and maintain the required lines by signing specific contracts with the state) [8]. Thus, CFE was legally separated in different subsidiaries for power generation, transmission, distribution, and retail activities to promote a more competitive structure. Correspondingly, multiple responsibilities were transferred to SENER (e.g. planning for system expansion), CRE (e.g. tariff regulation), and CENACE (e.g. system operation). Also, the Secretariat of Finance (Secretaría de Hacienda y Crédito Público, SHCP) was responsible to set certain electricity tariffs (mainly for residential and agriculture sectors). Derived from the 2013 energy reform several strategies, programs, and specific initiatives were developed. A detailed description and analysis of these policy documents may be found in [4]. Fig. 20 depicts the key legislation and main ***policy instruments*** in force by 2018 that the state adopted to promote a clean energy and low-carbon transition (some instruments derived from the 2013 reform and others were reformed in line with policy objectives)[18].

	Energy	Climate Change
Laws	Electricity Industry Law (LIE, 2014) Federal Electricity Commission Law (LCFE, 2014) Coordinated Energy Regulators Law (2014) Geothermal Energy Law (2014) Energy Transition Law (LTE, 2015)	General Climate Change Law (LGCC, 2012) Special Tax Law on Production and Services (carbon tax and credits, 2013) Law on Environmental and Industrial Safety (2014) General Law of Ecological Equilibrium and Environmental Protection (LGEEPA, 2018)
Plans	National Development Plan (PND 2013-2018)	
Strategies	National Energy Strategy (ENE 2014-2028) Transition Strategy to Promote the Use of Cleaner Technologies and Fuels (2016)	National Climate Change Strategy (ENCC, 2013) Intended Nationally Determined Contribution (INDC, 2015)
Programs	Energy Sectoral Program (PROSENER 2013-2018) National Electricity System Development Program (PRODESEN 2018-2032) National Program for Sustainable Use of Energy (PRONASE 2014-2018) Special Program for the Energy Transition (PETE 2017-2018) Special Program for the Use of Renewable Energy (PEAER 2014-2018)	Special Program for Climate Change (PECC 2014-2018) Nationally Appropriate Mitigation Actions (NAMA, 2015)
Initiatives	Energy Sustainability Fund (FSE) Energy Transition Fund (FOTEASE)	Climate Change Fund (FCC) National Emissions Inventory (NEI)

Fig. 20. Overview of Mexico's policy instruments and initiatives on energy and climate change in force by 2018. Source: adapted from [3] with information from [4,6,81,97].

The (new) Electricity Industry Law (Ley de la Industria Eléctrica, LIE) was promulgated in 2014, establishing a new regulatory framework for the electricity sector [10]. This new legislation created a wholesale market where suppliers and users were able to negotiate power supply contracts and tariffs. According to the law, the National Centre of Energy Control (Centro Nacional de Control de Energía, CENACE) became the national electricity system operator[19]. CENACE's aim is to meet electricity demand at lowest reasonable cost while guaranteeing the operation of the system in terms of reliability, efficiency, continuity, and safety. Also, the law introduced new ***policy instruments*** focused on promoting a clean energy transition. A clean energy quota obligation scheme (clean energy certificates, CECs[20]) was created to guarantee that generators sell a specific percentage of power produced with clean

[18] These documents are updated based on short, medium, and long-term policy objectives.
[19] CENACE started operations in 1977 as a specialised office within CFE. However, in 2014 this institution was declared as an independent public institution.
[20] The CECs scheme is similar to a tradable green certificates (or portfolio standard) scheme but is expanded to grant certificates for clean generation (which includes renewable energy technologies, nuclear power, hydrogen, efficient cogeneration, and fossil-fired generation with CCS).

energy technologies or acquire tradable certificates [8]. A central piece of the reform was a system of auctions for electricity generation, capacity, and CECs aimed at providing more certainty upon future cash flows for generation companies [4]. Three long-term power auctions (LTPAs) (in 2015, 2016, and 2017) and one medium-term power auction (MTPA) (called in 2017 and concluded in 2018) were organised, resulting in power purchase agreements (PPAs) between clean energy generators (mainly wind and solar energy) and retailers (being CFE the main retailer) [99]. Fig. 21 depicts the main actors of the system by 2018.

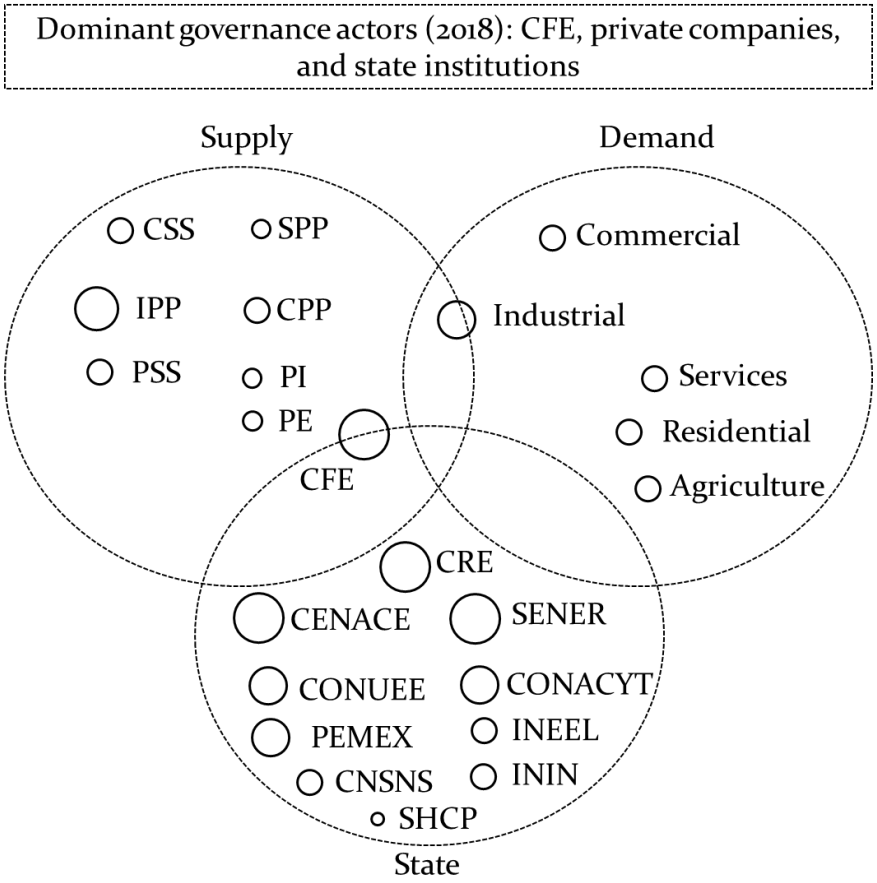


Fig. 21. Main actors within the governance system by 2018. Source: adapted from [8] with information from [2,4,6].

In August 2014, the Geothermal Energy Law was created aiming at regulating activities related to mapping, exploration, and exploitation of geothermal resources and allowing private-sector participation in electricity generation [100] (previously these activities were regulated by the National Water Law and CFE was the only organisation allowed to generate electricity from geothermal resources) [6,101]. As a result, in March 2015, the first private geothermal field started generation and commercialisation of electricity with the first two 5-MW units. This was the Domo de San Pedro geothermal field (Nayarit) owned by Grupo Dragon. In 2016, Grupo Dragon added another 25.5-MW unit. It is worth noting that Mexico has the world's fifth largest geothermal power installed capacity (after US, Philippines, Indonesia, and New Zealand) and has great potential for future development [4].

Regarding fiscal incentives, the Income Tax Law establishes that equipment and machinery used for power generation from clean energy sources have a 100% accelerated depreciation[21] [4]. On the other hand, a carbon tax on production and import of fuels was imposed in 2014 (on fuels with a higher CO_2 content than natural gas). Thus, the carbon tax applies to fossil

[21] This policy instrument (i.e. accelerated depreciation) was first introduced in in 2004 by a reform to the 2002 Income Tax Law and was maintained in the new 2013 Income Tax Law.

fuels (coal, coke, and oil and coal products) across all sectors, including when used for electricity generation [102]. The carbon tax was set at about 39 MXN/tonC (3 USD/tonC)[22] [81]. The Energy Transition Law (LTE) sets that SENER is able to propose additional tax or financial mechanisms to promote clean energy technologies when these mechanisms have the potential to increase savings (for either the state or consumers) or to reduce GHG emissions [4,103].

Although clean energy development was promoted by the state since 2008, little progress was achieved during this period. As 2018, around 80% of electricity production came from fossil-fuel technologies (see Fig. 22). An important international ***landscape*** is that Mexico officially became the 30th member country of the International Energy Agency in February 2018, and its first member in Latin America. This may bring benefits for Mexico in terms of access to energy data, adoption of best practices (i.e. ***policy diffusion***), ***technology diffusion*** (e.g. international spillovers, technological learning), and international collaboration focused on achieving (conditional) climate ***policy objectives***. For instance, co-operation on continued R&D and market deployment of new and improved energy technologies is highly encouraged by the IEA members to achieve shared goals on energy diversification, environmental protection, energy security, and economic growth. A noteworthy example of potential benefits for Mexico is the participation in the Technology Collaboration Programs (TCPs), an initiative that involves over 6,000 international experts across government, academia and industry dedicated to advancing innovation and application of specific energy technologies [104]. Fig. 23 and Table 6 represent the electricity system snapshot for this period.

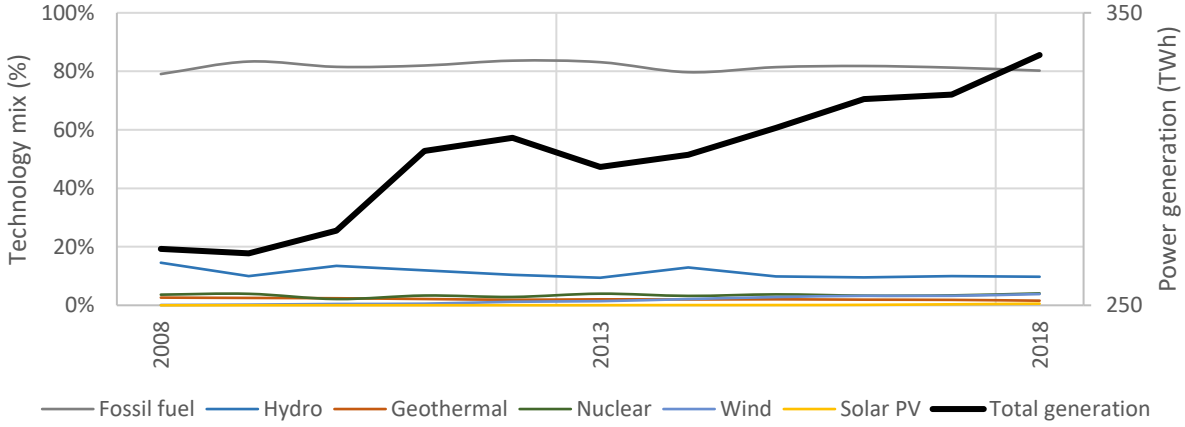


Fig. 22. Shares of technology mix (left) and total electricity generation (right) (2008-2018). Elaborated with information from [11,79,112–114,80,105–111].

[22] The exchange rate corresponds to the date when the law was approved (13 December 2013). One ton of C yields to 3.66 tons of CO_2 under perfect combustion conditions.

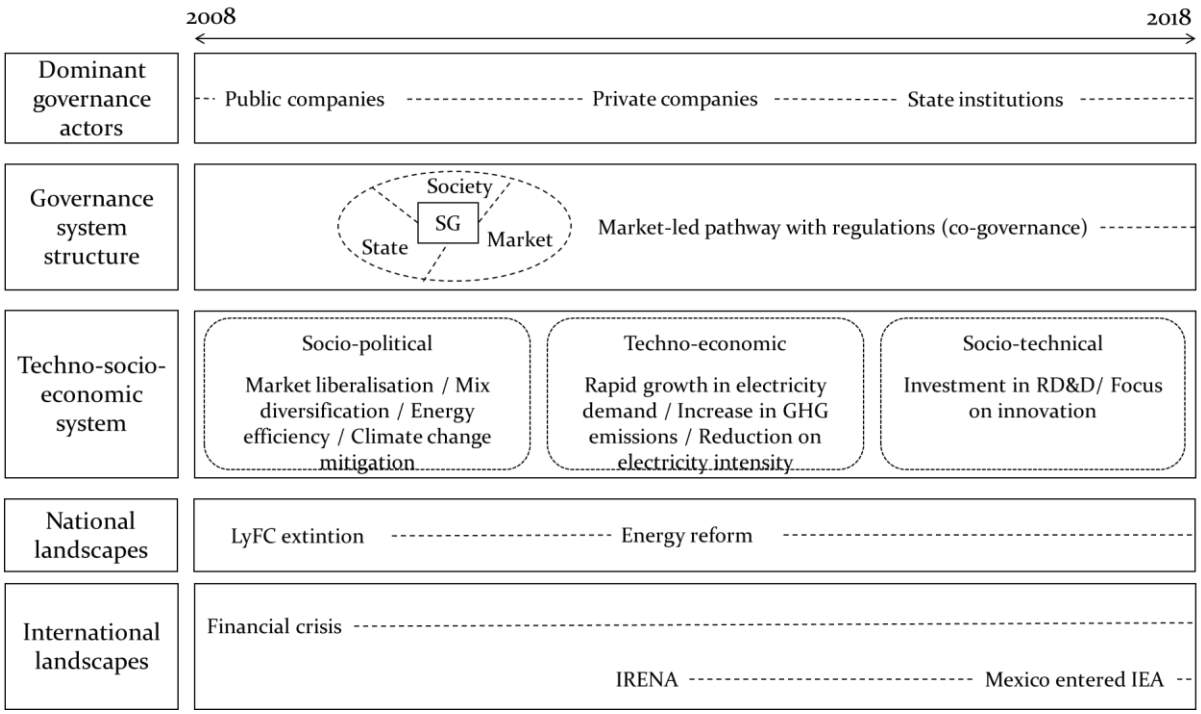


Fig. 23. Electricity system snapshot under the interactive governance approach (2008-2018) – system-to-be-governed, governance system, and external landscapes.

3.5. An administrative hurdle for clean energy development (2019-2021)

The original design of the 2013 energy reform granted the Federal Government with attributes to significantly influence the performance of the energy system (e.g. through different 'seats' within institutional committees) [115]. Thus, five years after the approval of the energy reform and part way in its implementation, the administration of Andrés Manuel López Obrador (who took office in December 2018) started a counter reform based on a ***policy paradigm shift*** towards nationalisation and energy sovereignty (i.e. a state-dominated governing system as opposed to the market-oriented reform). ***Policy objectives*** in the current administration are based on a state-controlled energy system led by the state-owned companies (i.e. CFE and PEMEX). Within the power sector, several modifications to previous ***policy instruments*** have been proposed and some already implemented in line with these policy objectives. For instance, the LIE has been modified in order to favour the dispatch of electricity generated by CFE and condition the access to new private participants (promoting unfair practices) [115–117]. Other amendments to the LIE include a new criteria to grant CELs, elimination of CFE's obligation to buy energy through auctions or competitive processes, and the ability of CRE to revoke self-supply permits [116,117]. Similarly, the state modified the terms for the strict separation of CFE (derived from the LIE and LCFE laws) [118]. Based on the argument that the legal separation has reduced CFE's performance and increased operational costs, the modifications implemented allow CFE to reorganise its generation assets to the discretion of SENER. Also, private participation in transmission projects has been cancelled under these modifications. In addition, the FSE has been involved in a restructuring process derived from a decree issued by the Federal Government ordering the extinction or termination of public trusts and similar mandates without organic structure [119]. The new policy paradigm adopted by the government has derived in significant socio-political tensions within the electricity system, resulting in legal actions against the state (mainly due to unfair market practices for private participants). Currently, the LIE reform (which was stayed by a Federal judge due to violations of the Mexican Constitution) and legal processes against modifications implemented by the state are pending the Supreme Court decision.

Table 6
Electricity system snapshot under the interactive governance approach (2008-2018) – governing interactions (actor level). Source: elaborated with information from [2,4,6,8,62].

From	Interactions	To
Market	Pressure for increasing long-term investment in new capacity to meet demand.	State
	Pressure for competitive tariffs with respect to international benchmarks.	
	Pressure for market liberalisation.	
	Pressure for improving interconnexion for private producers.	
	Pressure for strengthening innovation systems.	
Market	Promotion of reduced tariffs for specific sectors (subsidies).	Society
	Promotion of alternative solutions to satisfy specific needs (e.g. distributed generation).	
	Pressure for adopting energy efficiency measures.	
State	Intervention on market liberalisation.	Market
	Intervention on long-term energy planning.	
	Intervention on climate change mitigation.	
	Intervention on technology mix diversification.	
	Intervention on energy efficiency.	
	Regulation on electricity tariffs (subsidies adjustment).	
State	Promotion of better and more reliable supply services.	Society
	Promotion of sustainable development.	
	Intervention on energy efficiency measures.	
Society	Pressure for increasing government incentives (e.g. subsidies, tax reductions).	State
	Pressure for electricity access in remote zones.	
	Pressure for strengthening environmental regulations.	
Society	Pressure for reducing electricity tariffs.	Market
	Pressure for enhancing supply services.	
	Pressure for use of clean energy sources.	

An international ***landscape*** that significantly affected (and is still affecting) electricity production and consumption globally was the COVID-19 pandemic. In Mexico, the suspension of institutional activities and thus the extension of administrative processes in the electricity sector have been some effects of this landscape. This is evident, for instance, with CRE not granting permits for new private participants (action instructed by the Federal Government) and CENACE delaying interconnection studies of variable generation plants (e.g. solar PV and wind) for an indefinite period [115]. Another important international ***landscape*** was the United States-Mexico-Canada Agreement (USMCA) which entered into force in July 2020[23]. USMCA aimed at supporting mutually beneficial trade between the three countries, leading to freer markets, fairer trade, and robust economic growth in North America. Regarding energy matters, the USMCA aims at providing a predictable framework for the three countries to continue expanding trade in energy products by promoting good regulatory practices and encouraging environmental protection. However, the implementation of the USMCA (and other international agreements) may be threatened by the state's blockage of the Mexico's

[23] The USMCA agreement replaces the previous NAFTA agreement between the three North American countries.

path towards competitive liberalisation of the electricity market [117]. Fig. 24 and Table 7 depict the electricity system snapshot based on available relevant data for this period.

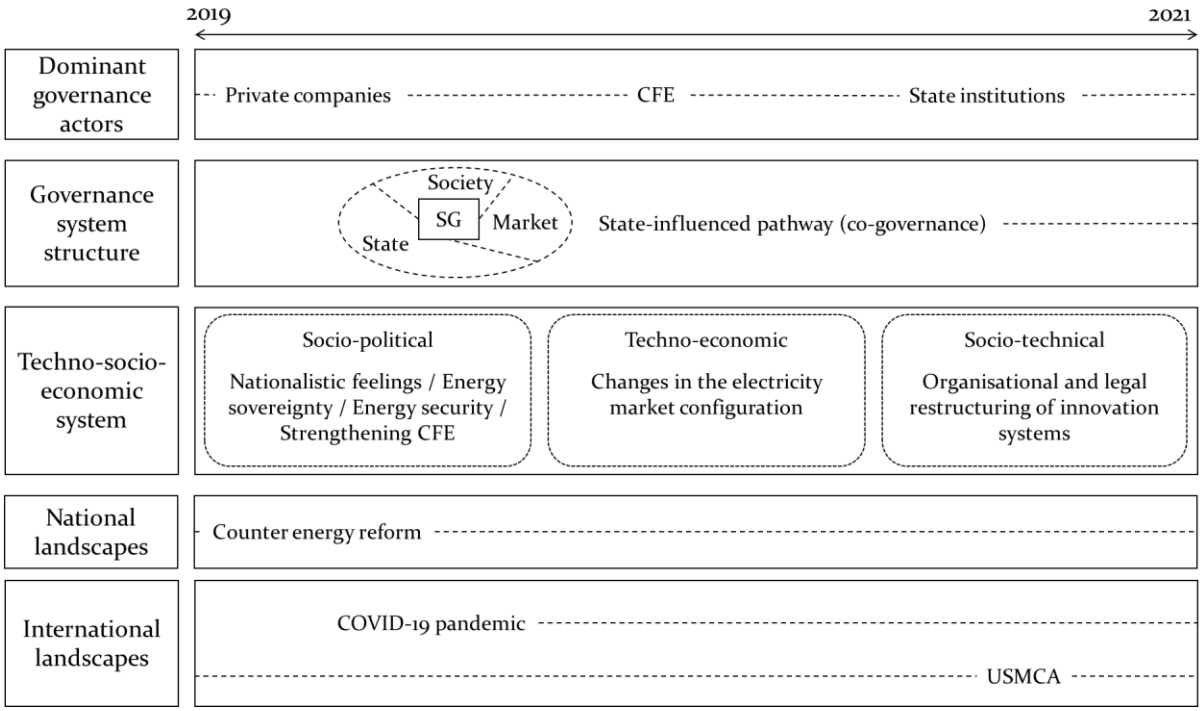


Fig. 24. Electricity system snapshot under the interactive governance approach (2019-2021) – system-to-be-governed, governance system, and external landscapes.

4. Towards a clean energy transition in Mexico

As many developing countries, Mexico's population is growing and urbanising, and thus more urban infrastructure needs to be built over the coming decades (including electricity infrastructure). Also, due to Mexico has a large export-oriented manufacturing sector, an increase in electricity consumption from the (largest electricity-consuming) industry sector is expected for coming years [4]. In 2019, more than 60% of electricity in Mexico was generated with natural gas, benefiting from low gas prices in US [120]. However, Mexico's dependence on (imported) natural gas has become a major concern. The increase of natural gas consumption for the industry and power sectors and the decline in national oil and gas production led to around 70% imports in natural gas in 2019 (mainly from US) [120,121]. Power generation to meet domestic demand could be affected by the volatility of natural gas prices. This highlights the relevance of clean energy technologies for keeping the supply-demand balance at reasonable costs (i.e. energy security).

Although the administration of López Obrador has changed market rules within the electricity industry, the Mexican government has reaffirmed the national ambitious targets regarding electricity generation with clean energy technologies, energy efficiency improvements based on energy intensity reduction, and GHG emission mitigation to address climate change (i.e. policy objectives). Based on a review of policy documents currently in force and complementary initiatives (including reformed versions of those presented in Fig. 20), the main policy objectives, specific targets, and performance indicators for a clean energy transition in Mexico are depicted in Tables 8-10. The focus is on the electricity sector; however cross-sector targets are also considered for reference (e.g. expected GHG emission reductions from all sectors). Specific policy instruments are needed to direct the process towards a smooth clean energy transition and overcome technological, economic, and social barriers. Thus, the main policy instruments identified for a clean energy transition in Mexico are discussed within this section (also included within Tables 8-10). These policy instrument

mixes aim at promoting the use of clean energy technologies, demand side management, distributed generation, and provide services to low-income population [8].

Table 7
Electricity system snapshot under the interactive governance approach (2019-2021) – governing interactions (actor level). Source: elaborated with information from [9,115-119].

From	Interactions	To
Market	Pressure for clear and fair market rules for private participants.	State
	Pressure for a robust institutional framework (e.g. ensuring the independence of regulatory bodies).	
	Pressure for non-discriminatory access to the networks.	
	Pressure for strengthening sector competitiveness (e.g. through international trade agreements).	
Market	Promotion of technology mix diversification.	Society
	Promotion of climate change mitigation.	
	Promotion of energy efficiency measures.	
State	Intervention on market configuration, promoting vertical integration led by CFE.	Market
	Determination of electricity tariffs for specific population groups.	
	Intervention on technology mix diversification, based on expansion plans and priority dispatch mechanisms.	
	Pressure for investment in generation, transmission, and distribution to meet increasing electricity demand.	
	Pressure for reducing operational inefficiencies.	
State	Promotion of reduced tariffs for specific sectors (subsidies).	Society
	Promotion of better and more reliable supply services.	
	Promotion of energy sovereignty.	
	Promotion of energy security.	
Society	Pressure for increasing electrification in rural communities and marginalised urban areas.	State
	Pressure for economy recovery (e.g. creating jobs).	
	Pressure for reducing climate pollutants.	
Society	Pressure for reducing electricity tariffs.	Market
	Pressure for improving supply services.	
	Pressure for increasing electricity access in remote areas.	
	Pressure for use of low-carbon energy sources.	

Table 8
Targets, performance indicators, and main policy instruments for electricity mix diversification. Source: Elaborated with information from [1,4,6,9,103,122–125].

Objective: Electricity mix diversification					
Targets	2021	2024	2030	2050	Reference
Share of power generation from clean energy sources (%)	33.5	35.1	38.2	50	[9]
Geothermal installed capacity (MW)		1,025.4	1,670.4		[122]
Solar PV installed capacity (on-grid) (MW)		5,000	9,000		[123]
Solar PV installed capacity (distributed generation) (MW)		2,000	13,000		[123]
Onshore wind installed capacity (MW)		14,000	21,000		[124]
Ocean energy installed capacity (MW)	11 (by 2022)	80 (by 2026)	500-1,000		[125]
Performance indicators					
Share of electricity generation from clean energy sources (%)					
Installed capacity by source (MW)					
Electricity generation by source (TWh)					
Main policy instruments					
Clean energy portfolio standard					
Soft cost reduction					
Increase transmission and distribution (T&D) lines					
Reduce T&D losses					
Distributed generation					
Public investment in clean energy RD&D					

The two most common policy instruments for promoting power generation from clean energy technologies are feed-in tariffs and renewable (or clean energy) portfolio standards [1]. Mexico has opted for a target-based clean energy standard to stimulate the market for clean generation. To meet these targets, a compliance system (CECs) and a price-finding mechanism (power auctions) were developed under the 2013 energy reform. Although a rapid clean energy market development was expected after the wholesale market started operations in 2016, new private generators have slowly increased their share in the market from 0.52% in 2016 to 11.82% in 2020 (based on verifiable installed capacity) [115]. Similarly, qualified suppliers only increased from zero to 3.4% of the total demanded capacity from 2016 to 2020 [115]. However, the number of permits granted by CFE for electricity generation was reduced by 86% in this period (from 158 in 2016 to 22 in 2020) [115]. Thus, clear market rules for non-discriminatory access and transparent regulatory independence should be sought to promote investment in clean energy infrastructure in line with the clean energy portfolio standard adopted by the state.

Soft costs (e.g. sitting and permitting) and connection to the grid may represent important challenges for clean energy technologies. Soft costs in energy infrastructure projects can be reduced by simplifying administrative processes (e.g. permit granting, pre-zoning). Mexico has

already worked on this potential barrier. For instance, the process to connect a power generation plant to the grid has been reduced from 47 to just 9 (administrative) steps [4]. In addition, a National Atlas of potential zones for clean energy deployment was published in 2017 aimed at reducing soft costs for large clean energy projects and helping planning expansion of national transmission and distribution (T&D) grids [4]. With new large-scale clean energy projects to be built, new T&D lines will be needed. Also, improvements in the National Transmission Grid and the General Distribution Grids will be required to support the expected growth in electricity supply from variable energy sources (i.e. wind and solar). Mexico's electricity losses are significantly higher than other OECD countries. More than 21% of the electricity generated is not charged due to technical (e.g. poor state of the network) and non-technical (e.g. theft, non-payment) losses, resulting in higher transmission and distribution costs [4]. Thus, reducing network losses is an important policy instrument to be included in the policy mix (e.g. through smart grid infrastructure). Also, bringing down technical and non-technical electricity losses may help to reduce the investment required for building new capacity and improve operational efficiency [4]. Similarly, development of distributed generation (mainly solar PV) may represent a potential solution for grid congestion and thus reducing investment needed in new T&D lines. Mexico has a significant potential for distributed generation due to vast available natural resources throughout the country and its further promotion may bring important social benefits to rural communities without access to electricity. It is worth noting that capacity for distributed generation in Mexico increased by 466% from 2012 to 2019 (from 14.86 to 692.86 MW), highlighting the interest in deploying this technology. However, financial mechanisms may be needed to facilitate accessibility to distributed generation in rural areas (e.g. temporary subsidies) [126].

Support for clean energy RD&D has been extensively recognised as a key policy instrument to reduce GHG emissions and combat climate change [127–129]. The Mexican government considers RD&D as a key technology-push policy lever to reach clean energy, energy efficiency, and climate long-term targets [9,130]. Significant progress has been made recently in this regard. For instance, innovation-focused systems (e.g. CEMIEs) have been strengthened and improved through specific policy instruments (e.g. public expenditure in RD&D). CEMIE-Sol can be taken as an example of technological progress in solar energy with 346 scientific publications, 7 business plans developed, 175 academic degrees obtained, 42 intellectual property applications submitted, and 29 technological packages reported by March 2019 [131]. Also, the current administration has acknowledged the importance of investment in RD&D for clean energy technologies by setting a funding scheme in favour of clean energy technologies (at 65%/35% for clean energy/hydrocarbons) [132], as previously suggested by the IEA [4]. However, additional efforts focused on innovation are needed to overcome technical issues with nascent and emerging technologies (e.g. energy storage). Although public investment in RD&D for clean energy technologies started late (2010) in Mexico compared to other OECD/IEA members (1973), Mexico's international memberships (e.g. IEA, IRENA) represent a significant opportunity to advance innovation by taking advantage of technology diffusion and technological knowledge spillovers. In order to overcome technical and market barriers towards a clean energy transition in Mexico, the integration of technology-push and market-pull mechanisms (i.e. coordinated energy innovation policy mixes) are needed.

Table 9
Targets, performance indicators, and main policy instruments for climate change mitigation. Source: Elaborated with information from [4,130,133–137].

Objective: Climate change mitigation			
Targets	2030	2050	Reference
GHG and Short-Lived Climate Pollutants (SLCPs) emissions reduction	25 – 40% from business as usual (BAU) (from 1,128 to 846-677 $MtCO_2e$)		[134–136]
GHG emissions reduction	22 – 36% from BAU (from 991 to 773-634 $MtCO_2e$)	50% from 2000 levels (Max. 320 $MtCO_2e$)	[130,133,134]
Black carbon emissions reduction	51 – 70% from BAU (from 137 to 67-41 $MtCO_2e$)		[130,134,136]
Reduction in emissions intensity	40% from 2013 levels		[130,134]
Reach emissions peak in 2026			[130,134]
GHG emissions reduction from electricity generation	31% from BAU (from 186 to 128 $MtCO_2e$)		[135,136]
Performance indicators			
GHG emissions by pollutant ($MtCO_2e$/year)			
GHG emissions by sector ($MtCO_2e$/year)			
Emissions intensity ($MtCO_2e$/GDP)			
Carbon intensity from electricity generation (tCO_2/MWh)			
Main policy instruments			
Carbon tax			
Emissions Trading System (ETS)			
Carbon Capture and Storage (CCS)			

The electricity sector is expected to be the major contributor to GHG emissions reduction. The main policy instrument implemented by the government is a carbon tax. Fuels used for electricity generation are subject to the carbon tax. However, natural gas is zero-rated under this mechanism and it has been considered as the 'transition fuel' to comply with GHG emission reductions [121]. With decreasing domestic production and high dependence on imported natural gas, a gradual increase in carbon tax level (e.g. 50-100/tCO_2 by 2050) should be considered to better reflect the social cost of carbon and thus reduce carbon emissions from the electricity sector. In addition, a complementary Emissions Trading System (ETS) (also called cap-and-trade) may provide additional benefits by providing quantity certainty (additional to price certainty from a carbon tax) [1]. In 2020 a ETS test program stated operations in Mexico aimed at enhancing the quality of data on emissions and building capacity in emissions trading. The pilot phase (2020-2021) covers direct CO_2 emissions from entities in the energy and industry sectors. The energy sector includes electricity generation,

transmission, and distribution, as well as fossil fuel extraction, production, transport, and distribution. The operational phase is expected to start in 2023 [138]. Additionally, carbon pricing policy instruments (e.g. carbon tax and/or ETS) may create economic incentives for carbon capture and storage (CCS) by reducing the cost of compliance [1].

Table 10
Targets, performance indicators, and main policy instruments for energy efficiency. Source: Elaborated with information from [1,4,9,103].

Objective: Increase energy efficiency				
Targets	2030	2035	2050	Reference
Reduction in final energy intensity rate		2.2% from 2020 to 2035	2.5% from 2035 to 2050	[9]
Reduction in total final energy consumption	24.7% from BAU (from 7,120 to 5,363 PJ)	30.1% from BAU (from 7,843 to 5,485 PJ)	43% from BAU (from 9,621 to 5,480 PJ)	[9]
Reduction in electricity demand	29.7% from BAU (from 428 to 301 TWh)	34.6% from BAU (from 492 to 322 TWh)	46.8% from BAU (from 723 to 385 TWh)	[9]
Performance indicators				
Final energy intensity (toe/GDP)				
Total final energy consumption (PJ)				
Total electricity demand (TWh)				
Electricity intensity (kWh/GDP)				
Main policy instruments				
Performance standards (e.g. buildings and appliances standards, industry energy efficiency standards)				
Demand side management – Demand response				
Reduction of electricity subsidies				
Electrify transportation sector				

Historically Mexico's energy policy design has posed significant attention to the supply side rather than the demand side [65]. Cross-sectoral energy efficiency policy instruments in Mexico have focused mainly on the residential and commercial sectors with the implementation of programs such as performance standards for buildings and appliances, replacement programs for refrigerators, air conditioning, and fluorescent lights, and a voluntary energy labelling program (FIDE stamp) [4]. Although electricity accounts for around 31% of the total consumption in the industrial sector, energy efficiency measures have been limited to energy audits, technical recommendations, and data collection on energy consumption [4]. Within the transport sector, 99.8% of the total fuel demand is fuelled by oil, with only a 0.2% share of electricity use. Thus, energy efficiency in the transport sector has been promoted mainly by improvements in light-duty vehicle standards [4].

Although Mexico has wide-ranging programs for energy efficiency, the Mexican society lacks awareness regarding their benefits. Energy efficiency policy instruments (e.g. industry energy efficiency standards, demand response) could play a stronger role in the policy mix to reach

energy objectives. Thus, energy efficiency standards already in place should be constantly revised and updated according to new technological improvements and more efficient technologies available. Also, as energy-intensity industries are expected to rise in the coming years, increasing the efficiency of industrial equipment through performance standards should be included in the policy mix (e.g. fostering efficiency improvement in electric motors, pumps, and commercial boilers). Demand response mechanisms may bring significant benefits to the system by reducing demand during peak periods, lower capacity requirements, and increasing reliability. Although Mexico has not defined a clear demand response mechanism, an effective program requires solid measurement and verification elements to ensure cost savings for all participants.

With new actors in the system (e.g. new industry players, new regulators, a new system operator) the state should install a new data collection system focused on keeping the supply-demand balance [4]. Mexico has an online database where information on energy supply and demand is published, the Energy Information System (Sistema de Información Energética, SIE). However, some data are not accurate and have not been updated regularly, creating uncertainty around electricity demand. A particular issue is that data on electricity consumption is not completely collected and/or uniformly reported (rather it is estimated), affecting the reliability of data on energy efficiency [4]. Thus, improvements in data collection, management, and analysis are needed to appropriately track energy efficiency progress.

Mexico has historically relied on an expensive and distorting tradition of electricity subsidies (electricity tariffs for farmers and households are subsidised by 60-70% of the total cost). As tariff is a key driver for behavioural change, artificially low electricity prices should be phase out and replaced with other policy instruments (e.g. promoting distributed generation and energy efficiency measures). The wholesale and retail markets under fair competition may help in reducing generation costs and facilitate a smooth process of phasing-out subsidies without an extraordinary increase in prices [4]. For instance, power auctions in Mexico have indicated that private companies can supply electricity from solar and wind technologies at highly competitive prices (as low as USD 17 per MWh for wind and USD 19 per MWh for solar PV in the third LTPA) [99]. Although retail electricity prices remain a politically sensitive issue, reducing subsidies may help to increase consumer's awareness of efficiency and thus to buy more efficient products, while bringing long-term budgetary benefits for the government (net subsidies to end users accounted for USD 37.6 billion from 2010 to 2015) [4].

The transportation sector is the largest energy consuming sector and the largest CO_2 emitter in Mexico [4], powered mainly by oil. Thus, as the carbon intensity of the electricity sector decreases, one promising policy strategy for decarbonising the economy is the electrification of the transportation sector (through subsidies for electric vehicles, development of charging infrastructure, and consumer education) [1]. Although electric vehicles are an emerging technology that must compete against oil-fuelled matured technologies (i.e. conventional vehicles) the state has considered EV deployment as a key energy efficiency strategy towards a clean energy transition [9].

5. Discussion and conclusions

Electricity is fundamental for meeting societal needs and supporting economic development. However, the electricity sector contributes to a significant share of greenhouse gas emissions. Power generation from clean energy sources may help to meet societal needs such as increasing electricity demand while enabling deep carbon reductions. The aim of this paper was to describe the development of clean energy technologies in Mexico from 1879 to 2021 using a multi-perspective approach. A series of qualitative storylines were synthesised in an analytical framework under the interactive governance approach. The empirical application of the framework proposed in Section 2 revealed that the ever-growing electricity demand in Mexico have called for exploring different technologies and available energy sources over time.

The decline in hydrocarbons domestic production, increasing environmental concerns and international agreements on climate change mitigation have been the main drivers for deploying clean technologies and adopting energy efficiency measures in Mexico. However, clean energy technologies have faced important barriers.

First, domestic available resources have played a crucial role in directing the pace and pathway of electricity generation in Mexico (i.e. path-dependence). In the early stages of the power sector in Mexico, the vast water resources allowed that most of the electricity was produced from hydropower technologies. However, access to a vast oil and gas resources promoted a transition to fossil-fuel power generation since 1971, reinforcing the position of fossil-fuel incumbent regimes and displacing clean energy technological niches. For instance, with a boom in oil production in the 1970's the state encouraged the use of fuel oil (produced by PEMEX) for power generation, creating a carbon lock-in effect. Although Mexico has abundant renewable energy resources and clean energy development has been promoted by the government since 2008, little progress has been achieved to date due to technological and socio-economic barriers (e.g. economies of scale from large-scale fossil fuel generation, political and institutional influence). A decrease in hydrocarbons national production since the mid-2000's may represent an opportunity for clean energy development. For instance, resource depletion may lead to a rise in extraction costs and thus may prompt technology shifts, use of more efficient equipment, or reduce consumption. However, technological lock-in has been (a will remain) a significant challenge for clean energy technologies if the state promotes the development of incumbent regimes (e.g. electricity production from conventional technologies) due to socio-political interest (e.g. by maintaining aging and inefficient power plants that burn fuel oil produced by PEMEX).

Second, although Mexico has a remarkable potential on renewable sources (e.g. wind, solar, geothermal, bioenergy), the lack of investment in RD&D and innovation for clean energy technologies have limited their development. Mexico has recently taken important steps towards boosting innovation on clean energy technologies (e.g. CEMIEs). However, historically the country has been rather a technological follower/adopter (i.e. periphery country) than a technological leader (i.e. core country). As discussed in Section 3, the lack of economic resources led to knowledge obsolescence and lack of interest in clean energy development at their early stages. However, technology diffusion and technological learning processes have played (and will play) a relevant role for the development of these technologies.

Third, policy paradigms have shifted based on (dynamic) societal needs and socio-political interests. As a result, governance structures (and their interactions) have change over time to satisfy these needs and interests. The state-led pathway adopted after the nationalisation of the electricity industry brought several benefits to society (e.g. reduction in electricity prices) but at the same time multiple economic and financial issues (e.g. financial constraints to expand the system). Thus, a policy paradigm shift towards the liberalisation of the sector was adopted since the 1990's. The opening of the market has led to the use of more attractive power generation technologies, from a cost perspective (mainly natural gas-fired technologies). Although private investors have shown significant interest in building clean energy power plants (mainly wind and solar PV) after the 2013 energy reform, the current administration of Andrés Manuel López Obrador (elected in 2018) has focused on strengthening CFE by increasing its generation capacity and recover its self-sufficiency. This policy paradigm shift may jeopardise the development of clean energy technologies by creating political uncertainty and posing financial challenges to the expansion of the system.

Multiple policy instruments to overcome these barriers and allow a transition towards a clean energy system in Mexico have been identified and discussed in Section 4 (some already implemented by the government). These policy instruments aim at providing promising mechanisms to achieve current policy objectives identified by the application of the proposed

analytical framework. Some policy mixes are more suited for countries under development. Electricity systems in developing countries have some common characteristics: continuous structural changes, the need for infrastructure expansion due to rapid growth in electricity demand, and significant (deep) uncertainties regarding future conditions [15]. The development of the clean energy market may be affected by factors outside the control of policymakers such as fuel prices for electricity production (mainly natural gas), technological progress, price-demand elasticities, population growth, and investment preference structures adopted by private generator companies. Based on the particular characteristics of the Mexico's electricity system described in this study, the exploration of different policy mixes considering different uncertain factors is proposed for future research. Thus, a quantitative analysis on future scenarios is needed to gain insights on what could be the most robust policy alternatives to efficiently meet the rapid growing demand, reach the long-term target of generating 50% of electricity with clean energy technologies by 2050 (compared to 20% in 2019), and meet international climate change commitments. Energy models can be used to explore the performance of different policy mixes. Additional to policy objectives presented in Section 4, the costs/savings of implementing alternative policy mixes should be considered by policymakers.

Different drivers and barriers for developing clean energy technologies in Mexico have been identified and discussed in this study. Also, current policy objectives, specific targets, performance indicators, and potential policy instruments towards a clean energy transition in Mexico were discussed. The use of concepts from a multi-perspective analytical framework and policy mixes for sustainability transitions were useful to understand the role of social actors, policy mixes, the system's performance, and technological change processes in the development of clean energy technologies. Also, the interactive governance theory was useful to synthetise the qualitative storylines derived from the multi-perspective analysis into a broader theoretical construct as suggested in previous studies.

The last period of analysis covered by this study (i.e. 2019-2021) may be considered as a partial (incomplete) representation of the ongoing structural transformations that have been taking place in recent years due to two main reasons. First, electricity transitions are characterised by long-term, complex, evolving processes of structural change where adaptations to policy mixes usually occur due to external and internal tensions in the system. Second, the lack of available data for some sustainability concepts used in this study (e.g. electricity generation, GHG emissions) limits the development of comprehensive storylines under the multi-perspective analytical framework described in Section 2.1. Thus, the application of the proposed theoretical framework (see Section 2) using updated relevant data offers an important avenue for future research. In addition, future research can be made by using additional complementary concepts from these or other analytical frameworks to generate alternative narratives about transformation processes not covered here. Also, a broader analysis of the energy sector as a whole may aid to better understand energy transitions in developing countries.

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Chapter 4

Modelling endogenous technological change for clean energy technologies

In the previous chapter, a multi-perspective analytical framework was developed and applied to describe the evolution of the Mexican electricity system in general, and the development of clean energy technologies in particular. The chapter highlighted the importance of technological learning processes in developing and deploying clean energy technologies and thus reducing GHG emissions and transition to a low-carbon future. Chapter 4 presents a comprehensive quantitative analysis on the influence of selecting different learning curve approaches (i.e. alternative definitions of explanatory variables in technological learning processes) to describe clean energy technology costs developments over time.

Based on the empirical findings presented and discussed in this chapter, a better statistical explanation was found when technological experience (based on installed capacity) and knowledge stock (based on public investment in RD&D) were modelled as sources of learning to explain historical technology cost changes for onshore wind and solar PV. In addition, the chapter highlights the critical relevance of learning through researching when innovation policymakers want to investigate the effects of energy RD&D in reducing GHG emissions and combat climate change. These findings are used to explicitly include technological experience and knowledge stock as sources of learning in the system dynamics model (i.e. EPS) used for the EMA process implementation. Thus, following the original implementation of the EPS model (i.e. stock and flow variables based on system dynamics theory), the development and implementation of causal diagrams to include these sources of learning are presented in this chapter. The modified EPS model structure allow the exploration of the potential impacts of public investment in RD&D for clean energy technologies on future technology cost developments by using a two-factor learning curve approach. In addition, the plausible long-term effects of different RD&D investment scenarios on electricity generation and GHG emissions using the modified version of the EPS model are presented and discussed within this chapter.

Chapter 4 methodologically and empirically contributes to this study by answering Question #4:

What is the role of technological learning processes on clean energy development?

- *What is the most suitable model configuration to investigate the plausible effects of technological learning on technology cost changes over time?*
- *What is the influence of different sources of learning in technology cost developments?*
- *How are these sources of learning formally defined for clean energy technologies?*
- *What are the policy implications of using alternative approaches to modelling technological learning?*
- *What is the impact of public investment in research, development, and demonstration (RD&D) for clean energy technologies in energy transitions?*

Chapter 4 is based on two journal articles:

"*Effects of learning curve models on onshore wind and solar PV cost developments in the USA*" published in *Renewable and Sustainable Energy Reviews*, and

"*Economic and environmental impacts of public investment in clean energy RD&D*" published in *Energy Policy*.

The format and numbering of the sections are according to the original publication styles (see Appendix D).

Effects of learning curve models on onshore wind and solar PV cost developments in the USA

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ABSTRACT

Technological innovation planning for developing and deploying clean energy technologies plays a key role in reducing greenhouse gas emissions and transition to a low-carbon future. Learning curve theory has been adopted as a common framework for exploring the relationship between endogenous technological learning and technology cost developments. The aim of this article is to analyse the effects of selecting different learning curve approaches (i.e. model formulations) to describe energy technology cost changes over time. Experience and knowledge stock are chosen as the sources of learning to be considered. A new definition of experience was developed to account for the interaction between global and local experience. The new definition of experience also accounts for learning sub-processes (i.e. learning-by-doing, learning-by-using, and experience spillovers) to estimate total experience gained through technology deployment. An integrative model is developed for estimating the effects of learning-by-deploying and learning-by-researching on cost developments for onshore wind and solar PV in the USA. Publicly available data from government departments and organisations were utilised. It was found that technology cost developments are better explained when: (1) experience is defined as a function of global and local experience; (2) knowledge stock is also considered in the model formulation; and (3) technological processes affect only a fraction of the total capital cost. The findings suggested that the application of learning rates for model-based energy planning is context-dependent and how technological factors are explicitly defined may have significantly different policy implications (i.e. different technology costs predictions based on alternative model formulations).

Highlights

- An integrative learning curve model is used for estimating learning rates.
- Experience and knowledge stock are chosen as the main sources of learning.
- A new definition of experience based on global and local experience is presented.
- Knowledge stock considers domestic public RD&D outlays and international spillovers.
- Contextual-based learning rates estimates are needed for energy policy analysis.

***Keywords*:** technological learning, learning curve, onshore wind, solar PV, energy RD&D, technological experience, knowledge stock.

Nomenclature

Symbols

a	domestic knowledge dissemination policies factor (-)
C	capital cost ($ kW^{-1})
CC	cumulative installed capacity (MW)
E	experience (MW)
KS	knowledge stock ($m)
KP	international knowledge pool ($m)
LM	learning multiplier (-)
LR	learning rate (-)
PR	progress ratio (-)
RDnD	public RD&D spending ($m)
SPILL	international knowledge spillovers ($m)
X	learning source (-)
Z	new knowledge creation ($m)

Greek Symbols

α	share of the total technology capital cost affected by learning processes (%)
β	share of domestic content (%)
ρ	annual depreciation rate of knowledge stock (%)
γ	experience spillover coefficient (-)
δ	domestic absorption capacity of international knowledge spillovers (-)

Subscripts

g	time lag between the RD&D activity and its effects (a)
lbdo	learning-by-doing
lbu	learning-by-using
n	country
spill	experience spillovers
t	technology
y	timestep (a)

Superscripts

b	public RD&D spending elasticity
c	knowledge stock elasticity
d	international knowledge spillover elasticity
ℓ	learning index
lbd	learning-by-deploying elasticity
lbr	learning-by-researching elasticity

Abbreviations

1FLC	One-factor learning curve
2FLC	Two-factor learning curve
GHG	Greenhouse gas
IEA	International Energy Agency
LbD	Learning-by-Deploying
LbR	Learning-by-Researching
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
R&D	Research and development
RD&D	Research, development, and demonstration
RMSE	Root mean square error
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

1. Introduction

It is widely recognised that technological innovation in low-carbon technologies plays a substantial role in combating climate change and reducing greenhouse gas (GHG) emissions without compromising economic growth [1]. Energy-related policymakers have developed and applied diverse policy strategies to promote clean energy transitions. These policies include technology-push (e.g. public investment in energy research and development) and market-pull (e.g. carbon pricing, feed-in tariffs) mechanisms [2,3]. Technological learning has been identified as a key driver for moving towards low-carbon energy systems [4].

Technological learning is widely accepted as a mechanism that leads to technology cost reductions over time [5]. Electricity generation costs from renewable energy technologies have dropped rapidly over the last decade. These reductions have been driven by several factors such as cumulative manufacturers experience, technological innovation, economies of scale, among others. Cost reductions are reflected in clean energy technology deployment with renewables accounting for 82% of all new capacity additions worldwide in 2020, leading with solar photovoltaic (PV) and onshore wind additions [6]. Thus, understanding how costs of electricity generation technologies change over time due to technological change processes is crucial for energy analysts, planners, and policymakers.

The most common framework for investigating the relationship between technological learning and technology costs changes is the learning curve approach [5,7]. However, what sources of learning and key parameters to include as explanatory variables to technology cost changes has been identified as a paramount source of uncertainty within this approach [8,9]. Technological experience and technological knowledge stock, hereafter referred as experience and knowledge stock, are the most common sources of learning that have been modelled within energy-economic models. Nonetheless, alternative definitions of these factors are found in the literature making it difficult to develop policy recommendations for decision makers regarding the role of technological learning processes on future cost developments.

The aim of this article is to analyse the influence of selecting different technological learning model structures (i.e. alternative definitions of explanatory variables) to describe renewable energy technology costs developments. Onshore wind and solar PV are the two renewable energy technologies with the fastest-growing electricity generation in the world and are of particular interest for energy transitions studies [10,11]. In 2020 the United States of America (USA) represented 32% and 21% of the Organisation for Economic Co-operation and Development (OECD) installed capacity for onshore wind and solar PV, respectively [12]. Thus, the focus in this article is on onshore wind and solar PV electricity generation technologies in the USA.

The article builds on existing learning curve literature by analysing the role of alternative approaches when modelling technological learning as a function of experience and knowledge stock as the main sources of learning. Due to different definitions of experience and knowledge stock, an integrative technological learning model has been developed by integrating multiple approaches to modelling technological learning. By changing key parameters within this integrative model, the impact of model definitions is explored as suggested by [13]. Thus, this article reveals the relative contributions of different variables to reducing capital costs for selected renewable energy technologies and provides an in-depth critical discussion on the implications of their use to inform energy policymaking. Also, the study contributes to the literature by providing a new definition of experience aimed at investigating the relative contribution of local and global experience on technology cost changes and accounting for different learning processes as suggested by previous studies [11,13]. Similarly, knowledge stock is modelled as a combination of global and local data to explore the relative contribution of domestic public energy R&D expenditures and

international knowledge spillovers as suggested by [11]. The present investigation is targeted at energy analysts, researchers, planners, and energy innovation policymakers.

The remainder of this article is organised as follows. Section 2 sets the background of the research by describing the role of learning curve theory in estimating future technology costs. An integrative technological learning model is presented and explained in Section 3. Data sources employed, parameter value settings, and alternative model structures are described within this section. In Section 4 estimated learning rates by applying different model structures are presented. Findings of the analysis, policy implications, limitations and potential future research are discussed in Section 5. The conclusions follow in Section 6.

2. Endogenous technological change in energy modelling

Neoclassical growth models, fundamentally derived from Solow [14], have usually considered technological change as an exogenous phenomenon to the economy. This approach suggests that technological change is an autonomous process that do not depend upon other variables (e.g. economic, policy, social, or environmental factors); a perspective with important limitations for policy analysis [15]. In energy modelling literature, it has been advocated that technological change should be modelled as a result of the interactions of other interrelated processes, such as government-funded research and development (R&D), private technology investment, and economy-of-scale effects [16]. Thus, the use of learning curves has been adopted for energy and environmental technology analysis to gain knowledge about the process of learning in energy systems [17]. This is particularly important in the context of energy and innovation policy analysis to determine whether resources to be allocated to foster renewable energy technologies are better spent on technology diffusion or innovation policies [15,18]. The learning curve theory has been applied to analyse the effect of induced technological change in electricity generation technologies. Recent reviews may be found in [9,11,13,19].

2.1. Learning curve theory

Efforts on quantitative explanation of technological change dated from the 1930's when it was observed that the production cost of military airplanes declined at a semi-constant rate for each doubling of aircraft produced [20]. This correlation is known as the learning curve. Learning curves are generally used to empirically estimate the cost of a given technology as a function of technological learning [21]. The learning curve theory relies on the assumption that future technology costs decline as technological learning increases. In the energy sector the learning curve theory is commonly applied to estimate future costs of electricity generation technologies as a function of learning processes [9–11,13,22]. Learning processes in energy systems may occur through various channels [11]. When the focus is on experience gained by technology diffusion (i.e. learning-by-deployment [11]), learning may increase through experience attained during the production process of a technology (learning-by-doing [23]), through the operation or use of a technology (learning-by-using [24]), and via exchange of experience-based knowledge derived from interactions among different stakeholders or regions (learning-by-interacting [25] or experience spillovers [26]). On the other hand, when the focus is on innovation, learning may increase through knowledge creation during research activities (learning-by-researching or learning-by-searching [27]).

A variety of geometric model formulations have been proposed within the learning curve literature to describe the relationship between technological learning processes and technology cost reductions (a review may be found in [28]). Among learning curve studies on energy technologies, the log-linear model is the most common method applied due to its simplicity and generally good fit to historical data [29]. Thus, this model formulation has become a common method of representing technological learning in energy-economic models for policy analysis [4]. However, significant different policy implications may be obtained (e.g. different values for learning rates) based on the selection of learning sources (e.g. experience

and knowledge stock) and assumptions to define technological progress in energy models [10]. How technological progress influences future electricity generation technology costs has been analysed through diverse energy models such as WITCH [30], MESSAGE [31], ReMIND-R [32], NEMS [33], and EPA-MARKAL [34]. A comprehensive review of efforts aimed at incorporating endogenous technological change in energy-economic models may be found in [35]. Also, research implications on endogenizing technological change in energy-economic models are discussed in [13]. It has been argued that endogenizing technological change in energy system models has a significant influence on the cost of climate policy actions based on learning sources used to describe technological processes [13].

One-factor learning curve (1FLC) models, often called experience curves [36], use experience as the only learning source to explain technology cost developments over time. The definition of experience in the case of electricity generation technologies may vary due to several empirical reasons (e.g. scope of the study, geographical delimitation, data availability). The most common definition of experience is cumulative installed capacity of the technology of interest [9,11]. However, electricity generated or number of plants (or parts of plants) built have been identified as the most frequent alternative definitions [9]. Other definitions have been proposed as proxies for experience for particular energy technologies, such as cumulative PV modules shipments for solar PV [37] and number of turbines in the case of wind [38]. Alternative definitions used for experience in electricity generation technologies may be found in [9] and [11].

In order to better represent technological change processes, two-factor learning curves (2FLCs) have been developed in [27,30,39,40]. The 2FLC approach was first proposed by [27] to include R&D expenditures, as a proxy for knowledge stock, as a second source of learning and thus adding a policy variable to the learning curve model. While it is widely accepted that both private and public investment in R&D activities may contribute to technology cost reductions, 2FLCs often include only public R&D expenditure, as private data generally are not publicly available [41]. Thus, learning-by-researching processes may incorporate public R&D expenditures or patents as the most common proxies for cumulative knowledge stock [15,42]. Alternative definitions for knowledge stock used for solar PV and wind may be found in [11]. Several studies have empirically tested 2FLC models to explore the impact of knowledge stock in technology cost developments (see, for instance, [15,21,39]). Results have shown that the contribution of knowledge stock compared to experience vary across different technologies and stages of development [11,41].

Multi-factor learning curves models (MFLC), including three or more factors, have been proposed in the literature. These include technology imports (i.e. learning-by-importing), economies-of-scale effects, supply-chain dynamics, input prices for materials, efficiency improvements, among many others [8,11]. However, multi-factor learning curves present major limitations such as difficulty to construct due to data limitations or high levels of multicollinearity [9,10,43,44].

2.2. Limitations of current learning curve models

The application of 1FLC models for predicting future technology cost developments has been extensively debated in the literature (see [9,13,15,45,46]). A key criticism of 1FLC models is the high level of aggregation to represent learning processes regarding technology deployment [9,11,13]. For instance, the relative role of learning-by-doing, learning-by-using, and experience spillovers cannot be revealed by using a traditional 1FLC approach [9,11]. Thus, it is argued that little explanation is offered by the statistical correlation between reductions in technology costs and cumulative installed capacity, used as a proxy for experience, when the process of technological learning is investigated using 1FLC models [8,46]. Considered as a partial model for technological learning processes, 1FLCs may produce inaccurate estimates of learning-by-deployment rates [15]. Thus, it has been suggested that a quantitative exploration of drivers

that may contribute to learning due to technological deployment is needed to avoid producing misleading conclusions about learning gained through experience [11,13].

In addition, some scholars have suggested that 1FLC models may overestimate the actual contribution of experience as this approach uses a single parameter (i.e. experience gained by technology deployment) to explain technology cost changes (i.e. omitted variable bias) [9,13]. Omitted variable bias occurs when alternative key cost-influencing factors (e.g. knowledge stock, spillover effects) are neglected from the analysis [9]. From a policy perspective, only market-pull recommendations may be developed while ignoring technology-push mechanisms if 1FLCs are applied in energy models [15]. If energy models miss critical pathways or inappropriately capture learning processes (e.g. poor representation of energy innovation processes), policymakers could potentially obtain incomplete or misleading policy conclusions [46]. Energy innovation-oriented policy strategies play a key role in learning processes and promoting technological development [47–50]. For instance, when the private sector is unable to capture the full social value of their R&D efforts, private underinvestment is evident (i.e. market failure) [51,52]. Thus, government interventions (e.g. through public investments in energy R&D) play a vital role to close this investment gap. Also, public support for R&D may aid to overcome other system failures [53]. For instance, innovation stakeholders may not be able to take advantage of the entire innovation potential if governments do not guarantee proper diffusion of new knowledge. Nevertheless, the risk of governmental failure exists when public investment in R&D is allocated based on policymakers' own interests or when the public investment is too high resulting in a crowd-out effect of private investment by public expenditures [54,55]. Thus, analysis of technological change processes including innovation-oriented policy strategies (e.g. public investment in energy R&D) is crucial to gain a deeper understanding on how public resources are spent and the effects of that expenditure.

Furthermore, although learning curve theory is widely used to predict future energy technology costs, significant uncertainties have been identified around learning curve model formulations and their use in energy-economic models for policy analysis [8]. A common question that has emerged among scholars, analysts, and policymakers is: what is the 'best' model formulation to represent technological learning for a specific technology? There are no definitive answers to this question [8]. It has been argued that outputs obtained from long-term modelling exercises are highly sensitive to input assumptions [29,56]. For example, while learning curves may explain how technology costs have evolved in the past, they may provide limited insights regarding how these costs are likely to change in the future [4]. Thus, the selection of model formulations and assumptions to project future technology costs may have considerably different policy implications (e.g. different technology deployment levels, different costs of mitigation policies) [10]. Additional inquiries related to structural definition include: what sources of learning better explain costs changes? How those sources of learning are defined and formulated? [4]. The selection of 'appropriate' definitions of learning sources and parameters to explain technology cost developments is closely related to the conceptualisation of the learning system and the definition of its boundaries [9].

Although additional caveats of learning curves have been discussed in the literature (e.g. learning rates are commonly assumed to be positive and remain constant over time, not accounting for radical improvements) [9,13], this article focusses on addressing three key limitations: (1) high level of aggregation regarding learning-by-deployment by proposing a new definition of experience to account for different learning processes (i.e. learning-by-doing, learning-by-using, and experience spillovers); (2) omitted variable bias by including knowledge stock as a second source of learning; and (3) structural uncertainty by investigating the potential policy implications of choosing alternative learning curve approaches to describe technological learning processes.

3. Methods and Data

Different review studies on the application of learning curve theory to energy technologies have been reported. These reviews encompass power generation technologies in general [9,10,19,57] and individual generation technologies in particular, such as solar PV [11,29,58–60], wind [11,39,61,62], and fossil fuel-based technologies [63]. Also, applications on energy efficiency [7], and energy demand technologies [64] have been investigated. A wide range of learning rates for energy technologies have been reported in past studies using different model structures, data periods, and geographical locations (see [19] for an overview of 444 estimated learning rates). Based on previous reviews [9–11,13,19], Table 1 and Table 2 present a summary of estimated learning rates for onshore wind and solar PV for the USA, respectively.

The studies above suggest that the process of estimating learning rates for energy technologies is driven by several factors such as model structure, definition of the learning factors to be used, boundary of the learning system, time period, and variables to be considered [9,15]. Thus, the estimation of learning rates depends on the context of analysis and differs per situation [65]. In this article an integrative learning curve model has been developed by combining different learning curve methods to explore the relative impact of alternative model structures on technology capital cost developments. The integrative model is used to estimate learning rates for onshore wind and solar PV in the USA using different variables and time periods.

3.1. An integrative learning curve model

The integrative learning curve model developed in this work starts from the general learning curve model adapted from [81] and defined in this article as in Eq. (1):

$$C(\mathrm{X})_{t,y} = C(\mathrm{X}_0)_t \left(\frac{\mathrm{X}_y}{\mathrm{X}_0} \right)_t^{-\ell} \quad (1)$$

where $C(\mathrm{X})_{t,y}$ represents the capital cost of technology t at year y as a function of technological learning processes, X denotes the learning source (e.g. accumulation of technological knowledge or experience), $C(\mathrm{X}_0)_t$ is the capital cost of technology t at time $y=0$ (i.e. initial capital cost), and ℓ is the learning index (i.e. elasticity of learning to capital cost). The learning index is related to the learning rate (LR) by Eq. (2), adapted from [71]:

$$LR = 1 - 2^{-\ell} \quad (2)$$

The learning rate represents the percentage of capital cost reduction of a technology for every doubling of cumulative values of learning factor(s). The progress ratio (PR) is an alternative option for representing this relationship. PR represents the relative remaining capital cost of the technology after a doubling of the cumulative learning factor(s) considered and is expressed as in Eq. (3), adapted from [71]:

$$PR = 1 - LR \quad (3)$$

In Eq. (1) only one source of learning is considered (i.e. X). However, technological learning may occur through multiple channels as discussed in Section 2. When more than one source of learning is considered, the term 'learning multiplier' (LM) is introduced in the model to account for the change in technology capital costs due to technological progress through multiple factors. Thus, LM represents the combined learning effects on technology capital cost developments. Based on the two-factor learning curve model proposed by [39], technological learning is defined in this article as a function of experience (E) and knowledge stock (KS) as in Eq. (4). Definitions of experience and knowledge stock are detailed in Sections 3.1.1 and 3.1.2.

Table 1
Summary of learning rates for onshore wind in the USA using different model formulations and time periods.

No	Model	Period	Dependent cost variable	Experience metric	LbD rate %	Knowledge stock metric	LbR rate %	Ref.
1	1FLC	1985-1994	Cost of electricity ($ kWh^{-1})	Cumulative electricity production (TWh)	32	-	-	[66]
2	1FLC	1982-2004	Installed project cost ($ kWh^{-1})	Installed capacity (MW)	14.4	-	-	[67]
3	1FLC	1982-2006	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	16	-	-	[68]
4	1FLC	1982-2010	Installed project cost ($ kWh^{-1})	Installed capacity (MW)	8.3	-	-	[67]
5	1FLC	1982-2015	Installed project cost ($ kWh^{-1})	Installed capacity (MW)	6.5	-	-	[69]
6	1FLC	1990-2015	Electricity generation costs ($ kWh^{-1})	Cumulative electricity generation (kWh)	10	-	-	[70]
7	1FLC	2006-2010	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	-10	-	-	[68]
8	1FLC	2010-2020	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	40	-	-	[68]
9	2FLC	1981-1997	Capital cost ($ kW^{-1})	Cumulative capacity (MW)	14.2	Public R&D ($m)	18	[71]
10	2FLC	1985-1995	Generation costs ($ MWh^{-1})	Number of turbines installed	18	Public R&D ($m)	32	[72]
11	2FLC	1986-2002	Investment cost ($ kW^{-1})	Cumulative capacity (MW)	6.89	Public R&D ($m)	8.62	[73]
12	2FLC	2009-2016	Investment costs ($ kW^{-1})	Cumulative installed capacity (MW)	17.5	Public R&D ($m)	37	[74]
13	MFLC*	1999-2006	Wind energy price ($ MWh^{-1})	Generating capacity (MW)	4.19	-	-	[75]

*Additional learning sources were used in MFLC such as economies of scale, market demand dynamics, and supply change dynamics.

Table 2
Summary of learning rates for solar PV in the USA using different model formulations and time periods.

No	Model	Period	Dependent cost variable	Experience metric	LbD rate %	Knowledge stock metric	LbR rate %	Ref.
1	1FLC	1959-1974	Specific sale price ($ kW_p^{-1})	Cumulative installed capacity (MW)	22	-	-	[76]
2	1FLC	1976-1988	Factory price of PV module ($ W_p^{-1})	Cumulative PV sales (W_p)	22	-	-	[77]
3	1FLC	1976-1992	PV module selling price ($ W_p^{-1})	Cumulative PV sales (W_p)	18.4	-	-	[78]
4	1FLC	1979-2005	PV module price ($ W^{-1})	Cumulative production (MW)	19	-	-	[79]
5	1FLC	1990-2000	PV module cost ($ W^{-1})	Cumulative output (shipments)	23	-	-	[80]
6	1FLC	1990-2000	PV module price ($ W_p^{-1})	Cumulative output (shipments)	20	-	-	[80]
7	1FLC	1992-2000	PV module price ($ W_p^{-1})	Cumulated capacity (MW)	32	-	-	[80]
8	1FLC	1992-2000	PV module price ($ W_p^{-1})	Cumulated electricity (GWh)	28	-	-	[80]
9	1FLC	2007-2014	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	12	-	-	[68]
10	1FLC	2014-2020	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	45	-	-	[68]
11	2FLC	1975-2000	Capital cost ($ kW^{-1})	Cumulative capacity (MW)	18.4	Public R&D ($m)	14.3	[71]
12	2FLC	2009-2016	Investment costs ($ kW^{-1})	Cumulative installed capacity (MW)	6.78	Public R&D ($m)	75.21	[74]

$$LM(E,KS)_{t,y} = \left(\frac{E_y}{E_0}\right)_t^{-lbd} \left(\frac{KS_y}{KS_0}\right)_t^{-lbr} \quad (4)$$

where *lbd* represents the learning-by-deployment elasticity, and *lbr* is the learning-by-researching elasticity. Thus, the change in technology capital cost is also defined in this article as a function of experience and knowledge stock as in Eq. (5).

$$C(E,KS)_{t,y} = C(E_0,KS_0)_t \cdot LM(E,KS)_{t,y} \quad (5)$$

In addition, in this work, not all the capital costs associated with a technology are affected by technological learning processes. As argued in the study conducted by Ferioli et al. [81], understanding cost structure is relevant because some cost components may not experience learning (e.g. financial or management costs) while other components do (e.g. domestic-produced and imported electricity generation equipment). For the case of renewable energy technologies (e.g. onshore wind and solar PV in the case of this study), electricity generation equipment (e.g. wind turbines and PV panels) may be affected by technological learning, usually known as 'hardware' costs [82], while other costs may not be reduced through technological learning processes (e.g. assembly, transportation, permitting). Thus, based on the component-based learning model developed by [81], the total technology cost in this article is split into diverse components where α is defined as the share of the total capital cost that can be affected by learning processes for technology *t*. Thus, the model proposed in this article focusses on the cost components affected by learning processes (i.e. technological-based capital cost) and it is redefined as in Eq. (6):

$$\alpha_t \cdot C(E,KS)_{t,y} = \alpha_t \cdot C(E_0,KS_0)_t \cdot LM(E,KS)_{t,y} \quad (6)$$

3.1.1. Definition of experience

Cumulative installed capacity of a particular energy technology is the most common variable used as a proxy in technological learning models to represent experience (see Table 1 and Table 2). The model developed in this article also uses cumulative installed capacity to represent experience. Some studies on energy technologies emphasise that experience is a global public good [21,35,83]. This assumption implies that domestic experience (i.e. local installed capacity) may spill over worldwide and thus the estimated learning rates are valid only to the case where global experience (i.e. global installed capacity) doubles [21]. However, estimates of learning rates based only on international explanatory variables may not be valid in a local setting [22,84]. For instance, quantitative support was found for the argument that improving national learning conditions (e.g. stable regulatory frameworks, skilled workforce) may have a more substantial impact on cost reductions in developing countries than global experience [84]. Thus, technological experience should encompass both a local and a global component. For instance, a study conducted by Ek [21] suggested that in the case of onshore wind power generation plants in Europe, the wind turbine may represent the global component because it is usually acquired in the international market and constitutes around 70% of the total capital costs. Thus, 30% may be attributed to domestic activities such as installation, electric connections, and management [21]. Similarly, a study conducted by Huenteler et al. [84] identified that, for the case of solar PV in Thailand, 57% of the total technology cost corresponds to globally sourced parts (e.g. PV modules and inverters) while 43% accounts for locally sourced parts (e.g. balance of system).

The relative contribution of local and global technological learning to the cost reductions of renewable electricity technologies has been investigated in [22,84–86]. It has been argued that energy companies not only learn from previous internal experience but they may also benefit from external technology deployment and R&D expenditures, described as spillover effects [4,22,87]. Knowledge flow contributes to the spread of basic and applied scientific

developments (i.e. knowledge spillovers) and the diffusion of energy technologies due to the economic benefits of innovation (i.e. experience spillovers) [40]. Knowledge and experience spillovers can be explained by different diffusion processes. For instance, the concept of *technology spillovers* refers to the case when different power generation technologies share one or more major components, which may be affected by technological learning (also known as *cluster effects* [4]). *Intra-industry spillovers* take place when knowledge is diffused among firms within the electricity industry in and within countries [35]. *Sectoral spillovers* occur when advancements in different sectors of the economy drive cost reductions in the power sector [88]. I*nternational spillovers* accounts for the knowledge diffused among countries [40]. Knowledge flow across countries is key in fostering technological innovation in regions different from where it was originally generated. In order to limit the scope of the article, technology and sectoral spillovers are not considered here.

International spillovers in energy systems consider that knowledge may flow across countries in two main forms: as tacit knowledge embodied in traded intermediate or final goods (e.g. solar panels, wind turbines) or information disembodied in patents, blueprints, exchange of ideas among researchers or scientific bodies, and imitation [40]. In order to account for the effect of embodied knowledge flow, the model proposed in this article splits experience into its local and global components, based on cumulative installed capacity (see Fig. 1). Disembodied knowledge stock is addressed in Section 3.1.2 through international knowledge spillover effects.

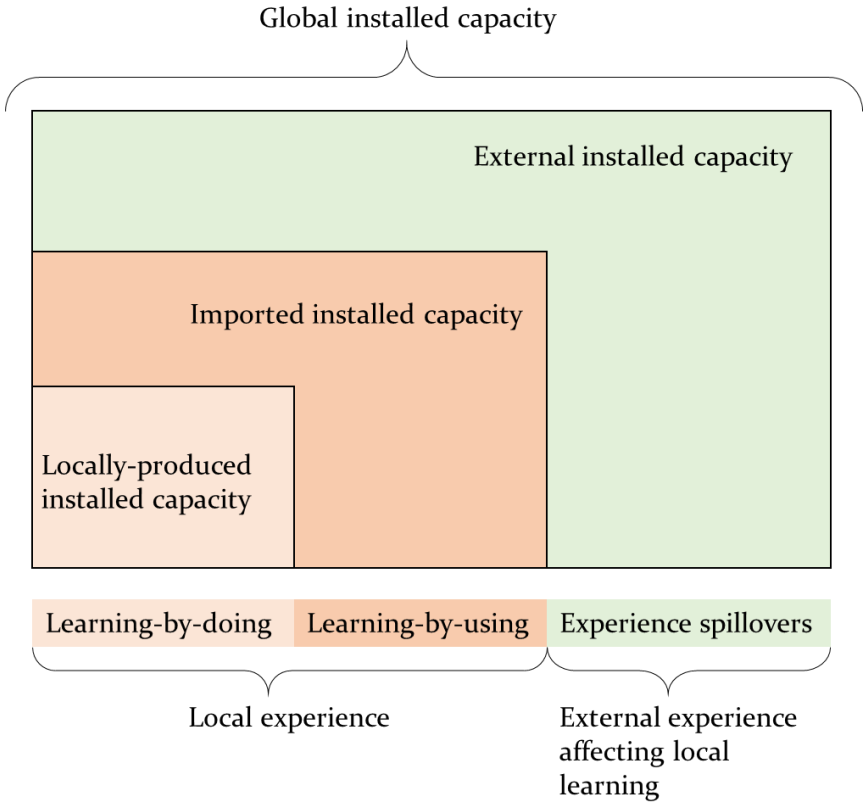


Fig. 1. Conceptualisation of experience based on local and global installed capacity and learning-by-deployment sub-processes.

Local experience is defined in this article as the sum of experience gained through learning-by-doing (i.e. locally produced installed capacity) and learning-by-using (i.e. share of imported installed capacity that is used and assimilated locally). Experience spillovers are conceptualised as the share of external installed capacity that influence learning processes locally (i.e. external experience affecting local learning). The sum of local experience and

external experience affecting local learning represents the total experience (i.e. learning-by-deploying).

Experience gained though learning-by-doing (E_{lbdo}) for technology t at year y is defined in this article as in Eq. (7):

$$(E_{lbdo})_{t,y} = \left(\beta \cdot CC_Dom\right)_{t,y} \tag{7}$$

where β represents the share of domestic content (i.e. locally sourced resources), and CC_Dom accounts for domestic cumulative installed capacity for technology t at year y.

To account for experience gained through learning-by-using two concepts are used within the proposed model: industry experience pool and industry absorptive capacity. What an industry can learn from intra-industry spillovers is a function of both the amount of spillover available to be learned (i.e. industry experience pool, represented by imported installed capacity in this case) and the absorptive capacity of the industry [86]. The concept of absorptive capacity was introduced by [89] to model the flow of scientific and technological knowledge at the firm level [26]. Although absorptive capacity has been extensively applied at the firm level (see [90] for a review), the concept can be extended to a specific industry (i.e. industry absorptive capacity), or to an entire country (i.e. national absorptive capacity) [26]. Based on [91], industry absorptive capacity refers to a broad array of skills that reflect the need to deal with the tacit components of transferred technology and also the need to modify a foreign-sourced technology for domestic applications. Applying the concept of absorptive capacity from [91] to technological experience gained through learning-by-using, industry absorptive capacity is defined in this article as the ratio of locally produced installed capacity to the industry technological frontier, represented in this case as the total domestic installed capacity. Thus, learning by using (E_{lbu}) of technology t at year y is represented in this article as in Eq. (8):

$$(E_{lbu})_{t,y} = \left(\frac{\beta \cdot CC_Dom}{CC_Dom} \cdot \left[(1-\beta) \cdot CC_Dom\right]\right)_{t,y} \tag{8}$$

In addition, based on [26,86], the experience spillover effect is represented in this study as a function of the external installed capacity (i.e. external to the country of interest) and the absorptive capacity of the country. The absorptive capacity of the country is defined in this study as the ratio of domestic installed capacity to the global installed capacity (i.e. international technological frontier, represented by the cumulative installed capacity of the OECD countries). Thus, the experience spillover effect (E_{spill}) of technology t at year y is defined as in Eq. (9):

$$(E_{spill})_{t,y} = \left(\frac{CC_Dom}{CC_Glo} \cdot (CC_Glo - CC_Dom)\right)_{t,y} \tag{9}$$

where CC_Glo and CC_Dom represent global and domestic cumulative installed capacity, respectively. External installed capacity (CC_Ext) is defined as the difference between global and domestic installed capacity (i.e. external experience stock available). Based on the concept of national absorptive capacity [91], the experience spillover coefficient (γ) is introduced in the model developed to account for the ratio of domestic installed capacity to the international technological frontier as previously proposed by [26,86]. Thus, technological experience for technology t at year y is redefined in this article as in Eq. (10):

$$E_{y,t} = \left[\beta \cdot (2-\beta) \cdot CC_Dom\right]_{t,y} + \left[\gamma \cdot CC_Ext\right]_{t,y} \tag{10}$$

where the first term represents local experience, gained through both learning-by-doing and learning-by-using, and the second term accounts for experience spillover effects. When β and γ are set equal to 1, only global experience is used to represent experience. On the other hand,

when $\beta=1$ and $\gamma=0$, only local experience is considered in the definition of experience. A summary of the combination of values for these two parameters and their effects is presented in Table 3. This article focusses on exploring the relative impact of experience represented by global only (i.e. $\beta=1$ and $\gamma=1$), local only (i.e. $\beta=1$ and $\gamma=0$), and when global and local experience are considered (i.e. $0<\beta<1$ and $0<\gamma<1$).

Table 3
Values for parameters used to represent experience.

β^a	γ^b	Experience is represented by
1	1	Global installed capacity
1	0	Domestic installed capacity
0	1	External installed capacity (no domestic experience is assumed)
0	0	No experience is assumed
0-1	0-1	Global and domestic installed capacity

[a] Share of domestic content.
[b] Experience spillover coefficient.

3.1.2. Definition of knowledge stock

Knowledge stock has been modelled using different structures in the literature. In its simplest form, knowledge stock is represented by cumulative R&D expenditures, as proposed by [27]. However, a study conducted by Klaassen et al. [39] extended the knowledge stock concept by incorporating a depreciation rate of knowledge and the time lag between the actual R&D spending and their addition to the knowledge stock. Additionally, studies [30,40] proposed that new knowledge is produced not only by R&D expenditures and previous cumulative knowledge stock but also by international knowledge spillovers. The method used in this article to estimate cumulative R&D-based knowledge stock (*KS*) is based on [92]. Thus, KS of technology t in year y is estimated as in Eq. (11):

$$KS_{y,t} = (1-\rho_t)KS_{y-1,t} + Z_{y,t} \quad (11)$$

where ρ ($0\leq\rho\leq1$) is the annual depreciation rate of KS of technology t in year y-1 (i.e. cumulative previous KS), and $Z_{y,t}$ is defined as the process of new knowledge creation for technology t at year y. Eq. (11) considers that previous knowledge depreciates (i.e. becomes more irrelevant) with time due to several factors such as staff turnover, retirement, and rapid innovation [39]. Each energy technology may have a different rate of depreciation (see Section 3.3.3). Knowledge creation can be modelled as a function of public research, development, and demonstration (RD&D) spending, cumulative previous KS, and international knowledge spillovers as developed in [30,40,92]. Thus, based on [92], $Z_{t,y}$ is defined in this study as in Eq. (12):

$$Z_{t,y} = a \cdot RDnD^{b}{}_{t,y-g} \cdot KS^{c}{}_{t,y-1} \cdot SPILL^{d}_{t,y-g} \quad (12)$$

where parameter a reflects the domestic knowledge dissemination policies factor, g represents the time lag between the RD&D activity and its effects, *RDnD* denotes RD&D investment in technology t in year y-g, *KS* is the cumulative knowledge stock of technology t at year y-1, *SPILL* is the international knowledge spillover effect, and b, c, and d denotes the elasticities of the creation of new knowledge to the independent variables. These elasticities are between 0 and 1 [92]. Also, empirical studies have shown that creation of new knowledge in the energy RD&D sector exhibits diminishing returns (i.e. $b+c+d<1$) [40,93].

Eq. (12) takes into account that RD&D expenditures, both domestic and international, do not have an instantaneous effect on learning, thus it may lead to tangible results after some time

(i.e. parameter *g*). Also, it considers that new knowledge created through public investment RD&D in energy technologies is a 'public good' and therefore it can be applied by almost everyone, with the background and resources needed, as soon as it is publicly available (i.e. knowledge spillovers) [55]. Knowledge dissemination policies (e.g. promotion of institutional collaboration, fostering open-source publications, or improving national innovation systems) may facilitate or hinder the assimilation of new knowledge created. If countries do not invest in building technological capabilities, they may not have the capacity to absorb new knowledge created in other countries [94].

The potential effects of international RD&D-based spillovers on the energy sector have been reported in the literature (see [40,92]). Based on [92], two variables are used in this article to estimate RD&D-based international spillover effects: international knowledge pool (*KP*) and domestic absorption capacity of international knowledge spillovers (δ). Public RD&D-based knowledge is generated globally, either by country-specific efforts or by international cooperation, and it may be available to all countries (i.e. the public-good aspect of public RD&D). However, the process of knowledge creation does not follow the same dynamics and pace everywhere. Thus, countries are exposed to a pool of knowledge generated by other countries where a portion of this knowledge can be absorbed by follower countries [92]. The knowledge gap between the sum of global KS and the country of interest's KS is defined as the international knowledge pool (i.e. the knowledge available to the country of interest). Based on [92], this difference is represented in this study as the distance between domestic public investment in RD&D and the technology frontier. Similar to [30], the technology frontier is denoted by the knowledge stock generated by the OECD countries in the model developed in this study. The absorption capacity of a country represents the portion of the available international knowledge pool that the country of interest may be able to absorb. This value depends on various factors such as specialised human resources, laboratories, patents, energy innovation research groups and institutions, which are influenced by public investment in RD&D of energy technologies [95,96]. Thus, based on [92], international knowledge spillovers (*SPILL*) for technology *t* in country *n* at year *y* is estimated in this article as in Eq. (13):

$$\begin{aligned} SPILL_{t,n,y} &= \delta_{t,n,y} \cdot KP_{t,n,y} \\ &= \frac{RDnD_{t,n,y}}{\sum_{n \in OECD} RDnD_{t,n,y}} \left(\sum_{n \in OECD} RDnD_{t,n,y} - RDnD_{t,n,y} \right) \end{aligned} \tag{13}$$

Thus, the technological-based capital cost of technology *t* in a country *n* at year *y* is redefined in this article using an integrated learning curve model as in Eq. (14):

$$\alpha_t \cdot C(E,KS)_{t,n,y} = \alpha_t \cdot C(E_0,KS_0) \left(\frac{E_y}{E_0} \right)_{t,n}^{-lbd} \left(\frac{KS_y}{KS_0} \right)_{t,n}^{-lbr} \tag{14}$$

where *E* is defined as in Eq. (10) and *KS* as in Eq. (11).

Using a logarithmic transformation, Eq. (14) can be expressed as in Eq. (15):

$$\log\left[\alpha_t \cdot C(E,KS)\right]_{t,n,y} = \log\left[\alpha_t \cdot C(E_0,KS_0)\right] - ldb \cdot \log\left[\left(\frac{E_y}{E_0} \right)_{t,n} \right] - lbr \cdot \log\left[\left(\frac{KS_y}{KS_0} \right)_{t,n} \right] \tag{15}$$

Eq. (15) is used to investigate the relative impact of using different technological learning approaches on technological-based capital costs for onshore wind and solar PV in the USA. The relative impact is revealed by estimating the corresponding learning rates. Learning-by-deploying (LbD) and learning-by-researching (LbR) rates are estimated based on the relationship between technological-based cost developments as a dependent variable, and

experience (using cumulative installed capacity as a proxy) and knowledge stock (using public RD&D expenditure as a proxy) as independent variables.

3.2. Data sources and periods of analysis

To estimate experience and knowledge stock, data collected on capital cost, cumulative installed capacity, and public expenditures in RD&D for onshore wind and solar PV are summarised in Table 4.

Table 4
Data collected for onshore wind and solar PV.

Item	Unit	Period	References
Domestic (USA) cumulative installed capacity	MW[a]	1974 – 2020	[12,97]
Global (OECD countries including USA) cumulative installed capacity	MW	1974 – 2020	[12,97]
Domestic (USA) annual public RD&D expenses	$m[b]	1974 – 2020	[98–103]
Global (OECD countries including USA) annual public RD&D expenses	$m	1974 – 2020	[98–103]
Domestic (USA) capital cost	$ kW^{-1}[c]	1983 – 2020 (onshore wind) 1974 – 2020 (solar PV)	[6,104–107]

[a] Megawatt (MW).
[b] Millions of USA dollars in constant 2020 prices and purchasing power parities rates ($m)
[c] 2020 USA dollars per Kilowatt (2020 $ kW^{-1}).

Monetary values were reported in 2020 USA dollars. They were estimated accounting for inflation based on the average annual consumer price index (CPI) in the USA [108]. A brief overview of the data used to estimate experience and knowledge stock is described in this section.

Onshore wind

Installed wind power project costs over time in the USA, based on capacity-weighted average, are depicted in Fig. 2. Data collected by the Lawrence Berkeley National Laboratory include 1,128 completed onshore wind projects accounting for around 88% of total land-based wind power generation installed capacity in the USA at the end of 2020 [107].

In Fig. 2, a declining trend in installed wind power project costs is observed from the 1980's (i.e. the beginning of the wind industry in the USA) to the early 2000's. However, from 2004 to 2010 costs increased significantly. This trend is attributed mainly to an increase in the cost of imported wind turbine components due to a weakening U.S. dollar, rising labour costs, changes in warranty provisions among turbine manufacturers, and increasing commodities and energy prices [106,109]. From 2010 to 2020 a new decreasing trend in costs values can be observed in Fig. 2. Some empirical studies have suggested that historical cost changes for specific technologies may be better explained by two or more periods with different learning rates (see [61,68,110]). This may be shown as learning curves with discontinuities [9]. Following this idea, this article estimates learning rates for onshore wind power generation technology for three different periods: 1989-2004 (first period of cost reduction trend), 2004-2010 (cost increase trend), and 2010-2020 (second period of cost reduction trend). Although data on installed wind power project costs are available from 1983 in [107], 1989 is selected as the initial modelling value due to data availability on cumulative installed capacity for onshore wind technologies for the USA (see Fig. 3).

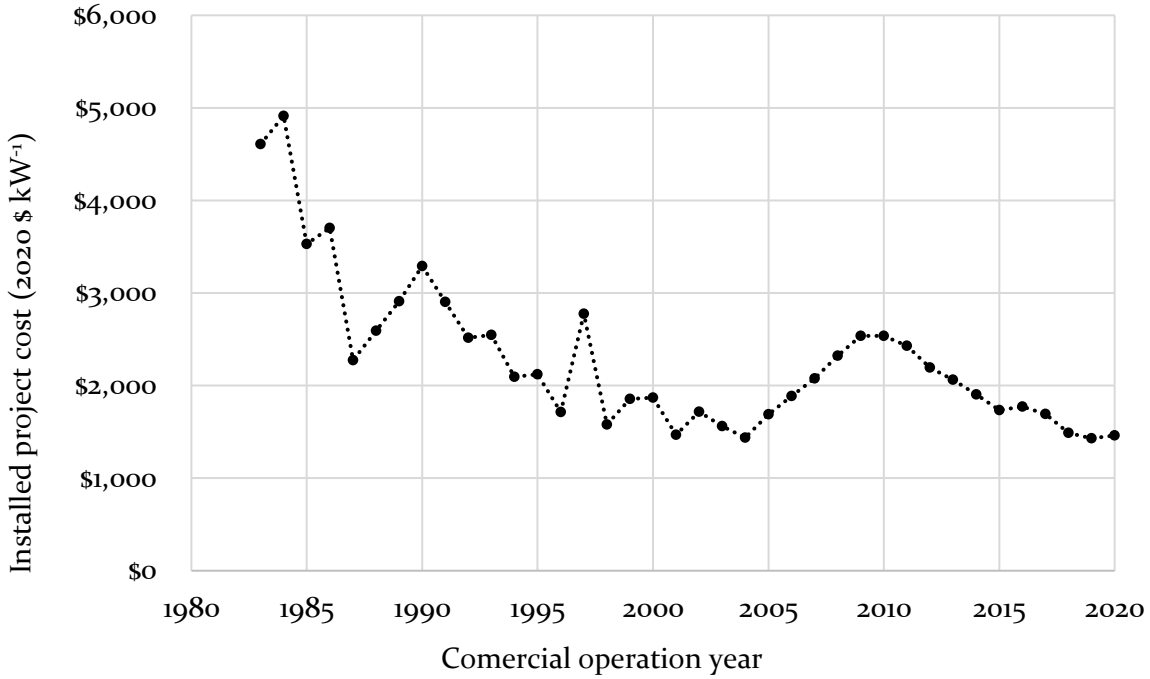


Fig. 2. Installed wind power project costs over time in the USA. Constructed with data from [106,107].

As the definition of experience in this article is based on global and local installed power generation capacity, the development of onshore wind cumulative installed capacity is depicted in Fig. 3. Although wind energy utilisation dates back more than five thousand years ago [111], available data regarding onshore wind power capacity within the IEA Electricity Information Statistics database [112] start from 1981 for OECD countries (1 MW) and 1989 for the USA (1337 MW domestic and 1650 MW international at the time). In 2020, the OECD installed capacity for wind was 368 GW, while USA domestic installed capacity accounted for 118 GW (around 32% of the OECD installed capacity) [12].

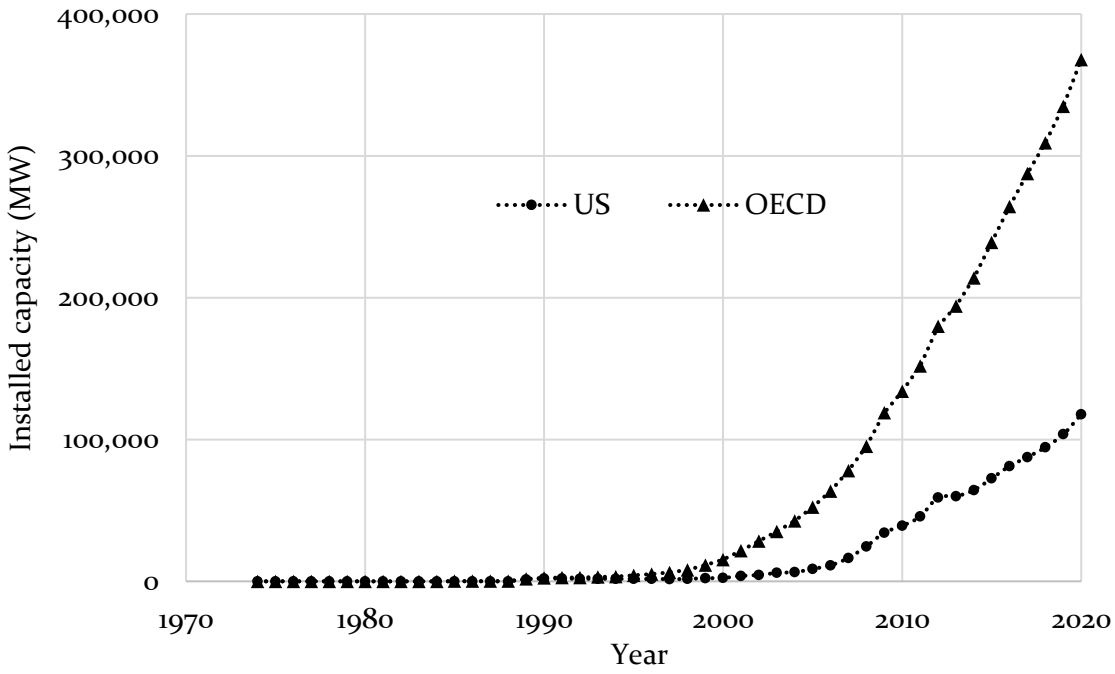


Fig. 3. Domestic (USA) and international (OECD) wind power generation installed capacity in MW. Constructed with data from [12,97].

In order to estimate knowledge stock, the analysis of public investment in RD&D is needed. Fig. 4 shows the development of annual public investment in RD&D for wind energy for the OECD countries and USA from 1974 to 2020. It is worth noting that the effects of different global and domestic events are visually evident throughout the period analysed. For instance, increasing RD&D expenditures for wind technologies after the main energy crises (1973, 1979, and 2008) are clearly shown in Fig. 4. Furthermore, the effects of international agreements on environmental concerns (e.g. the UNFCCC treaty adopted in 1992, and the Paris Agreement and Mission Innovation adopted in 2015) are evident in the figure accounting for a rise in public investment in RD&D for clean energy technologies in general and wind technologies in particular. On the other hand, the low oil prices along the second half of the 1980's had a negative effect on annual public investment RD&D in alternative energy sources of fossil fuels, including wind.

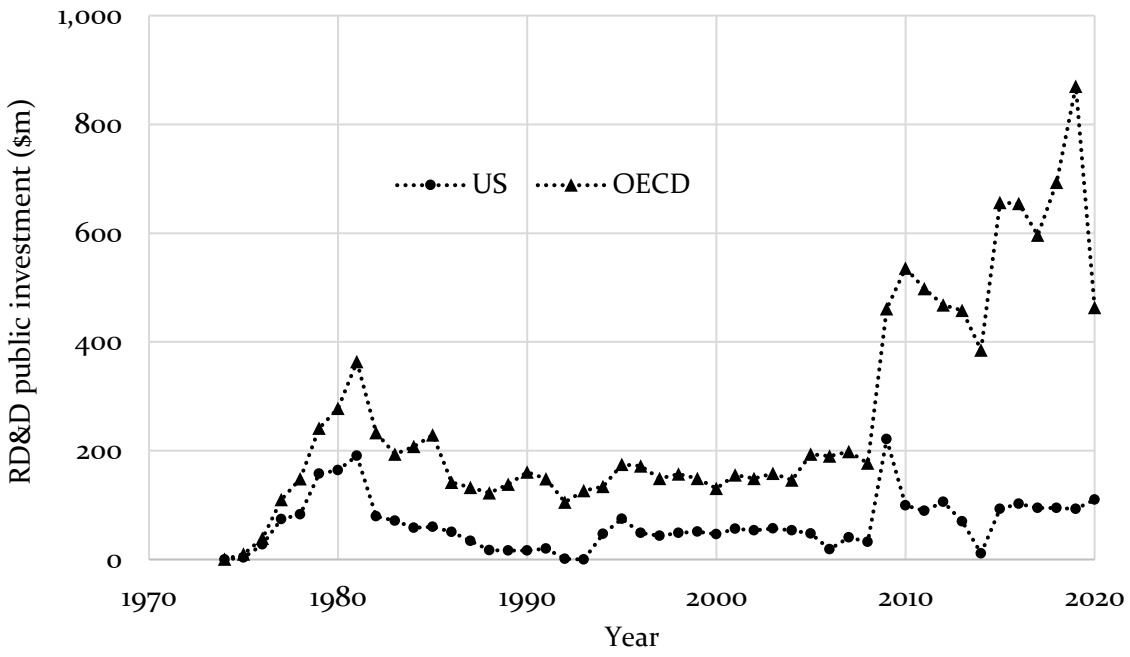


Fig. 4. Domestic (USA) and international (OECD) public investment in RD&D for wind technologies in 2020 $m and PPP. Constructed with data from [103].

Solar PV

Solar PV capital costs in the USA from 1974 to 2020 are depicted in Fig. 5. Unlike wind, the authors of this article did not have access to an integrative historical database for the whole period of analysis. Thus, learning rates for solar PV power generation technology are estimated for two different periods: 1992-2009 (based on data from [104,105]), and 2010-2020 (based on data from [6]). As for wind, the period of study for solar PV was defined based on data availability on installed capacity for both the USA and OECD countries (i.e. 1992 set as the initial modelling year).

Like onshore wind, power generation installed capacity for solar PV has rapidly increased in recent years (see Fig. 6). In 2020, the OECD installed capacity for solar PV was 344 GW, while USA domestic installed capacity accounted for 74 GW (around 21% of the OECD installed capacity) [6].

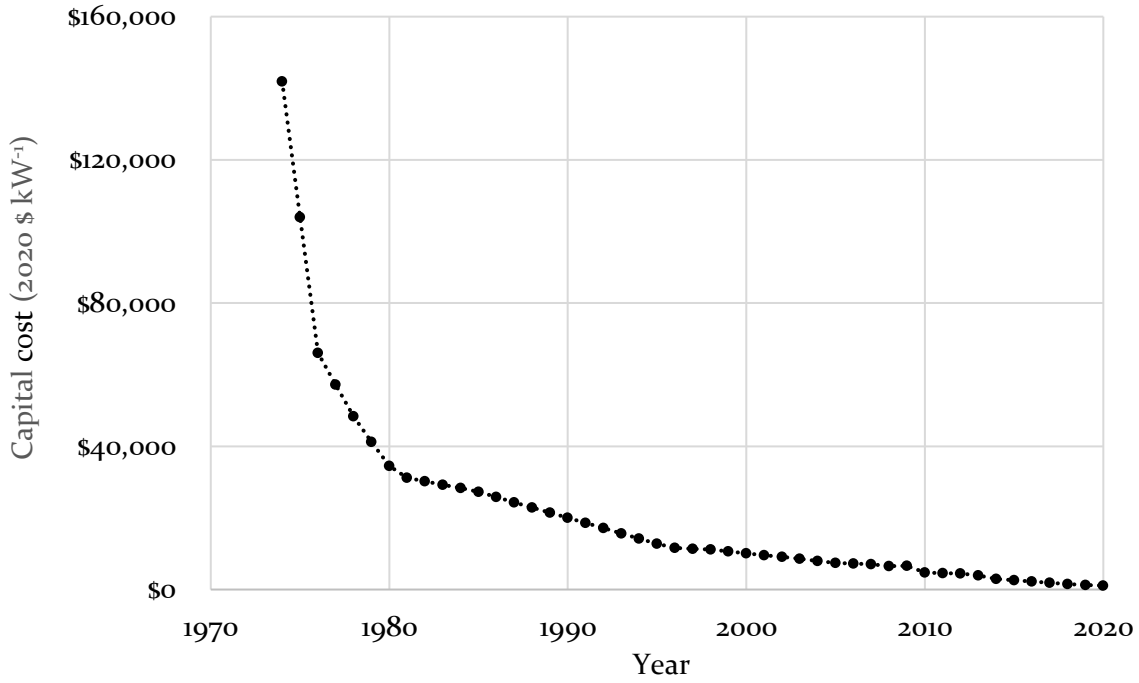


Fig. 5. Installed solar PV costs over time in the USA. Constructed with data from [6,104,105].

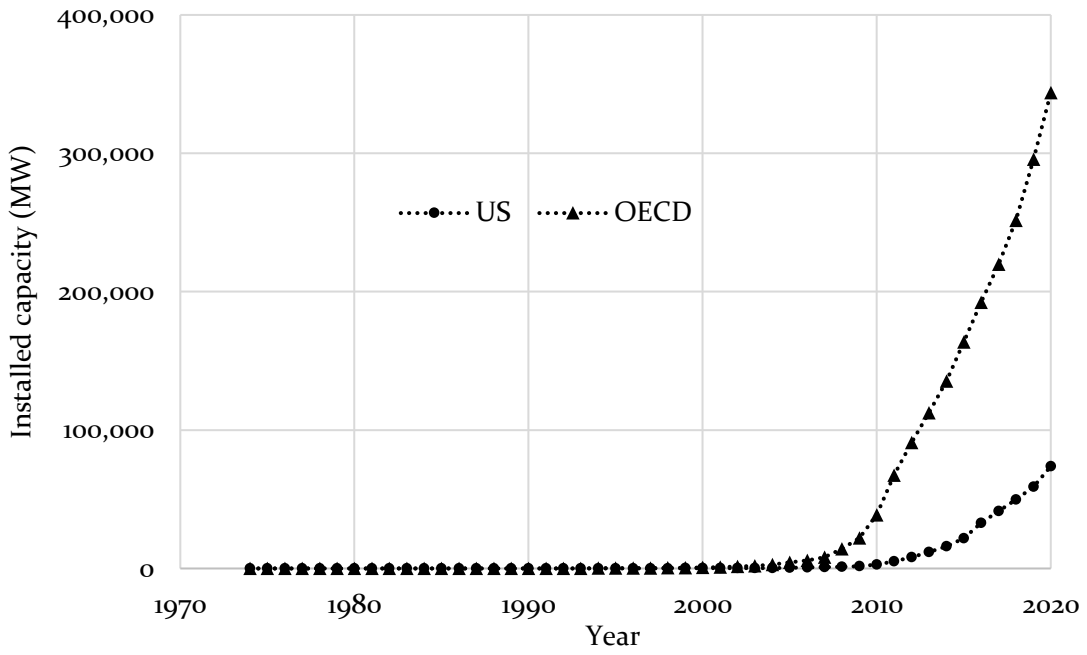


Fig. 6. Domestic (USA) and international (OECD) solar PV power generation installed capacity in MW. Constructed with data from [12,97].

Fig. 7 shows the development of annual public investment in RD&D for solar PV energy for the OECD countries and the USA from 1974 to 2020. Similar to wind, the effects of global and domestic events are noticeable throughout the period analysed. It is evident that there is a decreasing trend in public RD&D expenditure for solar PV worldwide, and no expenditure at all in the USA from 2016 to 2020.

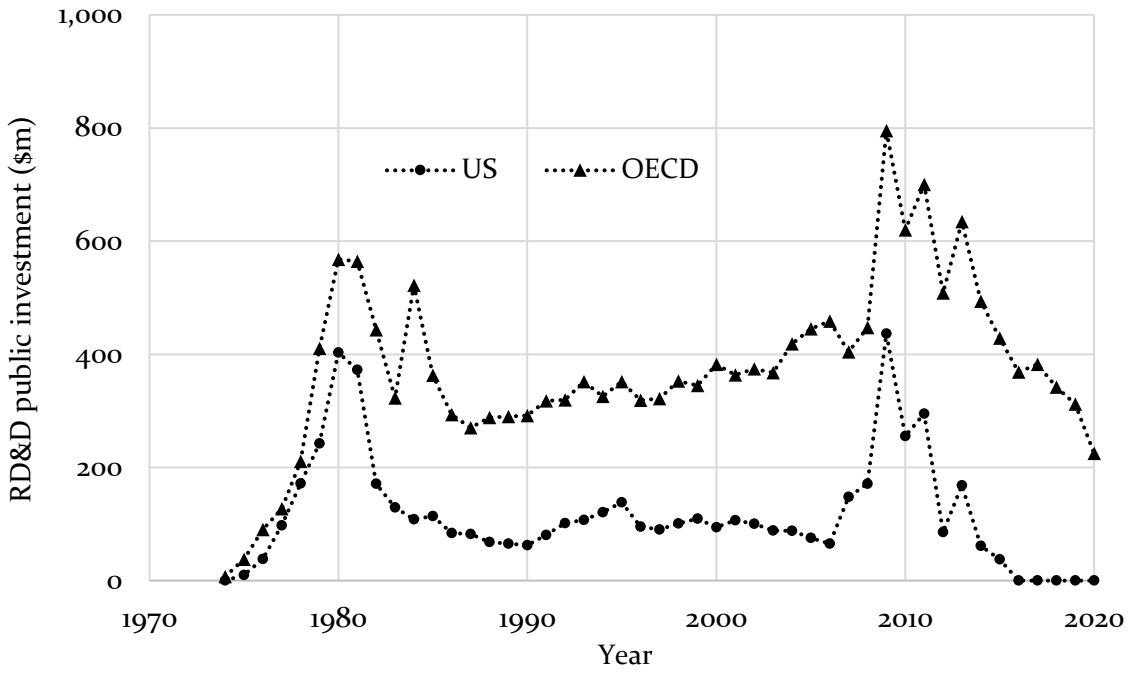


Fig. 7. Domestic (USA) and international (OECD) public investment in RD&D for solar PV in 2020 MM$ and PPP. Constructed with data from [98–103].

3.3. Parameters setting

To empirically estimate learning rates using Eq. (15), parameters considered in Eqs. (6, 7, 8, 10, 11, 12 and 14) must be set. Thus, based on previous studies these parameters are set and explained as follows.

3.3.1. Capital cost structure

Total capital cost structure differs among electricity generation technologies. For instance, for land-based wind projects not only the cost of the turbine (i.e. rotor, nacelle, and tower) is considered but also balance of system (BOS) costs and 'soft' costs. BOS costs for a wind power plant refer to infrastructure components other than the turbines (e.g. wiring, substation hardware). Soft costs encompass non-infrastructure costs associated with the plant (e.g. permitting) [113]. Similarly, for utility-scale solar PV the PV modules and inverters integrate the main hardware costs, while racking and wiring are encompassed within BOS costs, and soft costs include installation labour, system design, permitting, among others [82,114].

In order to define the share of the total technology cost that can be affected by learning processes (i.e. α) the study distinguishes between technological-based costs and non-technological costs. The former accounts for those that are affected by technological learning processes and the latter encompass costs that may not have a direct change due to learning processes. In the case of onshore wind, this study assumes that technological-based costs include the turbine (i.e. rotor, nacelle, and tower) and electrical infrastructure, while non-technological costs encompass foundation, turbine transportation, site access and staging, assembly and installation, project management, development, construction finance, and contingency. Similarly, technological-based costs for solar PV include the module, inverter, and hardware balance of system, while non-technological costs include permitting, inspection and interconnection, engineering, procurement and construction, labour costs, and other soft costs. Based on historical reviews on the cost structure of wind and solar energy technologies [82,115–123], this study assumes that technological-based costs account for 78% (i.e. α=0.78) and 62% (i.e. α =0.62) of the total technology capital cost for onshore wind and solar PV, respectively (see Fig. 8).

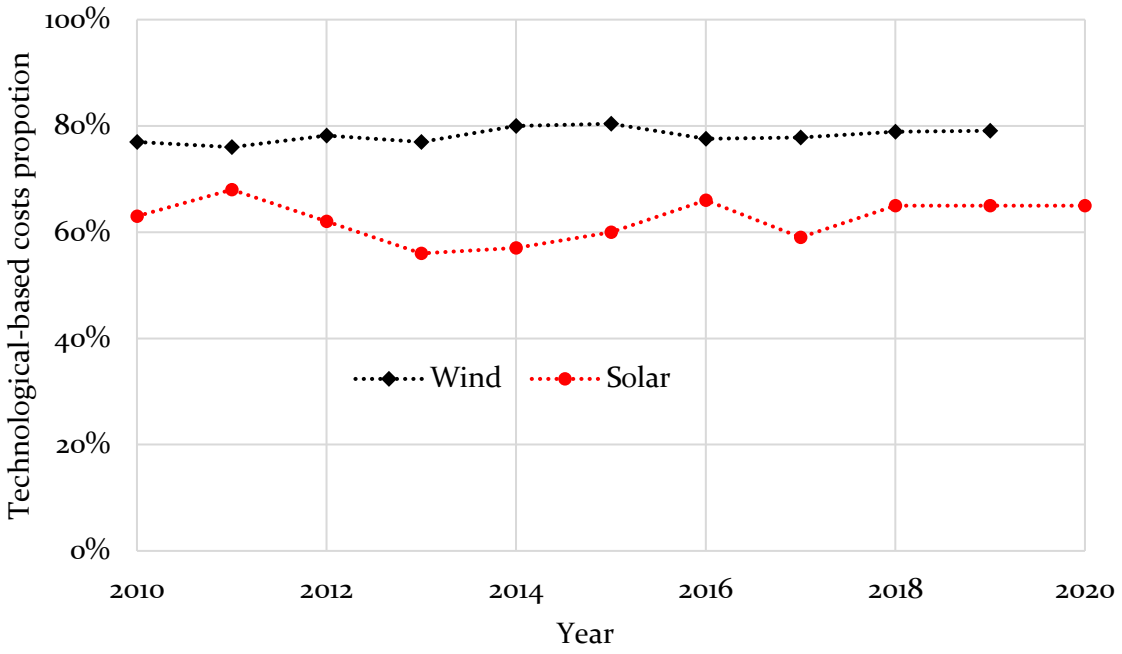


Fig. 8. Modelled trend of technological-based costs as a proportion of total capital cost for onshore wind and solar PV in the USA. Constructed with data from [82,115–123].

3.3.2. Domestic content and international trade

The renewable sector in the USA is highly reliant on foreign supply chains. However, imported content varies widely depending on the technology and the type of components. For instance, due to high transportation costs, large components for wind technologies such as tower and blades are more likely to be manufactured domestically [113]. Although domestic manufacturing content in the USA is strong for some wind turbine components (e.g. towers, blades and hubs), the wind industry also relies significantly on imports for some equipment (e.g. most components internal to the nacelle) [107]. It has been reported that imports of wind-related equipment into the USA declined substantially from around 80% in 2006-2007 to approximately 30% in 2012-2013 [124]. To estimate the share of domestic content for onshore wind over time, this study followed the approach presented in [124] (p. 24), based on estimated imports of tracked wind-related equipment into the USA, and by using updated data from [107]. Estimated share of domestic content (i.e. parameter β) for onshore wind in the USA varies from 22% in 2007 to 68% in 2020 (see Fig. 9), which is consistent with values previously reported in [124]. Due to lack of available data, 22% is assumed for years before 2007.

In contrast to the USA wind industry, the USA solar manufacturing supply chain is mainly reliant on imports for key components (e.g. inverters, cells, wafers, and many balance-of-system components) [125]. Although the first PV device was invented in New Jersey (USA) in 1954 and the USA government supported its development and deployment through the implementation of different policies (e.g. public RD&D), China became the dominant global player in the production of PV modules and cells since the 2010's, with significant help from government subsidies, affecting the global supply chain [126,127]. To estimate the share of domestic content for solar PV over time, this study used the ratio of USA solar PV annual production, obtained from [128], to the annual installed capacity of solar PV in the USA, presented in [97], from 1993 to 2012. Unlike onshore wind, the estimated share of domestic content for solar PV technologies in the USA declined from 100% in 2009 (i.e. all capacity was met domestically) to 27% in 2012 (see Fig. 9). Due to lack of available data, 27% is assumed for years after 2012.

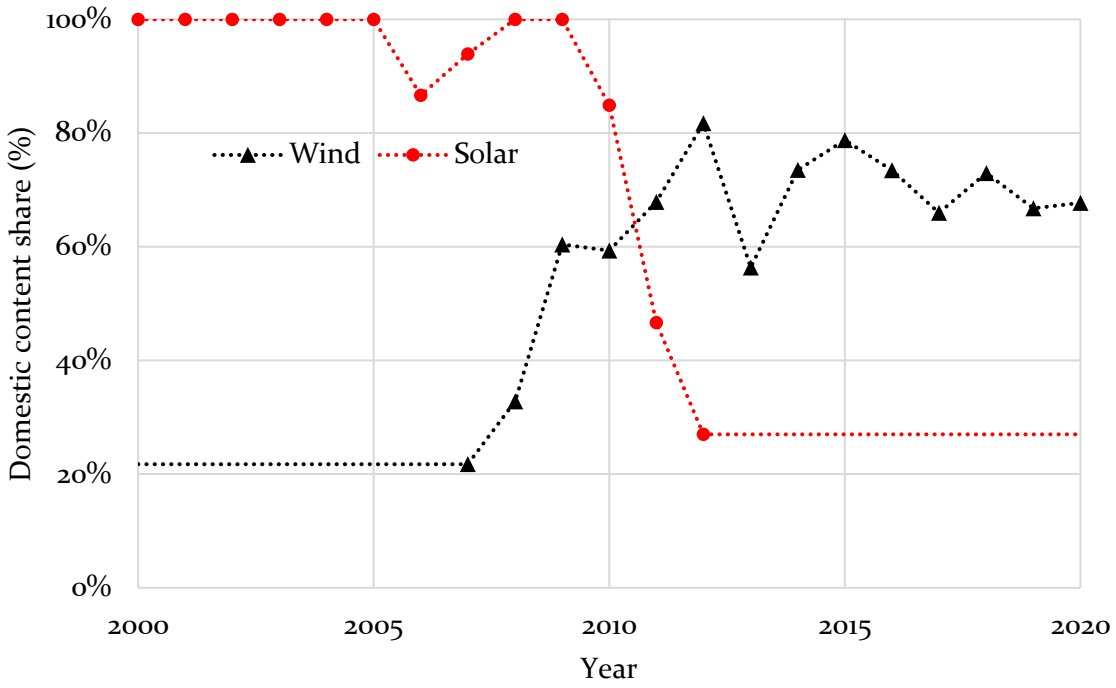


Fig. 9. Estimated share of national content for onshore wind and solar PV in the USA from 2000 to 2020. Constructed with data from [97,107,128].

3.3.3. Annual depreciation rate of knowledge and time lag for RD&D investment effects

Assumptions regarding annual depreciation rate of KS and time lag between energy RD&D expenditures and effects on KS are also needed to conduct this investigation. An examination of knowledge depreciation rates for the energy sector was carried out in a study conducted by Grubler et al. [129], where they found that typical rates ranges from 10% to 40%. However, in the case of renewable energy technologies these rates may be lower from the cited range. For instance, for wind technology, depreciation rates of 2.5% [71], 3% [43,130], 5% [39] and 10% [92] have been used in different studies.

In the case of the time lag between public investment RD&D in energy technologies and the gain of knowledge, most scholars have reported 2 to 5 years as the most suitable values for this parameter (see [39,43,71,131]). A sensitivity analysis regarding knowledge depreciation rates and time lags presented in [55], has found higher sensitivity of KS with respect to the obsolescence of knowledge among energy technologies (primarily due to changing innovation rates). However, 10% as the depreciation rate of previous KS and 3 years as the time lag between public investment in RD&D for energy technologies is commonly used in the literature (see [55,92]). Based on these previous studies, values of 10% for ρ and 3 year for g are assumed within this study.

3.3.4. International knowledge spillover effects

Constants and coefficients for international spillover effects have been empirically estimated and used in [40,92,132]. For instance, elasticity coefficients b, c, and d in Eq. (12) were set equal to 0.2, 0.55, and 0.15, respectively in [92] to investigate the influence of public RD&D and international spillover effects on the development of renewable energy sources. These elasticities represent the ratio of percentage change of the creation of new knowledge (i.e. Z) with respect to the change in the explanatory variables considered in Eq. (12) (i.e. *RDnD*, *KS*, and *SPILL*). When d is set to 0.15, an increment of 1% of international knowledge spillovers (*SPILL*) increases the output of Z (i.e. creation of new knowledge) by 0.15%.

A sensitivity analysis of the elasticity of new knowledge creation to international knowledge spillovers carried out in [92] revealed that 0.15 is a suitable value for *d*, as initially proposed in [40]. Due to lack of research on empirical foundation of the value of the elasticity of knowledge generation to international spillovers, this was chosen lower than the elasticity of knowledge production to domestic investments (e.g. equal to 0.18 in [40] and 0.20 in [92]), and about one third of the elasticity with respect to former KS (e.g. equal to 0.53 in the model without spillovers in [132] and 0.55 in [92]). Thus, to investigate the effect of international knowledge spillovers using the proposed model, parameters *b*, *c*, and *d* are set to 0.2, 0.55, and 0.15, respectively based on [92].

Due to lack of empirical evidence to define parameter *a*, this is set equal to 1 when KS is considered in the model. Thus, future research is suggested to gain knowledge regarding the quantitative role of innovation policies in the creation of new RD&D knowledge. Table 5 summarises the parameter setting assumptions used in this study.

Table 5
Parameter settings assumptions used to estimate experience and knowledge stock.

Parameter	Description (units)	Onshore wind	Solar PV
α	Share of the total technology capital cost affected by learning processes (%)	78	62
β	Share of domestic content (%)	22-82	27-100
γ	Experience spillover coefficient (-)	0-1	0-1
δ	Domestic absorption capacity of international knowledge spillovers (-)	0-1	0-1
ρ	Annual depreciation rate of knowledge stock (%)	10	10
g	Time lag between the RD&D activity and its effects (a)	3	3
a	Domestic knowledge dissemination policies factor (-)	1	1
b	Public RD&D spending elasticity (-)	1, 0.2	1, 0.2
c	Knowledge stock elasticity (-)	0, 0.55	0, 0.55
d	International knowledge spillover elasticity (-)	0, 0.15	0, 0.15

3.4. Alternative model structures definition

Model structures were defined to analyse the effects of alternative definitions for the learning factors. Model structures for the two selected renewable energy technologies are summarised in Table 6. Parameters were set based on Section 3.3. The first three model structures, 1FLC-A to 1FLC-C, assume experience as the only source of learning and only technological-based cost components are affected by this process. Model 1FLC-A assumes that only global experience (i.e. OECD installed capacity in this case) leads the process of learning. Model 1FLC-B assumes that only local experience (i.e. domestic installed capacity) affects learning processes. Model 1FLC-C estimates the joint effect of global and local learning by considering learning-by-doing, learning-by-using, and international experience spillovers, based on the new definition of experience explained in Section 3.1.1. The last two models in Table 6, 2FLC-D and 2FLC-E, include knowledge stock as a second source of learning. Following the definition of experience from Model 1FLC-C, Model 2FLC-D was used to analyse the impact of domestic public investment in RD&D for onshore wind and solar PV technologies, while Model 2FLC-E also considers the effect of international knowledge spillovers.

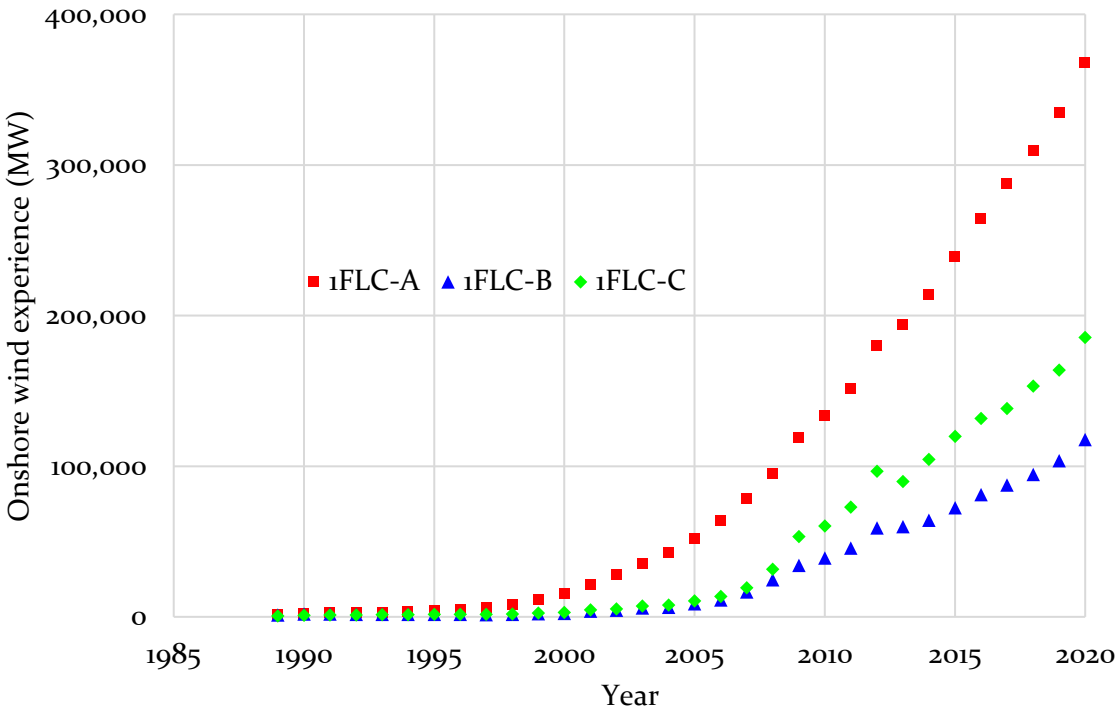
Table 6
Alternative model structures definition and specifications. See Section 3.3 for a description of each parameter.

Model	Description	Purpose	α	β	γ	ρ	g	a	b	c	d
1FLC-A	Only global experience leads to learning / Learning processes affect some components	To analyse the impact of global experience	0-1	1	1	-	-	-	-	-	-
1FLC-B	Only local experience leads to learning / Learning processes affect some components	To analyse the impact of local experience	0-1	1	0	-	-	-	-	-	-
1FLC-C	Local and global experience lead to learning / Learning processes affect some components	To analyse the impact of local and global experience	0-1	0-1	0-1	-	-	-	-	-	-
2FLC-D	Local and global experience, and knowledge stock lead to learning / Learning processes affect some components	To analyse the impact of RD&D-based knowledge stock	0-1	0-1	0-1	0.1	3	1	1	0	0
2FLC-E	Local and global experience, and knowledge stock lead to learning / Learning processes affect some components / International knowledge spillovers effect is included	To analyse the impact of RD&D-based knowledge stock and knowledge spillover effects	0-1	0-1	0-1	0.1	3	1	0.2	0.55	0.15

3.5. Estimated experience and knowledge stock

Experience and knowledge stock for onshore wind and solar PV in the USA are estimated using the model structures defined in Section 3.4. Fig. 10 depicts estimated experience based on global, local, and considering a joint effect of global and local cumulative installed capacity (i.e. model structures 1FLC-A to 1FLC-C) for (a) onshore wind, and (b) solar PV (see Section 5.1 for a discussion on this variable).

(a)



(b)

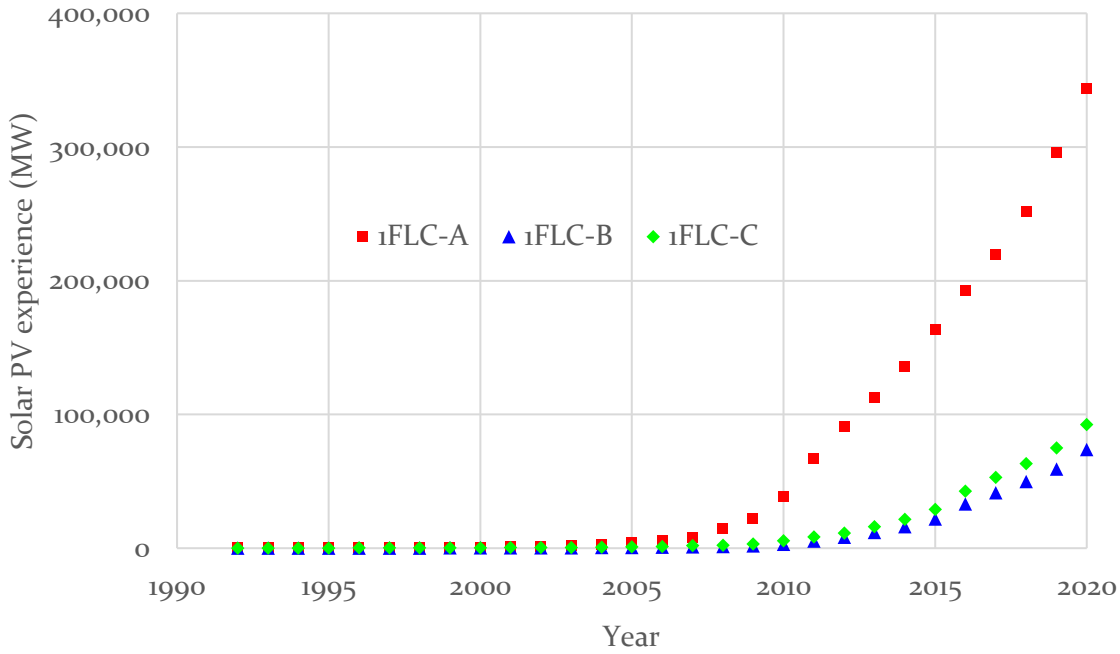
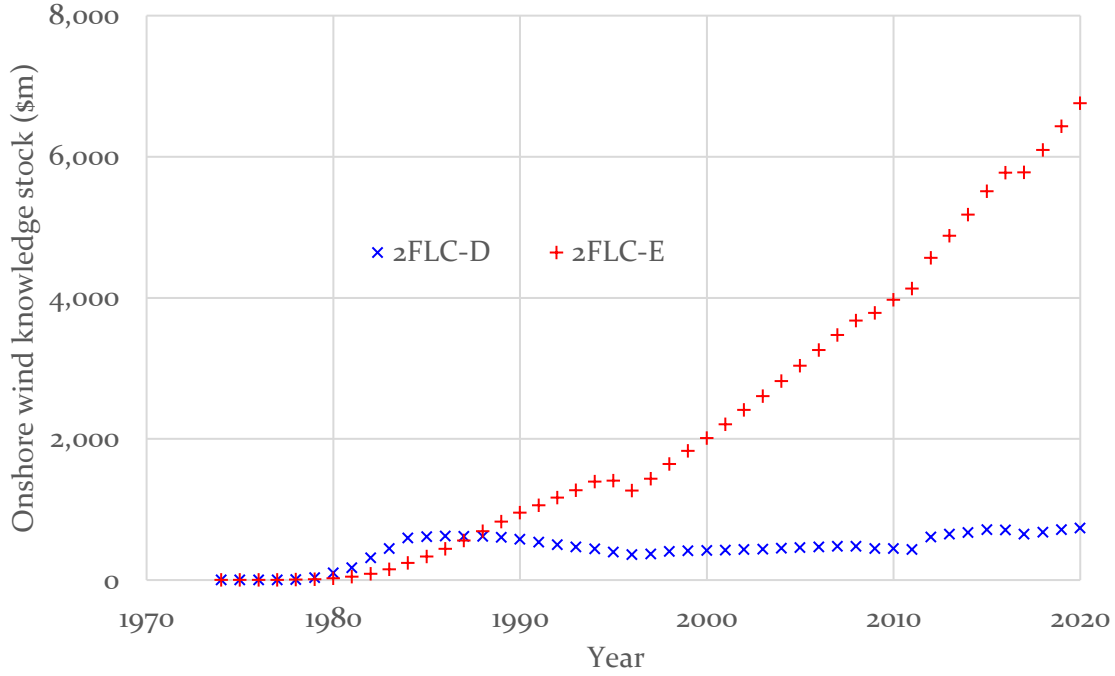


Fig. 10. Estimated experience for (a) onshore wind and (b) solar PV in the USA, using alternative model structures. Constructed with data from [12,97,107,128].

Fig. 11 shows the estimated knowledge stock based on domestic public investment in RD&D only (i.e. 2FLC-C) and including international knowledge spillover effects (i.e. 2FLC-D) for (a) onshore wind, and (b) solar PV (see Sections 5.2 and 5.3 for a discussion on this variable).

(a)



(b)

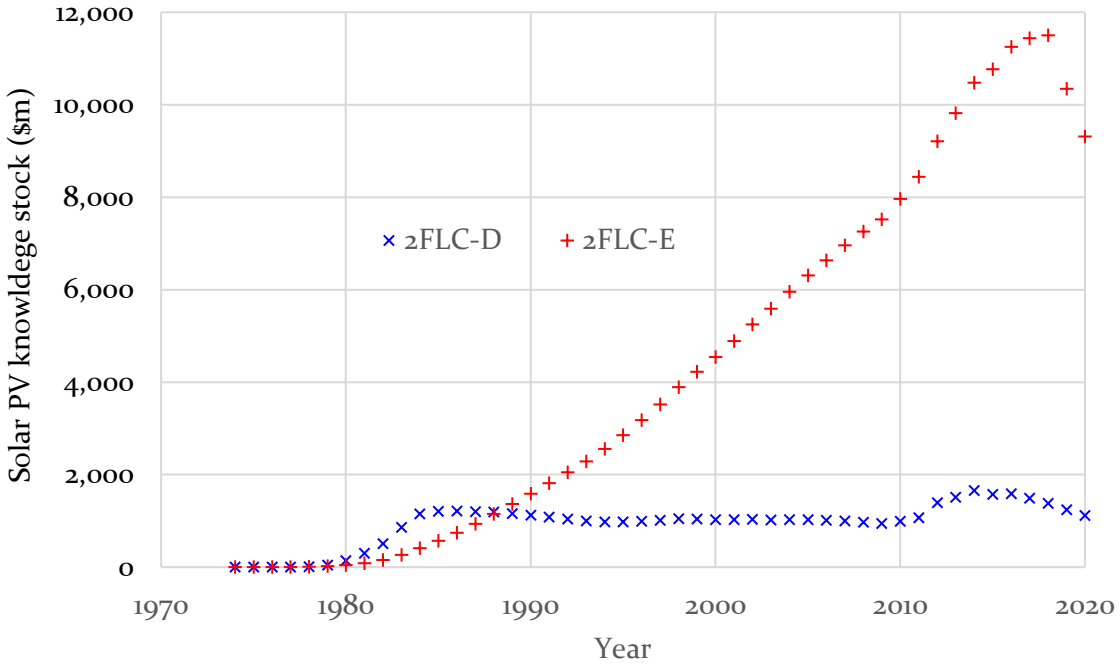


Fig. 11. Estimated knowledge stock for (a) onshore wind and (b) solar PV in the USA, using alternative model structures. Constructed with data from [92,98–103].

Estimated technological experience and knowledge stock were used as input variables to estimate the corresponding LbD and LdR rates using Eq. (15). Learning rates were estimated by applying an ordinary least-squares (OLS) method of regression analysis using Python 3.8.

4. Results

The regression results for onshore wind and solar PV in the USA are presented and described in this section. These include estimated values for learning-by-deploying (LbD) and learning-by-researching (LbR) rates for the different periods analysed, adjusted R-squared values for each model structure, significance levels, as well as the root mean square errors (RMSEs) for estimated learning rates were used to estimate technological-based costs over time.

4.1. Onshore wind

The empirical test results for onshore wind in the USA for different periods and different model structures are summarised in Table 7. The range of values empirically estimated for the learning rates varies considerably. When experience was considered as the only source of learning (i.e. 1FLC models), LbD rates varied from 13.93% to 22.64% for the period 1989-2004. When KS was also included within the model formulation (i.e. 2FLC models), LbD rates ranged from -5.52% to 17.13%, and LbR rates varied from -47.88% to 41.78% for the same period. Negative learning rates, estimated based on empirical data, represent an increase in costs and negative impacts on technology diffusion. Thus, for the period 2004-2010 all values for estimated learning rates were negative (see Table 7). On the other hand, estimated LbD rates presented less variability for the period 2010-2020 when only experience was considered in the model formulation, ranging from 32.11% to 33.96%. However, when KS was also included, LbD rates varied significantly from 2.89% to 31.38%, and LbR rates from 2.30% to 51.36%.

Fig. 12 depicts observed (solid line) and estimated (dotted lines) technological-based costs for onshore wind in the USA for three periods: (a) 1989-2004, (b) 2004-2010, and (c) 2010-2020. Estimated cost developments were obtained by using the alternative model structures defined in Section 3.4.

4.2. Solar PV

Estimated learning rates for solar PV in the USA for different periods and alternative model structures are summarised in Table 8. In the case of solar PV, estimated LbD rates vary from 11.20% to 16.04% for the period 1992-2009 if experience is encompassed as the only source of learning. When KS was also included, LbD rates varied from 3.96% to 15.72%, and LbR rates varied from 31.51% to 46.19% for the same period analysed. For the period 2010-2020, LbD rates ranged from 28.30% to 40.38% when only experience was considered, and from 33.19% to 36.66% when also KS was included. Furthermore, LbR rates varied from -127.91% to 46.19% for the same period.

Fig. 13 depicts observed (solid line) and estimated (dotted lines) technological-based costs for solar PV in the USA for two periods: (a) 1992-2009 and (b) 2010-2020. Estimated cost developments were obtained by using the alternative model structures defined in Section 3.4.

5. Discussion

The aim of this article is to investigate the potential impact of diverse sources of learning and the definition of explanatory variables on technological-based capital cost changes for onshore wind and solar PV. Thus, findings on the relative contribution of different sources of learning and definitions of these factors are presented and discussed one by one in this section. Also, previous literature is discussed considering the findings derived from the empirical results presented in Section 4.

Table 7
Empirical test results for onshore wind in the USA.

Model	Year	LbD[a] elasticity (-)	(p)[b]	LbR[c] elasticity (-)	(p)[b]	Adj. R^2 (-)	LbD rate (%)	LbR rate (%)	RMSE[d] ($ kW^{-1})
1FLC-A	1989-2004	-0.2164	(0.000)***	-	-	0.685	13.93	-	250.41
	2004-2010	0.4991	(0.000)***	-	-	0.970	-41.34	-	88.27
	2010-2020	-0.5986	(0.000)***	-	-	0.968	33.96	-	46.73
1FLC-B	1989-2004	-0.3703	(0.005)***	-	-	0.409	22.64	-	401.21
	2004-2010	0.3054	(0.000)***	-	-	0.967	-23.58	-	100.78
	2010-2020	-0.5702	(0.000)***	-	-	0.948	32.65	-	70.28
1FLC-C	1989-2004	-0.3237	(0.000)***	-	-	0.663	20.10	-	258.25
	2004-2010	0.2641	(0.000)***	-	-	0.935	-20.09	-	142.07
	2010-2020	-0.5587	(0.000)***	-	-	0.946	32.11	-	83.53
2FLC-D	1989-2004	-0.2711	(0.000)***	0.5644	(0.060)*	0.727	17.13	-47.88	305.65
	2004-2010	0.2779	(0.000)***	1.5476	(0.014)**	0.985	-21.24	-192.34	55.88
	2010-2020	-0.5432	(0.000)***	-0.0335	(0.842)	0.939	31.38	2.30	85.02
2FLC-E	1989-2004	0.0775	(0.768)	-0.7805	(0.133)	0.697	-5.52	41.78	264.70
	2004-2010	0.0296	(0.709)	1.5338	(0.031)**	0.978	-2.07	-189.54	58.87
	2010-2020	-0.0422	(0.836)	-1.0398	(0.029)**	0.968	2.89	51.36	41.46

[a] LbD = learning-by-deploying. [b] *, ** and *** denote significance levels better than 10% (i.e. 0.05≤p<0.1), 5% (i.e. 0.01≤p<0.05), and 1% (i.e. p<0.01), respectively. [c] LbR = learning-by-researching. [d] RMSE = Root Mean Square Error.

5.1. Impact of local, global, and combined experience

To investigate the relative potential effects of global and local experience on technological-based cost changes three model structures have been analysed and compared for both renewable technologies (i.e. models 1FLC-A, 1FLC-B, and 1FLC-C). When LbD rates were estimated based on global experience only (i.e. $\beta=1$ and $\gamma=1$) and local experience only (i.e. $\beta=1$ and $\gamma=0$), a remarkable difference can be highlighted between the two technologies. In the case of onshore wind, global experience better explains technological-based cost changes (i.e. higher Adj. R^2 values with similar significance levels and smaller statistical error). On the contrary, cost changes are better explained by local experience in the case of solar PV. The contrasting behaviour between technologies is consistent with the portion of domestic content to international trade found in the literature (see Section 3.3.2).

Table 8.
Empirical test results for solar PV in the USA.

Model	Year	LbD[a] elasticity (-)	(p)[b]	LbR[c] elasticity (-)	(p)[b]	Adj. R^2 (-)	LbD rate (%)	LbR rate (%)	RMSE[d] ($ kW^{-1})
1FLC-A	1992-2009	-0.1714	(0.000)***	-	-	0.944	11.20	-	1170.30
	2010-2020	-0.7461	(0.000)***	-	-	0.861	40.38	-	673.17
1FLC-B	1992-2009	-0.2523	(0.000)***	-	-	0.938	16.04	-	1212.01
	2010-2020	-0.4799	(0.000)***	-	-	0.900	28.30	-	544.22
1FLC-C	1992-2009	-0.2405	(0.000)***	-	-	0.944	15.35	-	1135.74
	2010-2020	-0.5461	(0.000)***	-	-	0.931	31.51	-	455.84
2FLC-D	1992-2009	-0.2468	(0.000)***	-0.8942	(0.161)	0.948	15.72	46.19	1260.53
	2010-2020	-0.5820	(0.000)***	-0.6761	(0.001)***	0.980	33.19	-59.79	218.98
2FLC-E	1992-2009	-0.0583	(0.045)**	-0.5459	(0.000)***	0.986	3.96	31.51	340.75
	2010-2020	-0.6590	(0.000)***	1.1885	(0.010)**	0.968	36.66	-127.91	318.33

[a] LbD = learning-by-deploying.
[b] *, ** and *** denote significance levels better than 10% (i.e. 0.05≤p<0.1), 5% (i.e. 0.01≤p<0.05), and 1% (i.e. p<0.01), respectively.
[c] LbR = learning-by-researching.
[d] RMSE = Root Mean Square Error.

Although the most common approach used for the estimation of learning rates has been when global experience is assumed as the only source of learning that explains technology cost changes for onshore wind and solar PV (see [11] for a review), the findings presented in Section 4 suggest that the definition of experience should include both a national and an international component, as previously discussed by [133]. Thus, a new definition of experience has been developed in this article to account for learning through local and global learning processes, and the interaction between them (see Section 3.1.1). The new definition encompasses three learning sub-processes: learning-by-doing, learning-by-using, and international experience spillovers. Based on experience gained through these three complementary sub-processes, total experience may increase in relation to domestic capabilities and external experience affecting local learning processes. Findings suggest that if the country of interest possesses a strong domestic supply chain (i.e. manufacturing capability) and leads the development of the technology under study (i.e. the country is a technological leader), experience may be better represented by global experience (i.e. global installed capacity in this case). However, if the country's supply chain significantly relies on imports and follows technological trends (i.e. the country is a technological follower), experience may be limited to its domestic capacity. By applying the new definition of experience, this distinction is evident in Fig. 10: a strong

domestic manufacturing capacity and relatively strong domestic absorptive capacity lead to 'more experience' in the case of onshore wind (see Fig. 10(a)), while a dependent supply chain and a relatively weak domestic absorptive capacity in the case of solar PV result in 'less experience' gained through learning-by-deploying processes (see Fig. 10(b)). Thus, the results obtained and presented in Section 4, empirically validate that technological-based cost changes may be better explained when both sources of experience are explicitly included within the model formulation (i.e. $0< \beta <1$ and $0<\gamma<1$) compared to global-only or local-only settings (i.e. similar Adj. R^2 values with similar or higher significance levels and similar or smaller statistical errors). Also, these findings may be relevant when policymakers are interested in exploring the effects of implementing regulations regarding domestic content for renewable energy technologies. Furthermore, the new definition of experience proposed in this article, quantitatively accounts for the relative contribution of learning-by-doing, learning-by-using, and experience spillovers in total experience gained through learning-by-deploying processes.

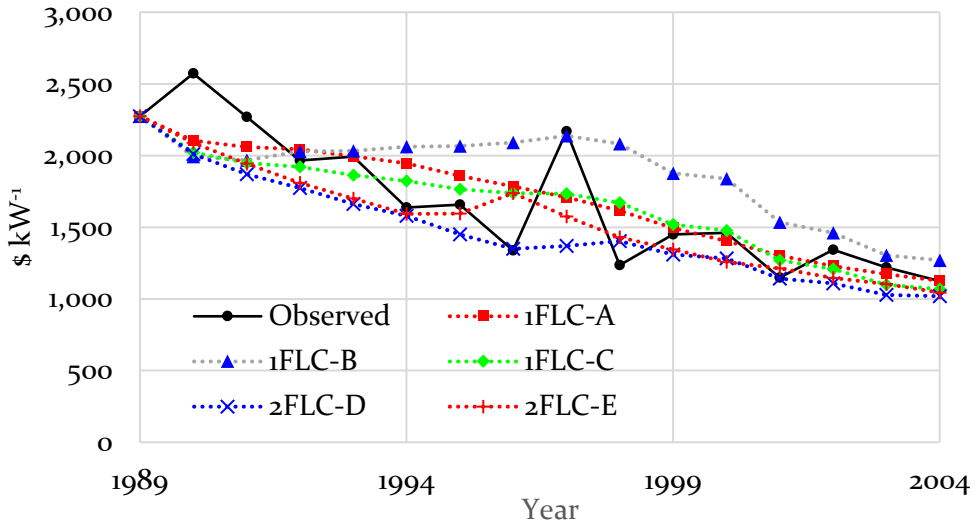
5.2. Impact of RD&D-based knowledge stock

When knowledge stock was modelled as a second source of learning, using domestic public RD&D expenditures as a proxy (i.e. model 2FLC-D), a better goodness of fit was found compared to 1FLC models (i.e. higher Adj. R^2 values with similar significance levels). However, insights, derived from the empirical results presented in Section 4, vary between the two renewable technologies when KS was included in the model. LbD rates in the case of solar PV tend to increase compared to 1FLC models, while LbR shows a positive effect on cost reductions in the period 1992-2009 and a negative effect in recent years (i.e. a negative LbR rate in the period 2010-2020). On the other hand, LbD rates for onshore wind tend to decrease when KS is included in the model formulation, while LbR had a negative impact on cost reductions from 1989 to 2010 and a positive impact in the period 2010-2020. It is worth noting that almost all LbD rates were found to be positive, except for the period of increasing costs for onshore wind from 2004 to 2010. These findings show that, for onshore wind and solar PV in the USA, experience often has had a positive impact on costs reductions, while domestic knowledge stock has had different impacts on these technologies depending on the period of analysis. This may be explained by the fact that public RD&D expenditures have increased just for specific periods of time (e.g. after energy crises), while installed capacity has followed an increasing trend over time. If no RD&D is allocated for a specific technology, KS decreases over time due to knowledge depreciation, creating a negative effect on costs reductions for that specific technology (see Section 3.5). Thus, poorly developed or delayed innovation policy adoption could have a negative impact on the rate of cost reduction [11]. Further research is needed to investigate the impact of stable funding for clean energy technologies as previously suggested by [47].

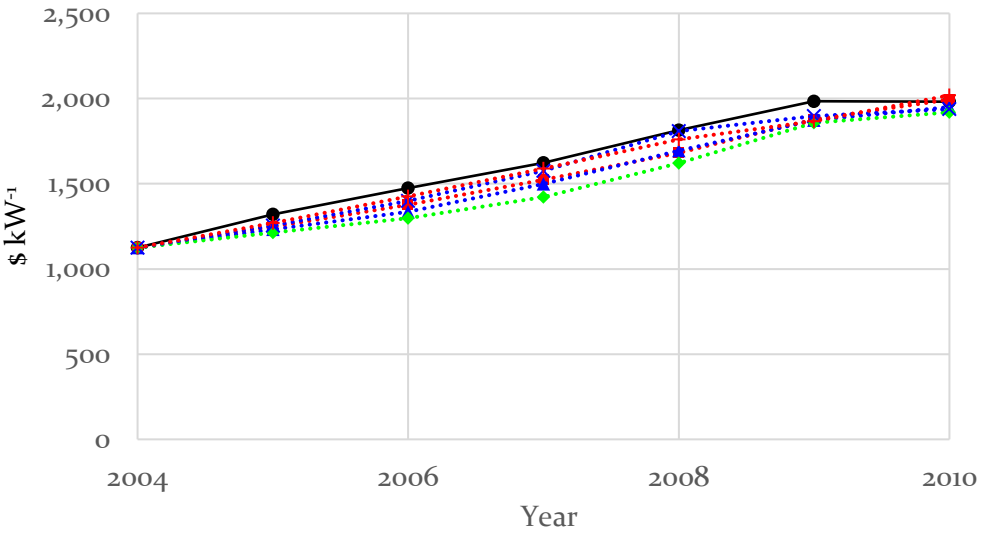
5.3. Impact of RD&D expenditures and spillovers

When not only domestic public RD&D expenditures but also international knowledge spillover effects are explicitly modelled (i.e. 2FLC-E), results also vary between the two technologies. Although LbD rates tend to increase through the different periods analysed for both technologies, LbR rates increased for onshore wind, from 41.78% in the period 1989-2004 to 51.36% in the period 2010-2020; and decreased for solar PV, from 31.51% in the period 1992-2009 to -127.91% in the period 2010-2020 (i.e. a negative effect in cost reductions). Also, compared to the 2FLC-D model, better statistical explanation was found for solar PV (i.e. higher Adj. R^2 values with similar significance levels and smaller statistical errors) and 'worse' statistical explanation for onshore wind (i.e. lower Adj. R^2 values with lower significance levels yet smaller statistical errors).

(a)



(b)



(c)

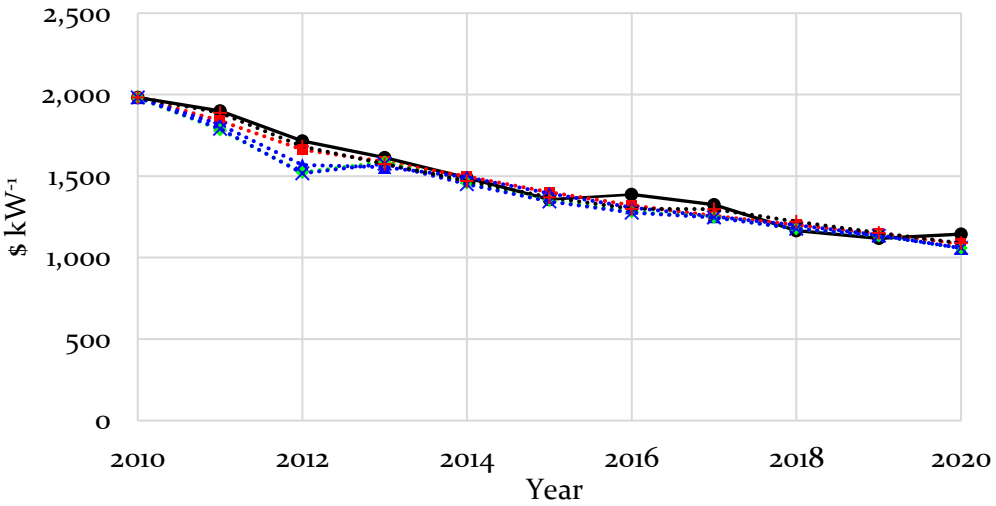
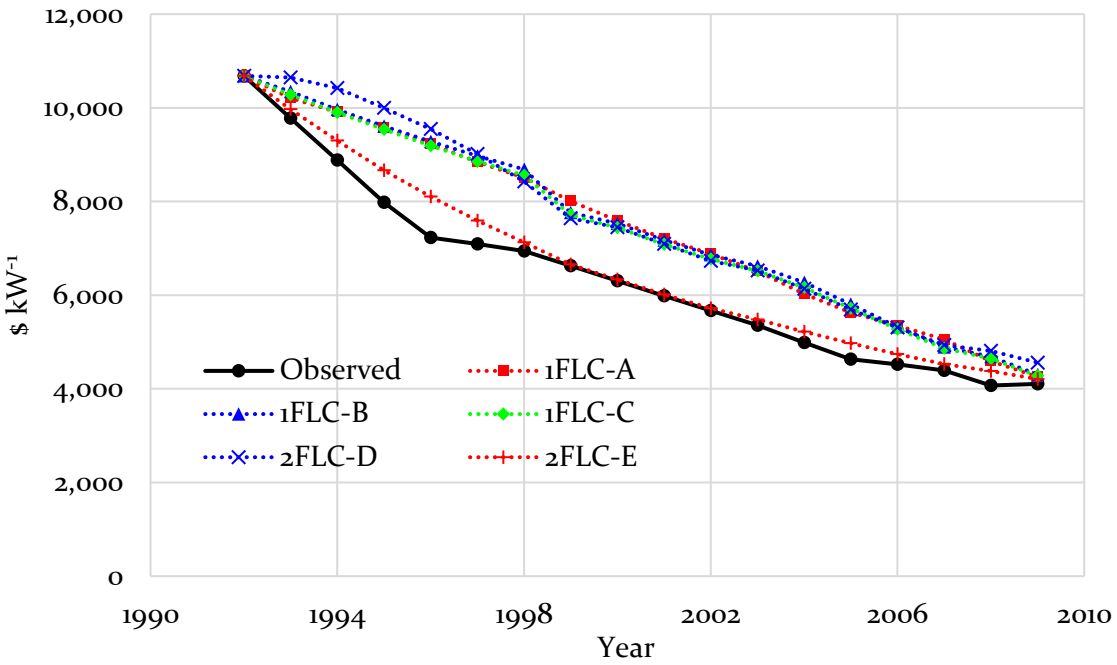


Fig. 12. Technological-based costs for onshore wind in the USA for: (a) 1989-2004, (b) 2004-2010, and (c) 2010-2020. Observed (solid line) and estimated (dotted lines).

(a)



(b)

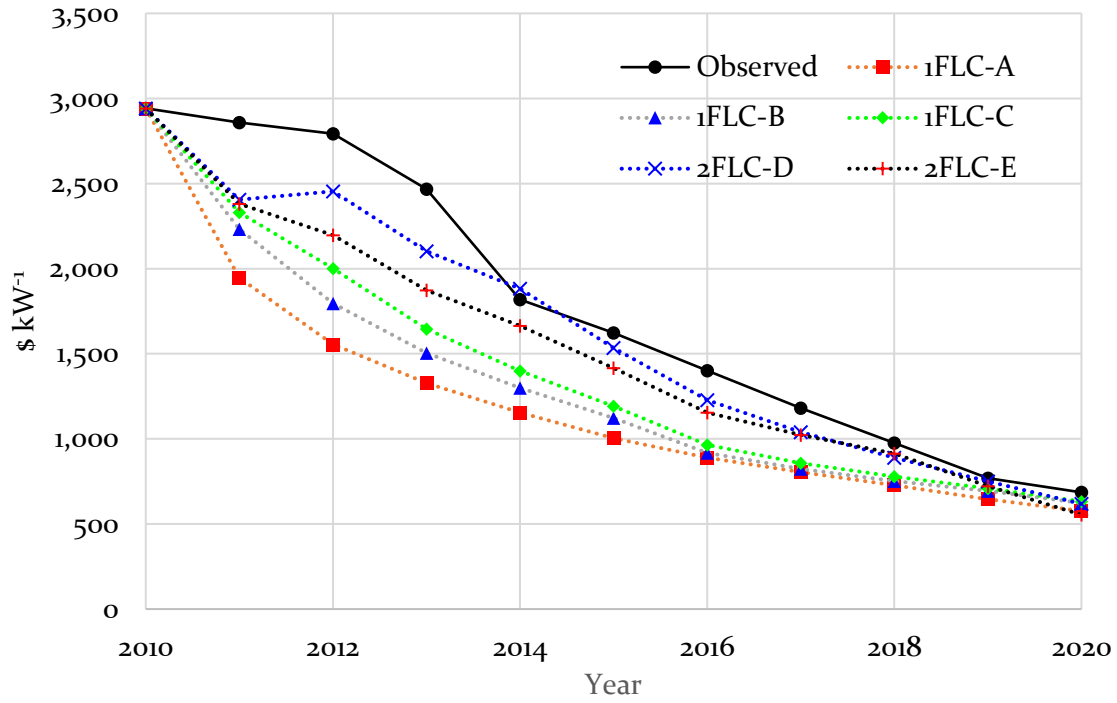


Fig. 13. Technological-based costs for solar PV in the USA for: (a) 1992-2009 and (b) 2010-2020. Observed (solid line) and estimated (dotted lines).

When compared to 1FLC models, estimated learning rates using the 2FLC-E model show larger variability with relatively lower significance levels (see Section 4). However, this model formulation outperformed the 1FLC models in terms of explanatory power (i.e. higher Adj. R^2 values). This finding shows that international knowledge flows between countries may play a key role in fostering the development of renewable energy technologies, empirically demonstrated in this article by observing higher Adj. R^2 values with smaller statistical error compared to 1FLC models. However, the way KS is defined and modelled needs further

attention to improve the statistical significance obtained within this article, based on parameter settings presented in Section 3.3.4.

5.4. Impact of periods analysed

In this article, the periods of analysis were chosen based on technology cost trends and data availability (see Section 3.2). These periods include different technological development stages. The analysis in this article includes demonstration stage, market formation, and full commercialisation for wind onshore and solar PV in the USA, based on the stages of development suggested by [11]. Estimated LbD rates for both technologies suggest that an accelerated learning process has taken place in more recent years (i.e. during the full commercialisation stage). Empirical results obtained in the last period of analysis (i.e. 2010 to 2020) show higher learning rates for both technologies compared to previous periods. For instance, using the 1FLC-A model for the first period of cost reductions for onshore wind (i.e. 1989-2004), the technological-based cost declined 13.93% per each doubling of cumulative installed capacity; and during the second period of cost reductions (i.e. 2010-2020) the LbD rate was estimated to be higher (i.e. 33.96%), showing a more rapid decline in technological-based costs for each doubling of experience. Similarly, the estimated LbD rate for solar PV from 1992 to 2009 using the 1FLC-B model formulation was found to be 16.04%, while from 2010 to 2020 was 28.33%. Estimated LbD rates follow this pattern in all model formulations used in this analysis (see Table 7 and Table 8). These findings suggest that learning does not necessarily decrease as technologies mature, as has been suggested by other recent study [68].

Empirical findings suggest that learning factors (i.e. experience and knowledge stock) may have different effects on cost changes depending on the development stage of the technology. When learning rates are employed to forecast future cost projections, the estimations based on historical cost changes may be misleading if development stages of the technology are not considered. For instance, when KS was considered in the model formulation (i.e. 2FLC models) to estimate learning rates for solar PV from 1992 to 2009, learning-by-researching presented a larger effect on cost reductions than learning gained by experience (i.e. higher LbR rates compared to LbD rates). On the contrary, in the period from 2010-2020, learning-by-researching had a negative impact on cost reductions (i.e. negative LbR rates) and thus, based on the empirical results, learning-by-deploying has led cost reductions in recent years. Similarly, when the 2FLC-D model was used to estimate learning rates for onshore wind, the empirical results show that experience has had a stronger effect on cost reductions (i.e. LbD rate of 31.38%) than knowledge stock (i.e. LbR of 2.30%) in recent years (i.e. period from 2010 to 2020). These findings highlight the relative importance of public investment in RD&D for energy technologies during the early stages of technological development, while investments from the market may play a more significant role during more advanced technological stages, as previously suggested by [1]. However, a generalisation of these findings may not be applicable to all periods and all model structures conducted in this study. For instance, when the 2FLC-E model is used to estimate learning rates for onshore wind from 2010 to 2020, KS presented a larger effect on cost reductions than experience (i.e. LbD rate of 51.36% compared with a LbR rate of 2.89%, but not statistically significant).

5.5. Policy implications

Learning curves are often used in energy-economic models to predict future technology cost developments and investigate plausible trajectories of energy systems. Policymakers can use learning curves as an analytical tool to explore the potential effects of public investment decisions aimed at guiding technology deployment and transformations in energy systems [1]. For instance, future technology cost developments, estimated by using learning curves, may be used to design the change of subsidies to emerging technologies (e.g. offshore wind, solar thermal) to attain a competitive level and plan a phasing-out strategy for these incentives during the full commercialisation stage of the technologies [1]. Also, the use of learning curves

may help decision makers to guide public and private investments in RD&D throughout the different technological development stages. However, model-based investment decisions may vary significantly based on the definition of endogenous technological change. As presented in Section 4, what learning factors to consider and how these are formulated may result in a large range of values for learning rates and thus in different technology cost predictions. Findings in this article suggest that the application of historical learning rates to specific technologies may result in arguably misleading policy decisions if context-dependent sources of learning and parameters are not previously analysed and defined accordingly within the model formulation. For instance, if a learning rate estimated based on data from one country (e.g. USA) or a specific technology (e.g. onshore wind) is used to estimate future cost developments for another country (e.g. India) or another technology (e.g. geothermal) with different technological dynamics, unrealistic results are likely to be obtained. When learning curves are used for policy analysis it is paramount to explicitly establish what sources of learning are to be included and how they are formulated. Thus, reliable contextual-based estimates of learning rates are needed if energy systems models are used to generate meaningful policy-oriented results [134].

The empirically estimated learning rates presented in this study exhibit large variability when the two selected sources of learning are explicitly modelled (i.e. experience and knowledge stock), and alternative definitions of these learning factors are formulated. These learning rates include positive and negative values (i.e. increasing and decreasing trends) showing cost variations over time. As estimations are affected by the model structure (i.e. inclusion of different sources of learning and explanatory variables) no single estimation can be considered robust for all cases. However, the 2FLC-D model generally outperformed compared to other model structures when looking at goodness of fit (i.e. Adj. R^2 values), significance levels (i.e. p-values), and the statistical error when estimated learning rates were used to forecast technological-based cost developments (i.e. RMSEs) for both technologies at different periods in time (i.e. see empirical results in Section 4). This finding suggests that, when data are available, the 2FLC-D model structure may be used to explore the effects of learning processes on future technological-based cost developments. Thus, the impact of technological progress on cost reductions can be explored by accounting for different learning sub-processes, global and local experience, and domestic public investment in RD&D for energy technologies. Although it has been argued that learning-by-deploying and learning-by-researching effects are challenging to be separated, it also has been recognised that the impact of R&D on future technology costs can have a large added value, mainly in early development stages of the technology [19,135,136], as empirically demonstrated with solar PV in this study. Also, consideration of public investment in RD&D for energy technologies adds a controllable policy variable to the model and reduces, to some extent, the issue of bias due to omitted variables compared to 1FLC models, as previously discussed in [15].

5.6. Limitations and potential future research

Although valuable insights, derived from the empirical results presented in Section 4, have been discussed within this article, the analysis conducted has some limitations. First, this article has investigated the effects of alternative model structures on technological-based cost developments based on the share of the total technology cost that can be affected by learning processes (i.e. parameter α). However, non-technological costs (e.g. soft costs) also play a role in the total technology capital cost and they should be included in model-based energy policy analysis. Non-technological costs may follow different dynamics and may vary in different regions, explained by other processes (e.g. paperwork requirements, permitting processes). Thus, future research may be oriented towards integrating complementary approaches (e.g. endogenous learning processes and exogenous administrative processes) to explain the complete picture of technology capital cost developments over time. Furthermore, parameter

α may vary based on the definition of technological-based capital costs (i.e. components to be affected by learning processes). Although this parameter was set based on historical reviews on the cost structure of wind and solar energy technologies in the USA (see Section 3.3.1), different values may lead to different future technology cost predictions (see the sensitivity analysis provided in Appendix A).

Second, the exploration of alternative approaches to model technological progress has revealed the relative effects of different learning sources and explanatory variables on technological-based cost developments over time for onshore wind and solar PV in the USA. However, the analysis may be also applied to other countries or regions by explicitly establishing the learning sources and periods of analysis to be used for the investigation. Also, its application may be extended to different energy technologies at different technological maturity stages (e.g. offshore wind, clean hydrogen). In addition, the approach adopted in this study may be used as an analytical tool to conduct comparative research between countries, technologies, and periods to extend its applicability and improve the generalisability of the findings.

Third, by untangling learning-by-deploying sub-processes (i.e. learning-by-doing, learning-by-using, and experience spillovers), valuable insights on technological experience were discussed in Section 5.1. However, the new definition of experience proposed in this article integrates the three sub-processes to quantitatively estimate total experience and then estimate LbD rates. Future research can focus on investigating the relative contribution of each one of these sub-processes in cost developments. For instance, learning-by-doing, learning-by-using, and experience spillover rates (e.g. *lbdo*, *ldu*, *spill*) may be estimated separately by applying a Cobb-Douglas production function, rather than a single learning rate derived from total experience (i.e. learning-by-deploying rate).

Fourth, while the 2FLC approach can improve the understanding of technological processes, data availability has been found to be an issue [8,10]. Data on private investment in RD&D for energy technologies are usually not publicly available. Thus, the 2FLC approach often encompasses public RD&D expenditures only. The inclusion of private expenditures in the 2FLC formulation may reveal how private and public RD&D expenditures affects technology cost projections at different stages of development. Thus, including private RD&D investment within the model formulation and investigating its relationship with public RD&D expenses is an important task for future research.

Fifth, technological progress in energy systems is driven by complex dynamic interactions involving multiple factors. Apart from experience and knowledge stock, there may be other factors to be considered when informing policy-making decisions. Future research could be oriented to investigate the possible impact of those factors on energy systems (e.g. societal influences). For instance, societal factors such as opposition to a specific technology or public acceptability to specific policies (e.g. carbon pricing) may strongly influence the pace of learning and diffusion of energy technologies [8,137].

In addition, although future technology changes may be estimated using quantitative methods, such as the learning curve approach, complementary qualitative methods (e.g. expert elicitation, energy policy analysis studies) may help to better explain the effects of technological progress on technology cost developments [11,138]. A promising mixed approach (i.e. quantitative and qualitative analyses) to deal with structural and parametric uncertainty by investigating diverse model structures based on historical developments may be found in [139].

6. Conclusions

Learning curves have been used extensively to estimate technology cost developments over time. Multiple factors and their interactions may influence technological progress in renewable energy development towards a low-carbon future. This article investigated the plausible effects of technological learning processes on technology cost changes over time by using alternative model structures. Technological experience and knowledge stock were chosen as the main sources of learning. Learning-by-deploying and learning-by-researching rates were estimated for onshore wind and solar PV in the United States of America using different learning curve approaches. The findings suggest that alternative explicit definitions of learning sources may have significantly different policy implications when learning rates are used for model-based energy policymaking.

The empirical results presented within this article revealed the relative impact of diverse variables on reducing technological-based capital costs for selected renewable energy technologies. An integrative technological learning model has been developed based on various approaches to endogenous learning and relevant data on onshore wind and solar PV technologies. By choosing how different sources of learning and key parameters are defined, the influence of alternative approaches was explored. A new definition of experience was developed and presented in this study to account for the interaction between global and local experience. The findings presented in this study empirically validate that technological-based capital cost developments may be better explained when both sources of experience are explicitly modelled. The new definition of experience also accounts for learning sub-processes (i.e. learning-by-doing, learning-by-using, and international experience spillovers) to estimate total experience gained through technology deployment. This new definition may be useful for energy policymakers to investigate the impact of domestic content regulations on energy technology cost developments.

Learning through researching is of critical relevance for innovation policymakers when the effects of energy RD&D are to be investigated. When knowledge stock was modelled as a second source of learning, a relatively better statistical explanation was found for technological-based cost changes over time. Alternative definitions of learning sources and the investigation of their impact is suggested as further work. The analysis carried out within this article may support energy policymakers and innovation institutions to actively try to influence the pathway and pace of energy-related technological progress at different stages of development.

CRediT authorship contribution statement

Omar Castrejon-Campos: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualisation. **Lu-Aye:** Validation, Resources, Writing - review & editing, Visualisation, Supervision, Project administration, Funding acquisition. **Felix Kin Peng Hui:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Data Availability

Datasets related to this article can be found at https://dx.doi.org/10.17632/82nfwvcgdz.1, an open-source online data repository hosted at Mendeley Data [140].

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Appendix A. Sensitivity analysis on share of total technological capital costs affected by learning processes (i.e. parameter α)

As discussed in Section 5.6, there is some uncertainty around parameter α (i.e. share of total technological capital costs affected by learning processes). As discussed in Section 3.3.1, parameter α depends on the selection of components that may be affected by technological learning processes. For instance, it is assumed that the total capital cost may be affected by learning processes if α is set to one (i.e. α=1). On the other hand, when α is assumed to be 0.5 only half of the total capital cost may be affected by learning processes. Although estimated learning rates do not vary based on the value assigned to this parameter (see Eq. (6)), root mean square errors (RMSEs) varied when these learning rates were used to estimate technological-based costs. Thus, a sensitivity analysis was performed relative to assumed values presented in Section 3.3.1.

Figures A1 and A2 present the change in RMSE relative to assumed values for onshore wind and solar PV, respectively. These figures suggest that technological cost developments are highly sensitive to assumed values for parameter α. The higher the value assumed for this parameter the greater the statistical error. Thus, a previous analysis of what components may be affected by learning processes is needed, as discussed in Section 3.3.1.

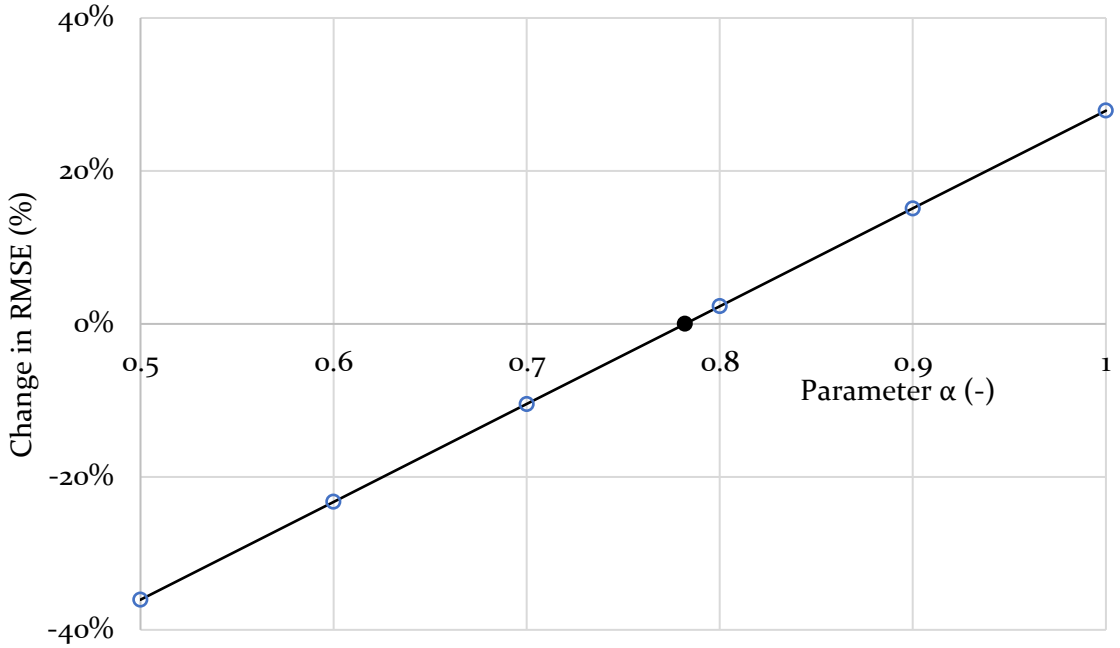


Fig. A1. Relative change in RMSE for different values assigned to parameter α for onshore wind in the USA. Change in RMSE was estimated relative to values assumed in this study (i.e. the black dot).

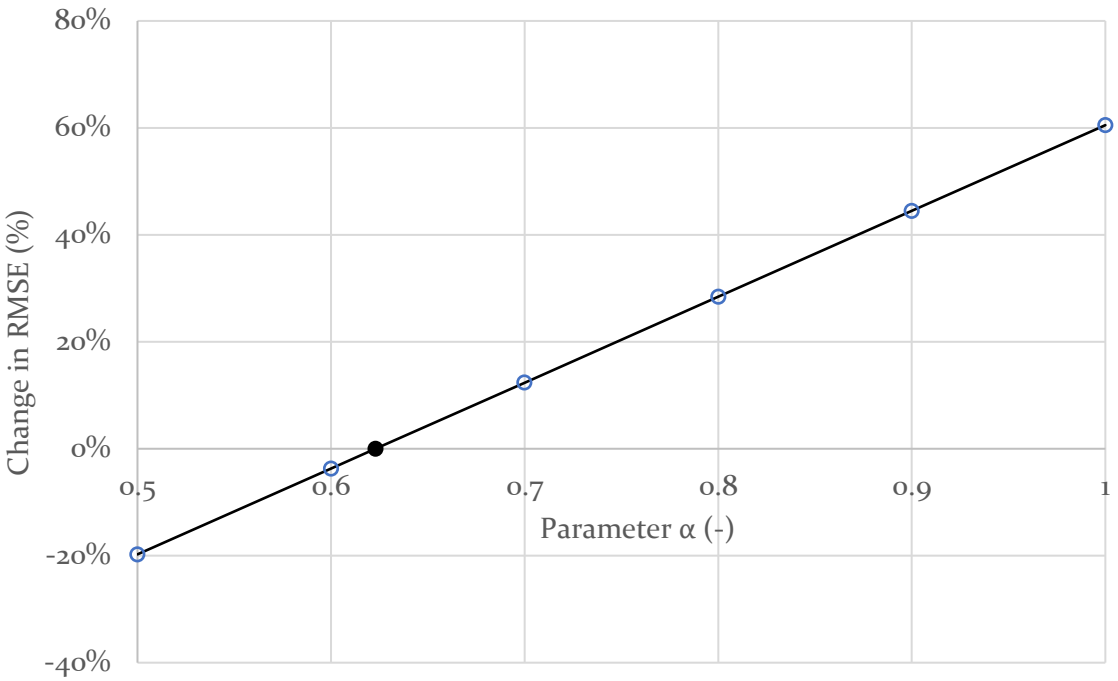


Fig. A2. Relative change in RMSE for different values assigned to parameter α for solar PV in the USA. Change in RMSE was estimated relative to values assumed in this study (i.e. the black dot).

Appendix B. Sensitivity analysis on share of domestic content (i.e. parameter β)

As discussed in Section 3.3.2, values for parameter β (i.e. share of domestic content) for both technologies were assumed to be constant for specific periods of analysis due to lack of available data. Thus, a sensitivity analysis was performed around these assumed values. Upper and lower bound were set to 0.1 and 0.5, respectively. Figures B1 and B2 show the relationship between parameter β and estimated learning rates for onshore wind and solar PV in the USA at different periods (i.e. from 1989 to 2004 for onshore wind and from 2010 to 2020 for solar PV). The sensitivity analysis shows that learning rates are relatively sensitive to values assumed for parameter β. Thus, further research is needed to realistically set values for this parameter across all periods of analysis and thus improve the reliability of the findings presented in this study (see Section 5.1 for a discussion on this issue).

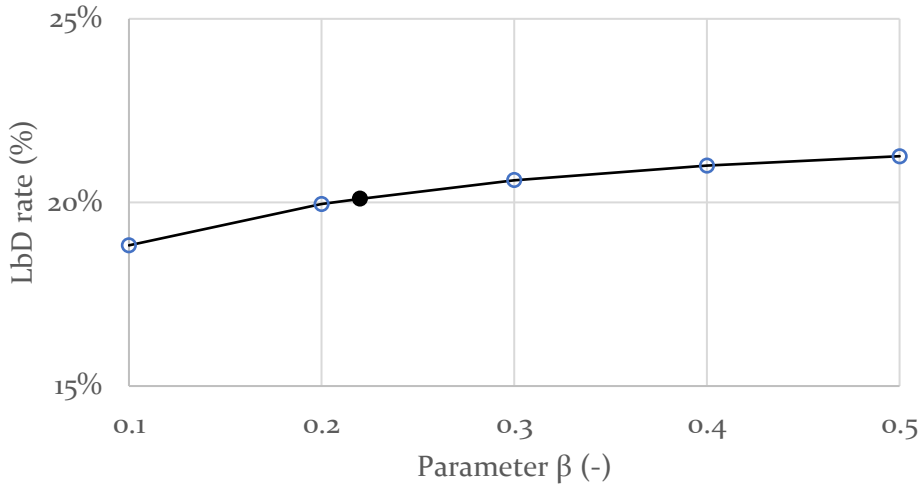


Fig. B1. Estimated learning-by-deploying (LbD) rates for different values assigned to parameter β for onshore wind for the USA in the period 1989-2004. Estimated LbD rate using the value assumed in Section 3.3.2 is highlighted as a black dot.

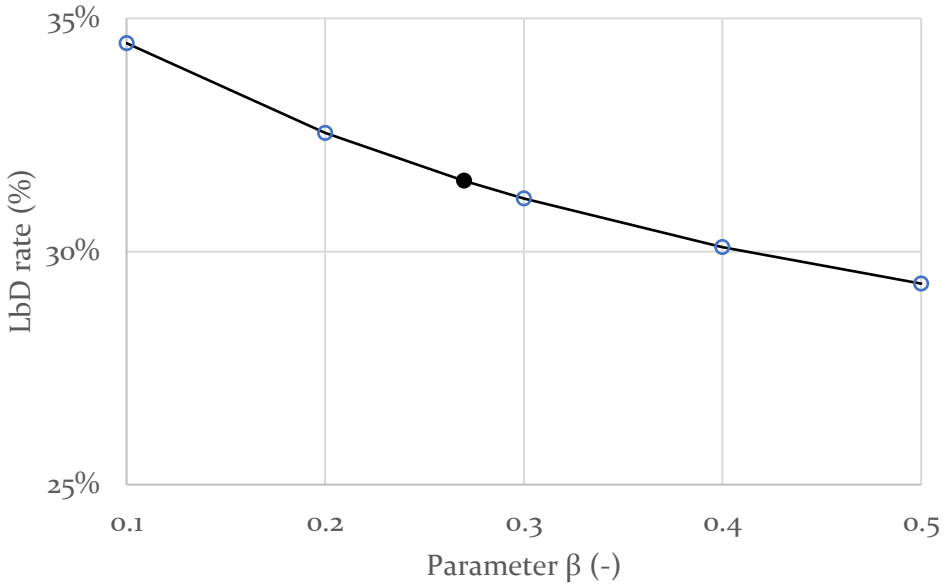


Fig. B2. Estimated learning-by-deploying (LbD) rates for different values assigned to parameter β for solar PV in the USA for the period 2010-2020. Estimated LbD rate using the value assumed in Section 3.3.2 is highlighted as a black dot.

Economic and environmental impacts of public investment in clean energy RD&D

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ABSTRACT

Learning curve theory has been adopted for investigating the relationship between technological learning and technology cost developments. The aim is to explore the impacts of public investment in clean energy research, development, and demonstration (RD&D) on future technology cost developments by using a two-factor learning curve approach. Learning-by-deploying and learning-by-researching were chosen as the main sources of learning. The focus is on onshore wind and solar photovoltaics in the United States of America. Publicly available data were utilised for estimating the learning rates. We found that the learning-by-deploying rates were 31.4% and 27.6%; and the learning-by-researching rates were 2.3% and 4.7% for onshore wind and solar PV, respectively. An additional $1,322 and $819 mil. are expected to be spent in RD&D for onshore wind and solar PV, respectively by 2050. Additionally, we have explored the plausible long-term effects of diverse RD&D investment scenarios on electricity generation and greenhouse gas (GHG) emissions using a system dynamics model. The findings reveal that public investment in RD&D for clean energy technologies may play a key role in the rate of capital cost reductions and technology diffusion. However, relatively little long-term effects of RD&D efforts alone were found on market dynamics and GHG emissions.

***Keywords*:** technological learning; learning curve; energy RD&D; clean energy; innovation diffusion; knowledge stock

Nomenclature

Symbols

C	capital cost ($ kW^{-1}), $ reported in this article are US dollars
CC	cumulative installed capacity (MW)
Dom	Domestic (-)
E	experience (MW)
Ext	external (-)
KS	knowledge stock ($ mil.)
LM	learning multiplier (-)
LR	learning rate (-)
RDnD	public RD&D spending ($ mil.)

Greek Symbols

α	share of the total technology capital cost affected by learning processes (%)
β	share of domestic sourced resources (%)
ρ	annual depreciation rate of knowledge stock (%)
γ	experience spillover coefficient (-)

Subscripts

g	time lag between the RD&D activity and its effects (a)
t	technology
y	timestep (a)

Superscripts

lbd	learning-by-deploying elasticity (-)
lbr	learning-by-researching elasticity (-)

Abbreviations

1FLC	One-factor learning curve
2FLC	Two-factor learning curve
ABM	Agent-based modelling
BAU	Business as usual
BNEF	Bloomberg New Energy Finance
CPI	Consumer price index
DEM	Discrete event modelling
EPS	Energy Policy Simulator
GHG	Greenhouse gas
IEA	International Energy Agency
ITC	Induced technological change
lbd	Learning-by-deploying
lbr	Learning-by-researching
LCOE	Levelised cost of electricity
LIN	Low innovation
MFLC	Multi-factor learning curve
MW	Megawatt
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary least-squares
PV	Photovoltaics
R&D	Research and development
RD&D	Research, development, and demonstration
RMSE	Root mean square error
SD	System dynamics
SDM	System dynamics modelling
USA	United States of America

1. Introduction

Innovation is a central driver of growth in all economic sectors (Wiesenthal et al. 2012). Innovation researchers seek to understand how technological progress may benefit society, and how policy strategies can be framed accordingly to meet economic and societal needs while complying with contemporary global challenges (e.g. climate change) (Bettin 2020). Thus, a more comprehensive understanding of the role of the state to enable (or hinder) innovation processes for energy technologies is paramount for policy analysis (Bettin 2020). One of the main drivers behind innovation in the energy sector is research, development, and demonstration (RD&D) (Bointner 2014). Support for energy RD&D has been extensively recognised as a key policy strategy to reduce greenhouse gas (GHG) emissions (Garrone & Grilli 2010; Miremadi, Saboohi & Arasti 2019; Koçak & Ulucak 2019). However, the relationship between investment in energy RD&D and GHG emission reductions is highly uncertain (Harvey, Orvis & Rissman 2018; Anadón, Baker & Bosetti 2017). Thus, insights on the potential impacts of RD&D on technology cost reductions, and therefore reduction on emissions due to market dynamics, may aid policymakers and energy analysists to recognise the long-term implications of short-term policy actions.

Learning curve has been adopted as a widely applied technological forecasting framework for investigating the relationship between endogenous technological learning and technology cost developments (see Castrejon-Campos et al., 2022a; Elia et al., 2021; Samadi, 2018; Thomassen et al., 2020). The aim of this article is to explore the potential impacts of public investment in energy RD&D on future renewable technology cost developments under the learning curve approach. The focus is on onshore wind and solar photovoltaics (PV) in the United States of America (USA) as these are the two renewable energy technologies with the fastest-growing electricity generation capacity worldwide and are of particular interest for sustainable energy transitions (Rubin et al. 2015).

The main contribution of this article is the prospective exploration of the relative effects of diverse innovation-oriented policy strategies on capital cost developments for selected clean energy technologies, as well as their plausible long-term impacts on market dynamics (i.e. installed capacity and electricity generation) and environmental concerns (i.e. GHG emissions). Although the impact of RD&D has been discussed in diverse retrospective studies (using historical data), finding future costs to extrapolate its learning effects has been identified as a key challenge for prospective studies (Thomassen et al., 2020). Thus, this article builds on a previous retrospective study that explored the effects of technological learning processes on technology cost developments over time by using alternative model structures (Castrejon-Campos et al., 2022a). The previous study revealed valuable insights regarding the relative effects of different learning sources and explanatory variables on historical cost developments. The motivation of this article is to extend its applicability to prospective studies by exploring diverse RD&D investment scenarios, and therefore it provides new insights for model-based energy policy analysis for clean energy transitions. In addition, this article empirically contributes to existing learning curve literature and energy systems modelling by comparing the relative effects of innovation processes when technological learning is modelled as a function of technological experience only (using installed capacity as a proxy) and when RD&D-based knowledge stock is included as a second source of learning (using cumulative public RD&D expenditure as a proxy). The research provides an in-depth critical discussion of their implications to inform model-based energy policymaking. This article targets at energy innovation policymakers, innovation researchers, and energy analysts.

The rest of this article is organised as follows. Section 2 sets the background of the research by briefly describing the learning curve theory and the role of RD&D in technology cost developments. The analytical structure is presented and explained in Section 3. Data sources employed, learning parameters, and input data needed for the modelling and simulation

processes are also described in this section. In Section 4 simulation results are presented and discussed based on the diverse scenarios explored. Findings of the analysis, limitations, and potential future research are also discussed within this section. Conclusions and policy implications are presented in Section 5.

2. Technological learning for model-based policy analysis

Neoclassical models of economic growth, fundamentally derived from the Solow's neoclassical school (Solow 1956), have suggested that technological progress is exogenous to the economic process (Verspagen 1992); an approach with significant limitations for policy analysis (Jamasb 2007). Romer (1986), based on macroeconomic growth theory and technological change theory, proposed an alternative approach by suggesting that technological progress in economic growth models should be modelled endogenously. In energy modelling literature, Grubb et al. (2002) advocated that technological progress should be modelled endogenously deriving from the interactions of interrelated economic, social, and policy processes, including economies of scales derived from technology deployment, and private and government-funded investment in research and development activities. Thus, the application of learning curve theory has been adopted in energy policy analysis to gain better understanding on learning processes in energy systems. The application of learning curves is particularly relevant for energy and innovation planning if limited financial resources may be better allocated on diffusion or innovation policy strategies towards clean energy transitions (Jamasb 2007).

2.1. Learning curve theory

Quantitative explanation of technological progress dated from the 1930's when it was observed that the cost of producing military aircrafts declined at a semi-constant rate for each doubling of airplanes produced (Wright 1936). This correlation is commonly explained in terms of a learning process taking on the form of a learning curve. The learning curve approach suggests that future technology costs decline as technological learning increases. Multiple structural models have been proposed within the learning curve literature. However, the log-linear model is the most commonly structural formulation used in diverse studies due to its simplicity and generally good fit to historical data (Nemet 2006). This model formulation has become a common method to integrate endogenous technological change in energy-economic models for policy analysis (EPRI 2013). Learning curves are generally used to empirically estimate technology costs as a function of learning processes (Ek & Söderholm 2010). The learning curve theory has been applied to explore the impact of technological learning on cost developments for electricity generation technologies (Hayward & Graham 2013; Samadi 2018; Rubin et al. 2015; Kamp, Smits & Andriesse 2004). Recent reviews may be found in (Samadi 2018; Elia et al. 2021; Thomassen, Van Passel & Dewulf 2020).

Different (learning) sources may drive learning progress within energy systems, such as technological experience and knowledge stock (Yeh & Rubin 2012; Elia et al. 2021). When the focus is on experience gained through production processes (i.e. technology diffusion) learning may increase through learning-by-doing (Arrow 1962), learning-by-using (Rosenberg 1982), and/or learning-by-interacting (Lundvall & Andersen 1988). Alternatively, when the focus is on innovation processes, learning may rise through learning-by-researching (also known as learning-by-searching (Kouvaritakis, Soria & Isoard 2000)).

One-factor learning curves (1FLCs), often called experience curves (Junginger et al. 2010), uses (only) experience as the independent variable to explain technology costs developments over time. The application of a 1FLC approach has been extensively debated in the literature (see Castrejon-Campos et al., 2022a; Jamasb, 2007; Jamasb and Köhler, 2007; Nordhaus, 2009). From a policy perspective, if a 1FLC approach is applied only market-pull policy strategies (e.g. carbon tax, renewable portfolio standards) may be developed while ignoring technology-push mechanisms (e.g. R&D investment) within learning processes (Castrejon-Campos, Aye & Hui

2022a). Considered as a partial model for representing technological progress, experience curves (1FLCs) may produce inaccurate estimates of learning rates and therefore incomplete, erroneous, or misleading policy conclusions (Jamasb 2007; Nordhaus 2009). Thus, in order to better represent innovation processes, two-factor learning curves (2FLCs) have been developed (Kouvaritakis, Soria & Isoard 2000; Klaassen et al. 2005; Bosetti et al. 2006, 2008). The 2FLC approach was first proposed by Kouvaritakis et al. (2000) to include R&D expenditures as a second source of learning, adding a policy variable to the learning curve model. Learning through researching is of critical relevance for innovation policymakers when the effects of energy RD&D are to be investigated.

2.2. The role of public investment in RD&D for energy technologies

Public companies tend to limit their RD&D investment to low-risk, short-term projects (e.g. demonstration plants) (Anadón 2012). The low RD&D intensity of utilities can be explained due to electricity-generation technologies usually do not provide differentiated or additional services (i.e. electricity generation technologies generate a homogeneous output, so end-users usually do not care where the electricity comes from) and operate in a heavy regulated sector (Anadón 2012). When the private sector is unable to capture the full social value of their RD&D efforts, private underinvestment may be revealed due to market dynamics (i.e. market failure) (Jaffe, Newell & Stavins 2005). Public investments in energy RD&D may play a strategic role in closing this investment gap. Thus, analysis of technological learning processes is of particular interest to gain a deeper understanding on how public resources could be spent to promote clean energy development without harming the environment.

The design of energy RD&D investment portfolios has followed commonly a two-staged analytical process. The first stage consists of analysing how future technology costs could be affected by RD&D expenditures and then, the second stage focuses on investigating how technology costs affect energy and climate policies (Anadón, Baker & Bosetti 2017). Policy mixes can activate innovation processes and trigger structural change, but at the same time these changes may influence policy decisions (Bettin 2020; Rogge & Reichardt 2016). In the context of this article, the focus is on decisions regarding public investment in energy RD&D (i.e. former stage). How technological change influences future electricity generation technologies costs has been analysed through diverse energy-economic models such as WITCH (Bosetti et al. 2006), MESSAGE (Messner & Strubegger 1995), ReMIND-R (Luderer et al. 2010), NEMS (DOE 2019), EPA-MARKAL (Shay et al. 2006), and EPS (Energy Innovation 2021). A comprehensive review on endogenous technological change in energy-economic models may be found in (IPCC 2007).

Although multiple studies have discussed the potential effects of public investment in energy RD&D for sustainable development (see Thomassen et al., 2020 for a review), the prospective exploration of learning through researching processes has been seldom addressed in the literature due to diverse reasons. For instance, (Rubin et al. 2015) argued that finding historic data to estimate learning-by-researching effects is a significant challenge. In addition, (Thomassen, Van Passel & Dewulf 2020) indicated that the extrapolation of these learning effects is even more challenging if reliable data is not available to estimate future values. However, it has been advocated that when data available, learning-by-researching should be included to explore the effects of learning processes on technology cost changes over time (Thomassen, Van Passel & Dewulf 2020; Castrejon-Campos, Aye & Hui 2022a). The relative effects of different learning sources and explanatory variables on historical cost developments have been recently explored by using publicly available data from government departments and international organisations (Castrejon-Campos, Aye & Hui 2022a). It was found that technology cost developments may be better explained when learning through deployment and learning through researching are included in energy models. In this article, we extended the application of the 2FLC model developed in (Castrejon-Campos, Aye & Hui 2022a) to

explore the potential effects of learning-by-researching on future technology cost developments.

3. Methods and data

To investigate the potential economic and environmental impacts of public investment in energy RD&D, a process of six complementary phases was adopted in this study (see Fig. 1). During the initial (and continuing) phase, literature review on innovation and technological learning was conducted. The aim of this phase was to identify relevant approaches to model endogenous technological learning and innovation processes for energy policy analysis. During Phase 2, data on domestic (USA) and international (Organisation for Economic Co-operation and Development –OECD–) installed capacity, domestic and international annual public RD&D expenses, and domestic capital cost for onshore wind and solar PV were collected from the sources described in Section 3.2. In addition, learning parameters needed to empirically estimate learning rates (e.g. domestic content, knowledge depreciation rate, time lag between investment in RD&D and its effects) were established in this section. Learning rates were estimated in Phase 3 based on the accumulation of experience (learning-by-deploying) and knowledge stock (learning-by-researching) in Section 3.3.1. Also, future RD&D public investment was forecasted based on historical data as described in Section 3.3.2. Estimated learning rates and forecasted RD&D expenditures were used as input data in the simulation model to investigate the potential effects of public investment in energy RD&D on future cost developments. A system dynamics (SD) modelling approach was adopted in this study to implement the model structure (Phase 4). The simulation model, implemented in Vensim DSS (available at https://vensim.com/), is briefly described in Section 3.4. During Phase 5, the main outputs of interest were selected, and simulation was conducted using the SD model. To investigate the effects of variations in RD&D expenditures two scenarios were proposed as described in Section 3.5. Lastly, results were analysed and discussed in Phase 6.

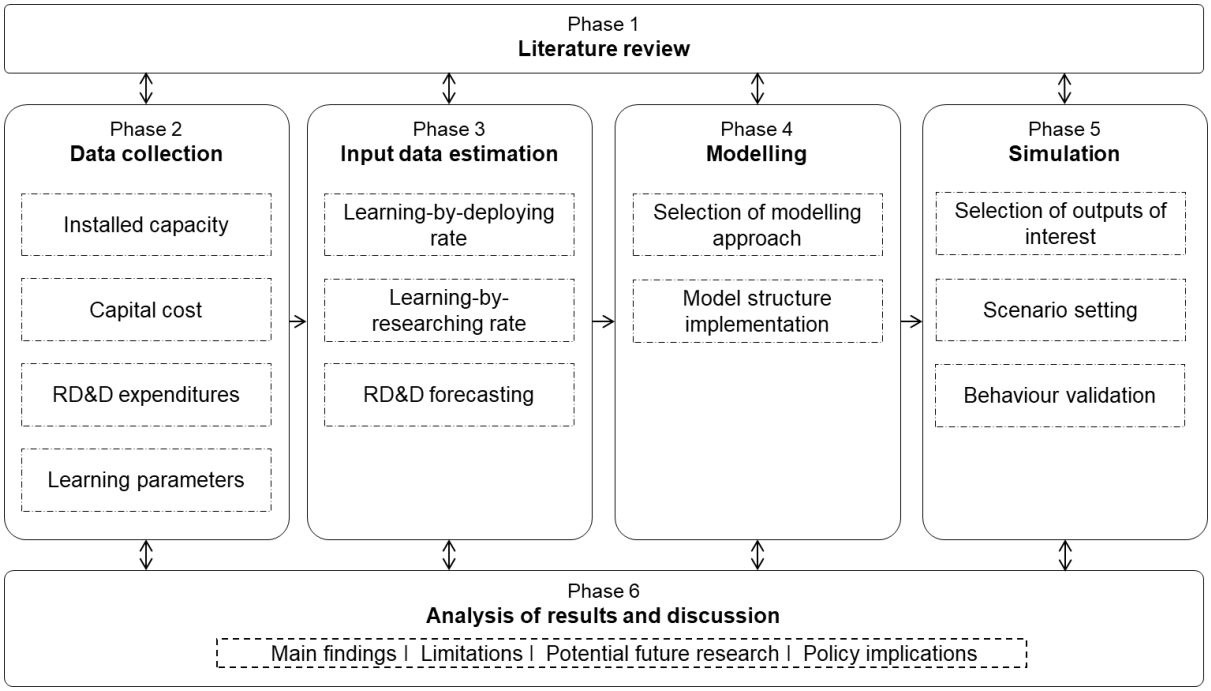


Fig. 1. Research design followed by this investigation.

3.1. A learning curve model for electricity generation technologies

The process of estimating learning rates is driven by several factors such as variables to be considered, definition of learning factors, model structure, geographical delimitation, and period of analysis (Jamasb 2007; Samadi 2018; Castrejon-Campos, Aye & Hui 2022a). The

application of learning curve theory to energy technologies has been widely reviewed and discussed in the literature. Thus, a broad range of values for learning rates in the energy sector has been reported in previous studies. These studies comprise energy technologies in general (McDonald & Schrattenholzer 2001; Samadi 2018; Rubin et al. 2015; Thomassen, Van Passel & Dewulf 2020) and individual electricity generation technologies in particular, such as wind (Ibenholt 2002; Klaassen et al. 2005; Wiser & Millstein 2020; Castrejon-Campos, Aye & Hui 2022a) and solar PV (Elshurafa et al. 2018; Nemet 2006; Yu, van Sark & Alsema 2011; Mauleón 2016; Castrejon-Campos, Aye & Hui 2022a).

An integrative learning curve model was developed in (Castrejon-Campos, Aye & Hui 2022a) to explore the relative impact of alternative model structures (based on diverse learning curve approaches) on historical capital cost developments for onshore wind and solar PV in the USA. By exploring diverse periods of analysis and how multiple sources of learning and key parameters were defined, the study found that technology cost developments may be better explained when: (1) technological processes affect only a fraction of the total capital cost (i.e. technological-based capital cost), (2) experience is defined as a function of local and global experience, and (3) knowledge stock is also included in the model structure (Castrejon-Campos, Aye & Hui 2022a).

Based on the empirical findings presented in (Castrejon-Campos, Aye & Hui 2022a), technological learning is defined in this article as a function of experience (*E*) and knowledge stock (*KS*) as the main sources of learning (see Eq. 1).

$$\alpha_t \cdot C(E,KS)_{t,y} = \alpha_t \cdot C(E_0,KS_0)_t \cdot LM(E,KS)_{t,y} \quad (1)$$

where α_t is defined as the share of the total capital cost that can be affected by learning processes for technology *t*, $C(E,KS)_{t,y}$ represents the technological-based capital cost of technology *t* at year *y* as a function of technological learning processes (i.e. based on experience and knowledge stock), $C(E_0, KS_0)_t$ denotes the initial capital cost of technology *t* at year *y=0*, and $LM(E,KS)_{t,y}$ represents the combined learning effects on technology capital cost changes for technology *t* at year *y* (i.e. known as the learning multiplier (Castrejon-Campos, Aye & Hui 2022a)).

Based on the two-factor learning curve model proposed by (Klaassen et al. 2005), *LM* is defined in this article as follows:

$$LM(E,KS)_{t,y} = \left(\frac{E_y}{E_0}\right)_t^{-lbd} \left(\frac{KS_y}{KS_0}\right)_t^{-lbr} \quad (2)$$

where *lbd* represents the learning-by-deployment elasticity, and *lbr* is the learning-by-researching elasticity.

Based on (Castrejon-Campos, Aye & Hui 2022a), technological experience (*E*) is defined in this article as a function of local experience and external experience affecting local learning, using installed capacity as a proxy, and is represented as in Eq. 3:

$$E_{y,t} = \left[\beta \cdot (2-\beta) \cdot CC_Dom\right]_{t,y} + \left[\gamma \cdot CC_Ext\right]_{t,y} \quad (3)$$

where parameter β ($0 \leq \beta \leq 1$) represents the share of domestic content (i.e. locally sourced resources), *CC_Dom* accounts for domestic installed capacity of technology *t* at year *y*, parameter γ ($0 \leq \gamma \leq 1$) is defined as the experience spillover coefficient which accounts for the ratio of domestic installed capacity to the international technological frontier, and *CC_Ext* represents the external installed capacity (i.e. difference between global and domestic installed capacity). The first term in Eq. 3 represents local experience, gained through learning-by-doing and learning-by-using, and the second term accounts for experience spillover effects (also known as learning-by-interacting (Lundvall & Andersen 1988)). A detail

description of the mathematical definition of experience and an in-depth discussion on the relative contribution of these learning sub-processes within the learning-by-deploying process may be found in (Castrejon-Campos, Aye & Hui 2022a).

In addition, the method used in this article to estimate cumulative RD&D-based knowledge stock (*KS*) of technology *t* in year *y* is based on (Klaassen et al. 2005). Thus, KS is estimated as in Eq. (4):

$$KS_{t,y} = (1-\rho_t)KS_{t,y-1} + RDnD_{t,y-g} \tag{4}$$

where ρ ($0 \leq \rho \leq 1$) is the annual knowledge depreciation rate of KS of technology *t* in year *y-1* (i.e. cumulative previous KS), *g* represents the time lag between the RD&D activity and its effects, and *RDnD* denotes public RD&D expenditures in technology *t* in year *y-g*. Eq. (4) considers that previous knowledge depreciates (i.e. becomes more irrelevant or even obsolete) with time due to several factors such as rapid innovation, staff turnover, and retirement (Klaassen et al. 2005). Also, it takes into account that RD&D expenditures do not have an instantaneous effect on learning, thus it may lead to tangible results after some time (i.e. parameter *g*).

Based on the definition of experience (Eq. 3) and knowledge stock (Eq. 4), technological-based capital cost of technology *t* at year *y* is defined in this article as in Eq. (5):

$$\alpha_t \cdot C(E,KS)_{t,y} = \alpha_t \cdot C(E_0,KS_0)\left(\frac{E_y}{E_0}\right)_t^{-lbd}\left(\frac{KS_y}{KS_0}\right)_t^{-lbr} \tag{5}$$

By applying a logarithmic transformation to Eq. (5), Eq. (6) is used in Section 3.3 to estimate the learning-by-deploying and learning-by-researching rates for wind and solar PV in the USA based on historical data and learning parameters described in Section 3.2.

$$\log\left[\alpha_t \cdot C(E,KS)\right]_{t,y} = \log\left[\alpha_t \cdot C(E_0,KS_0)\right] - ldb \cdot \log\left[\left(\frac{E_y}{E_0}\right)_t\right] - lbr \cdot \log\left[\left(\frac{KS_y}{KS_0}\right)_t\right] \tag{6}$$

3.2. Data collection

To estimate the accumulation of technological experience and knowledge stock, data collected for onshore wind and solar PV are summarised in Table 1. In addition, to empirically estimate learning rates (i.e. learning-by-deploying and learning-by-researching) using Eq. (6), parameters considered in Eqs. (1, 3, and 4) were established based on previous studies and they are presented in Table 2. A detailed description of data collected and learning parameters used within this investigation may be found in (Castrejon-Campos, Aye & Hui 2022a, 2022b).

3.3. Input data estimation

To explore the potential impacts of technological learning on future technology cost developments, a two-factor learning curve approach is adopted in this investigation. Technological learning is modelled in this article as a function of technological experience and RD&D-based knowledge stock. Data collected and parameters described in Section 3.2 are used to estimate learning rates based on the accumulation of experience (learning-by-deploying) and knowledge stock (learning-by-researching). In addition, future RD&D public investment is forecasted following a logistic curve approach based on historical data as described in this section.

Table 1
Data collected to estimate technological experience and knowledge stock for onshore wind and solar PV. Sources: (Castrejon-Campos, Aye & Hui 2022a, 2022b).

Item	Unit	Period
Domestic (USA) installed capacity	MW[a]	1974-2020
International (OECD countries including USA) installed capacity	MW	1974-2020
Domestic (USA) annual public RD&D expenses	$ mil.[b]	1974-2020
International (OECD countries including USA) annual public RD&D expenses	$ mil.	1974-2020
Domestic (USA) capital cost	$ kW^{-1}[c]	1983-2020 (onshore wind) 1974-2020 (solar PV)

[a] Megawatt (MW).
[b] Millions of US dollars in constant 2020 prices and purchasing power parities rates ($ mil.)
[c] US dollars (2020) per Kilowatt (2020 $ kW^{-1}).
Monetary values were reported in 2020 US dollars. They were estimated accounting for inflation based on the average annual consumer price index (CPI) in the USA.

Table 2
Assumptions for learning parameters used to estimate learning rates for onshore wind and solar PV. Sources: (Castrejon-Campos, Aye & Hui 2022a, 2022b).

Parameter	Description (units)	Onshore wind	Solar PV
α	Share of the total technology capital cost affected by learning processes (%)	78	62
β	Share of domestic content (%)	68	27
γ	Experience spillover coefficient (-)	0-1	0-1
ρ	Annual depreciation rate of knowledge stock (%)	10	10
g	Time lag between the RD&D activity and its effects (a)	3	5

3.3.1. Learning rates estimation

Learning rates were estimated based on the relationship between technological-based cost changes as a dependent variable, and experience (using installed capacity as a proxy) and knowledge stock (using public RD&D expenditure as a proxy) as independent variables. Using the model formulation described in Section 3.1, learning rates were estimated by applying an ordinary least-squares (OLS) method of regression analysis using Python 3.8.2 as explained in (Castrejon-Campos, Aye & Hui 2022b). A summary of the results is presented in Table 3. The period of analysis for each technology was selected based on four main reasons. First, during the 2000's onshore wind and solar PV technologies reached the full-commercialisation stage in the USA (Elia et al. 2021). Second, a period of 10-12 years' worth of historical data has been suggested to achieve stable estimates on learning rates (Santhakumar, Meerman & Faaij 2021). Third, an increasing interest for electricity generation diversification through public RD&D investment can be observed in 2008 (see Fig. 2). Fourth, although it is widely accepted that technological learning leads to technology cost reductions over time (Wei, Smith & Sohn 2017), the estimation of learning rates should consider external market factors (e.g. market power, response to policies and regulations) that may result in market-structural change (e.g. increase in technology costs for onshore wind from 2004 to 2010 due to market dynamics) (Santhakumar, Meerman & Faaij 2021; Castrejon-Campos, Aye & Hui 2022a). A sensitivity analysis for alternative periods of analysis is presented in Appendix A.

Table 3
Estimated learning rates for onshore wind and solar PV for the USA.

Technology	Learning factors	Period of analysis	Estimated learning rates	Model validation
Solar PV	Experience (MW) Knowledge stock ($ mil.)	2008 – 2020	lbd[a] rate = 27.56% lbr[b] rate = 4.72%	R-squared = 0.81 RMSE[c] = 484.44 ($ MW^{-1})
Onshore wind	Experience (MW) Knowledge stock ($ mil.)	2010 – 2020	lbd rate = 31.38% lbr rate = 2.3%	R-squared = 0.91 RMSE = 85.02 ($ MW^{-1})

[a] lbd = learning-by-deploying, [b] lbr = learning-by-researching, [c] RMSE = Root Mean Square Error

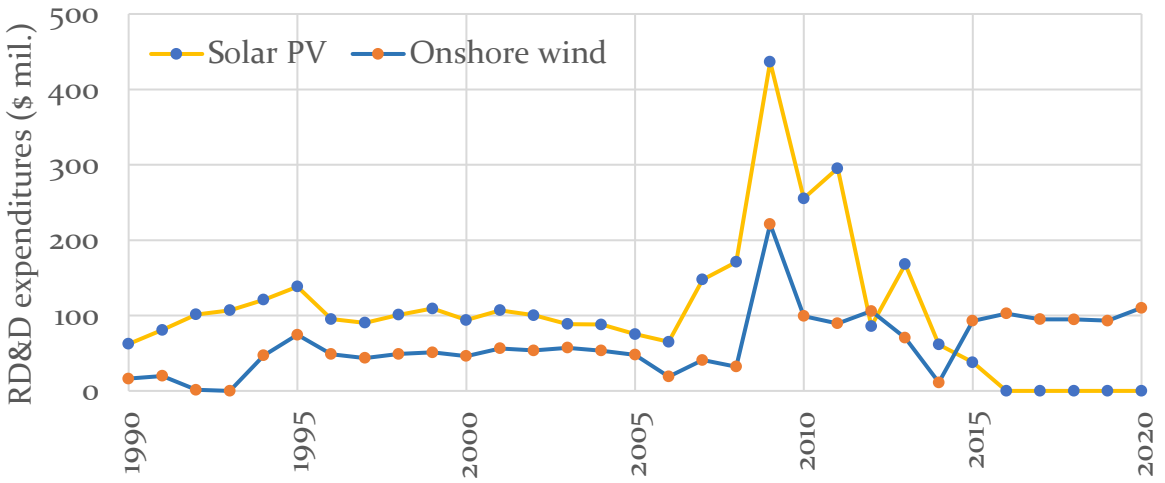


Fig. 2. RD&D public investment for solar PV and wind in the US from 1990 to 2020. Source: constructed with data from (IEA 2020).

3.3.2. Future trends in public investment in RD&D

Innovation diffusion has been one of the most researched issues in social sciences, albeit with multiple approaches (Bettin 2020). Resources for energy RD&D are limited and how to better allocate them to develop and deploy energy technologies is a key policy issue (Kim, Lee & Koo 2014). Different efforts to predict future energy RD&D public investment have been found in the literature (Miremadi, Saboohi & Arasti 2019; Usui, Furubayashi & Nakata 2017; Kim, Lee & Koo 2014). In this investigation, we adopted the logistic curve approach to model knowledge development and diffusion (based on energy RD&D expenses). This assumption has been made based on the idea that RD&D investment plays a paramount role in advancing technological knowledge for emerging technologies, however the role of public and private funding is different throughout the diverse innovation stages. At the R&D stage, knowledge creation and spillovers are commonly sustained from government financial support with public investment (with little or no private R&D investment). When technologies reach a demonstration phase, usually private investors gain interest in expanding their businesses in new technological directions by adopting these new technologies. Thus, private investment complements public funding for demonstration (or pilot) plants. However, to overcome some pre-commercialisation technical and economic barriers, a continuous level of government support is needed. During the early technology diffusion stage, private RD&D investment may

increase. Thus, new knowledge creation also occurs within industry (mainly leaders in the market), increasing the importance of private intellectual property (aiming at protecting their businesses). During this phase, experience gained by improvements in production, operation, and management (i.e. learning-by-deploying) gain more relevance as a key driver in technology deployment. To overcome technical issues and support technology niche markets, governments need to ensure a consistent long-term RD&D investment strategy. During the full-commercialisation stage, knowledge is created mainly at industrial level and collaboration between companies. Thus, public investment decreases over time and learning-by-deploying usually turns the main driver for cost reduction and technology diffusion. The government's role during this stage usually focuses more on market-pull policies (e.g. improving regulatory processes, energy efficiency) and less on technology-push mechanisms (e.g. public RD&D investment) (Elia et al. 2021).

The logistic curve model describes the diffusion of innovation as an S-shaped sigmoid curve that shows initial slow adoption, a sudden uptake, and a long stabilisation period (Bettin 2020) (see Fig. 3). According to this model, diffusion of an energy technology can be described by using three parameters: L represents the maximum innovation adoption (or curve's maximum value), k denotes the speed of diffusion (or logistic growth), and x_0 that refers to the inflection point (the x value of the sigmoid curve midpoint).

$$f(x) = \frac{L}{1 + e^{-k(x - x_0)}} \tag{7}$$

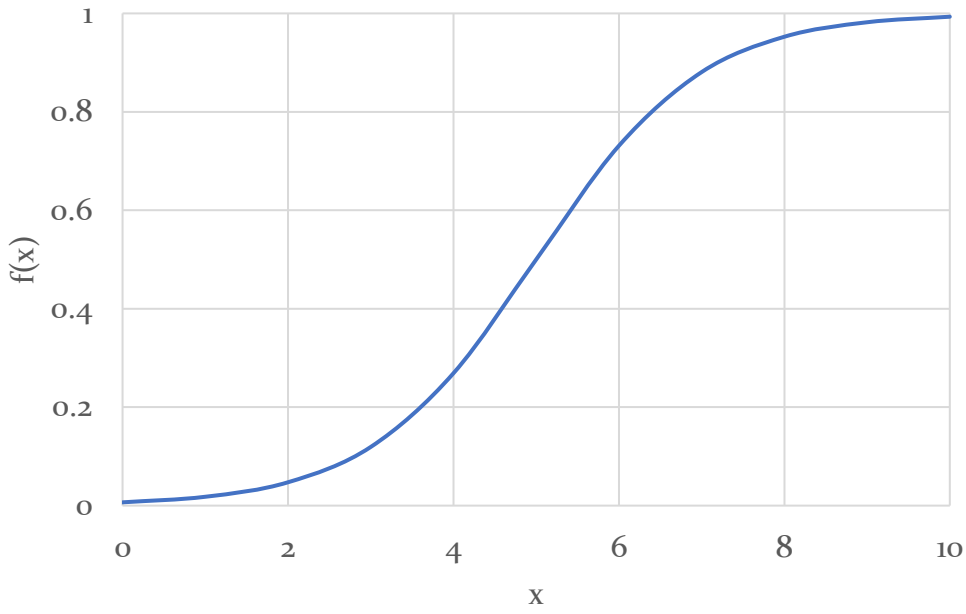


Fig. 3. Example of a logistic growth curve (with parameters: L=1, k=1, x0=5). Source: own elaboration.

The first step to predict future RD&D expenses was to analyse historical data for the clean energy technologies selected for this investigation. Then we conducted logistic regression in Python (using scipy.optimize package) to estimate the parameters of the logistic function (see Fig. 4 and Fig. 5). These parameters were used to predict future values for public RD&D investment for onshore wind and solar PV to 2050. The Python codes can be made available upon request.

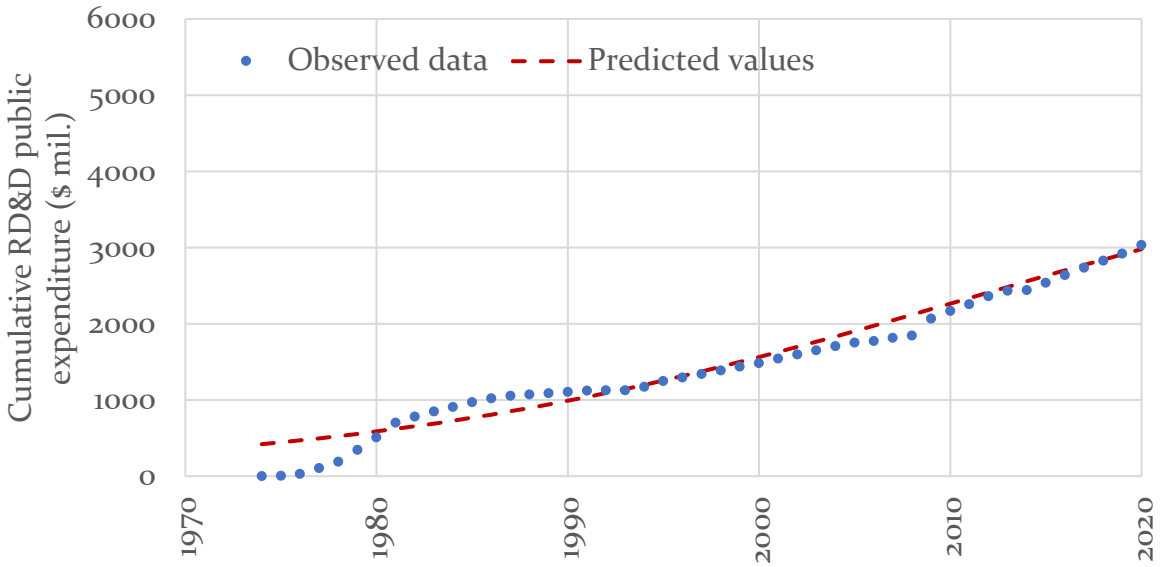


Fig. 4. Estimated logistic curve for onshore wind based on historical data. L= 4,675 ($ mil.), k= 0.06 ($ mil. a^{-1}), xo= 2011 (a), R-square=0.96 (-), RMSE=168.9 ($ mil.).

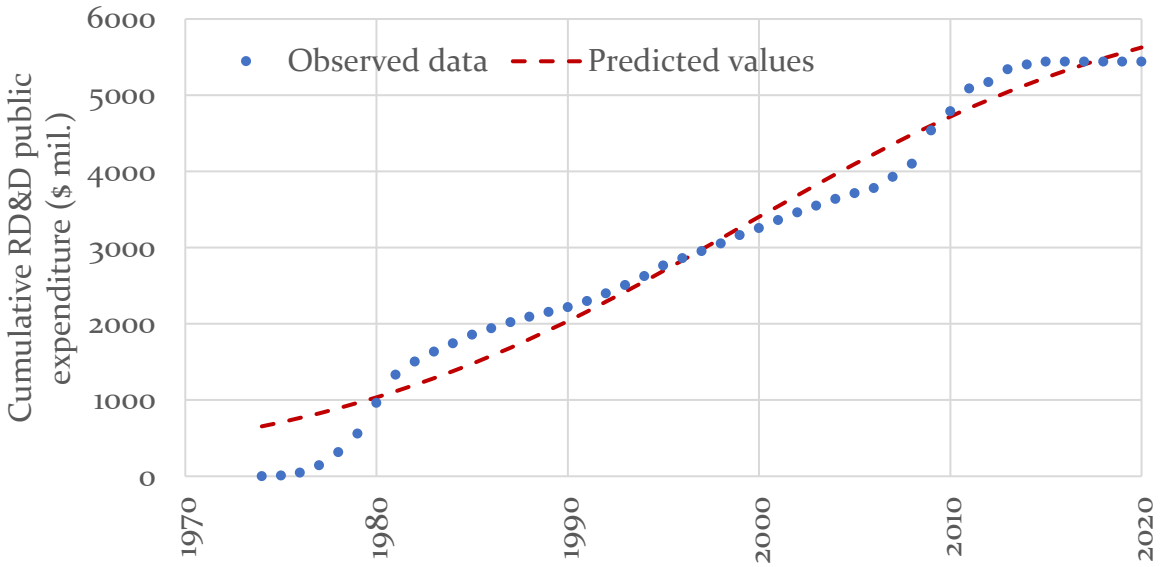


Fig. 5. Estimated logistic curve for solar PV based on historical data. L= 6,519 ($ mil.), k= 0.09 ($mil. a^{-1}), xo= 1999 (a), R-square=0.96 (-), RMSE=317.7 ($ mil.).

3.4. Model description

Energy systems are characterised by dynamic complexities such as non-linearities among variables of the system, time delays, inter-temporal interactions, and side-effects between system variables (Castrejon-Campos, Aye & Hui 2020). Interactions in energy systems can be analysed using different modelling approaches (e.g. Agent-Based Modelling (ABM), System Dynamics Modelling (SDM), or Discrete Event Modelling (DEM)). Following an endogenous approach, we have adopted System Dynamics (SD) (Sterman 2000) as the simulation modelling approach. SD is used to formulate and test structural (energy and climate) policies.

It is performed by modelling and simulating complex (energy) systems and analysing their resulting non-linear behaviour over time (Kwakkel & Pruyt 2013). SD focuses on the use of simulation models to explore the relationship between a specific system structure and its dynamic behaviour, based on established assumptions (Kwakkel & Pruyt 2015). SD has been selected due to three main reasons. First, it allows us to integrate explicit behavioural rules (i.e. policy instruments) via information feedback loops and delays in perception and adjustment (Bolwig et al. 2019). Second, the focus is on disequilibrium dynamics and feedback complexity rather than on equilibrium and optimal factor allocations (Gallagher et al. 2019). Third, it allows us to explore the behaviour of the system by considering interactions among both pricing and non-pricing policy instruments. Although alternative modelling techniques such as ABM or DEM can be applied to energy policymaking, they require a vast amount of historical or empirical data to simulate the behaviour of individual entities (Castrejon-Campos, Aye & Hui 2020; Bolwig et al. 2019).

This article applied a modified configuration of the last version (3.3.1, released in January 2022) of the USA energy policy simulator (EPS) developed by Energy Innovation LLC (Energy Innovation 2021). A public web-based version of the original model may be available at https://us.energypolicy.solutions/. The EPS is an open-source and peer-reviewed SD computer model aiming at quantifying the plausible effects of energy and climate policies on GHG emissions at a national or regional level. The EPS allows users to control multiple parameters that affect energy use and production, as well as GHG emissions (Austin & Denzinger 2020). The EPS model has been used to explore the impact of different policy mixes in diverse regions such as Indonesia (Chandra Setiawan, Indarto & Deendarlianto 2021), China (Gallagher et al. 2019), Mexico (Stevens 2020), and Alberta, Canada (Austin & Denzinger 2020).

The EPS model uses a combination of exogenous and endogenous learning approaches to estimate technology cost developments depending on the maturity level of each technology (Energy Innovation 2021). In case of endogenous learning, the EPS model adopts the one-factor learning curve (1FLC) approach being installed capacity the only driver for future technological-based cost developments in the case of wind and solar PV. We extended the approach to include knowledge stock as a second source of learning in order to explore its potential economic and environmental effects. In addition, although the effects of domestic and external (i.e. outside the modelled region) technology deployment has been considered in the last version of the EPS model (see Fig. 6), the value proposed to limit the contribution of deployment outside the modelled region to learning calculations lacks a well-grounded justification. Thus, modifications to the EPS model were implemented to account for technological experience based on diverse learning sub-processes (i.e. learning-by-doing, learning-by-using, and experience spillovers) and RD&D-based knowledge stock as suggested by (Castrejon-Campos, Aye & Hui 2022a; Thomassen, Van Passel & Dewulf 2020). Based on (Castrejon-Campos, Aye & Hui 2022a), the main structural modifications within the EPS model for onshore wind and solar PV were implemented within the *Endogenous learning sheet* (see Fig. 7). The modified version of the EPS model can be made available upon request.

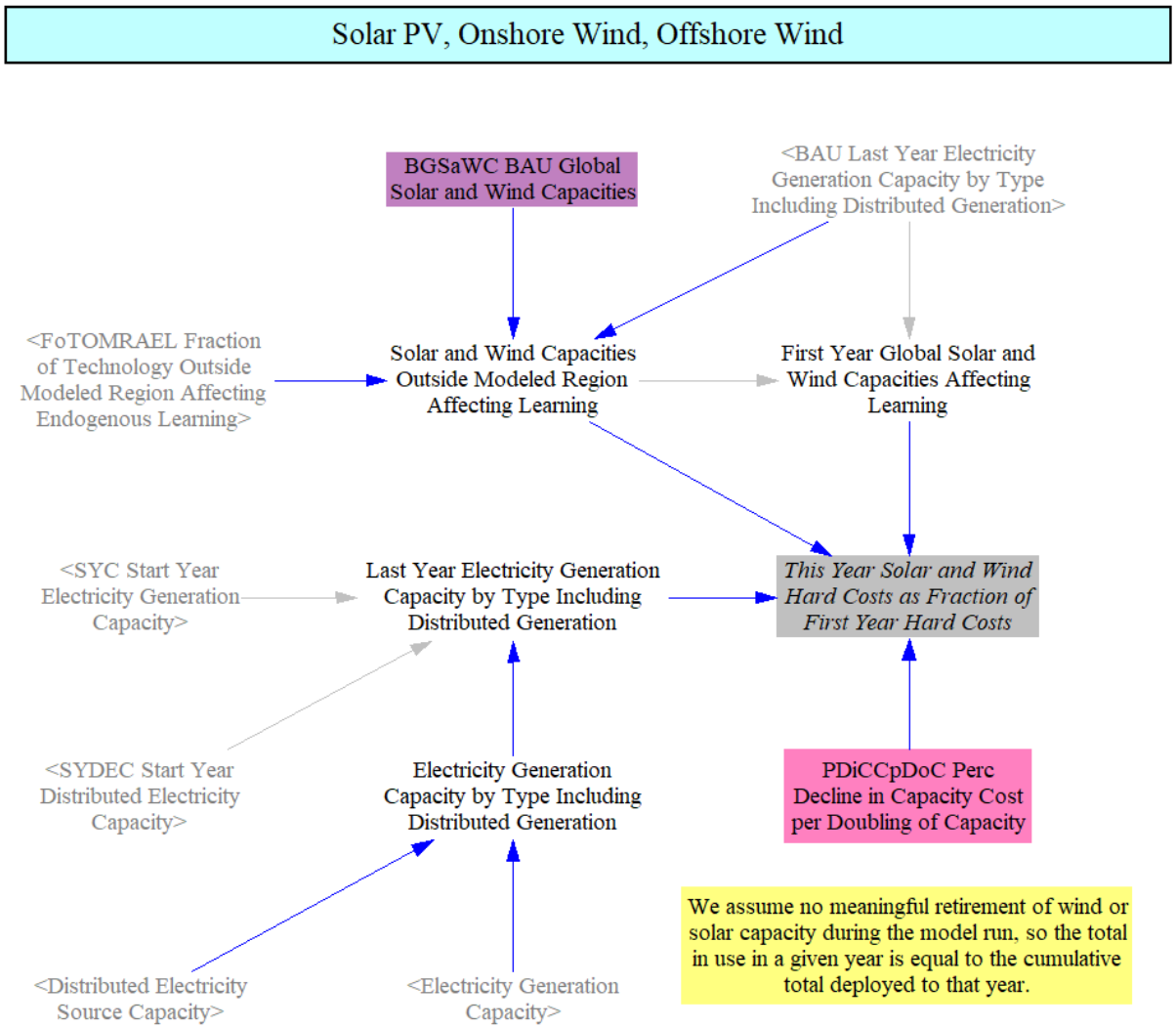


Fig. 6. Endogenous learning structure for selected energy technologies (original EPS model based on IFLC). Source: (Energy Innovation, 2021). Description of coloured variables refer to (Energy Innovation, 2021).

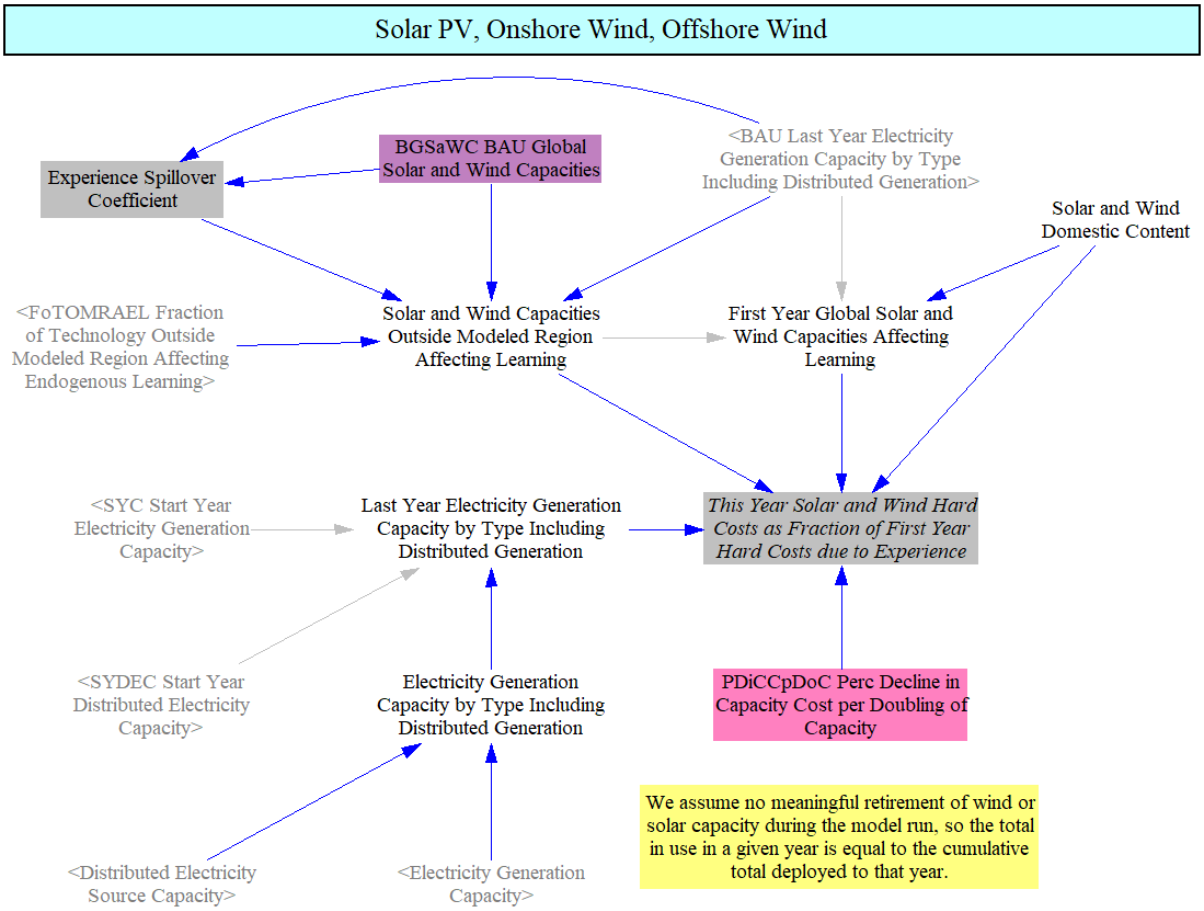


Fig. 7. Endogenous learning structure for selected energy technologies (modified EPS model based on a 2FLC approach). Description of coloured variables refer to (Source: (Energy Innovation 2021).

Knowledge stock is estimated based on domestic RD&D public investment. An additional policy was introduced to explore the role of additional public investment (or underinvestment) in energy RD&D for the electricity technologies selected. The model structure for estimating knowledge stock is presented in Fig. 8.

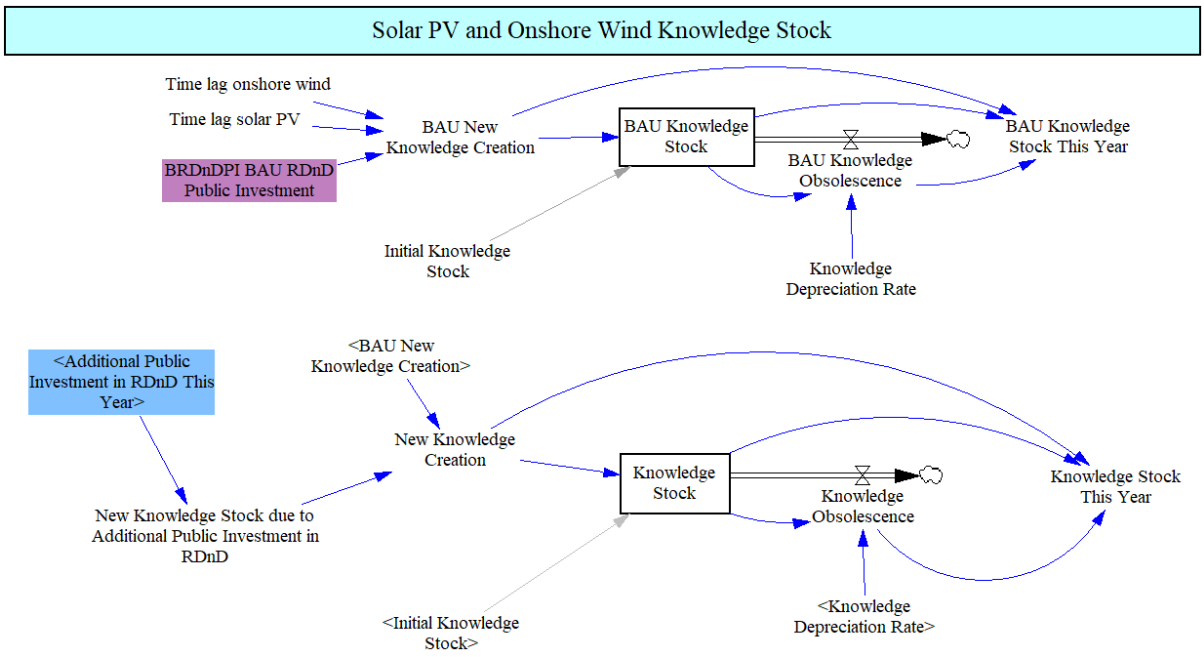


Fig. 8. Knowledge stock estimation for energy technologies selected. Description of coloured variables refer to (Source: (Energy Innovation 2021).

The variable labelled *This Year Solar and Wind Hard Costs as Fraction of First Year Hard Costs* (see Fig. 7) was replaced by the concept of *Learning Multiplier* (*LM*) defined in Section 3.1. This variable depends not only on the experience (estimated through domestic and external installed capacities) but also on technological knowledge stock created due to RD&D expenditures. The former was labelled as *Experience Multiplier* and the latter as *Knowledge Stock Multiplier* (see Fig. 9).

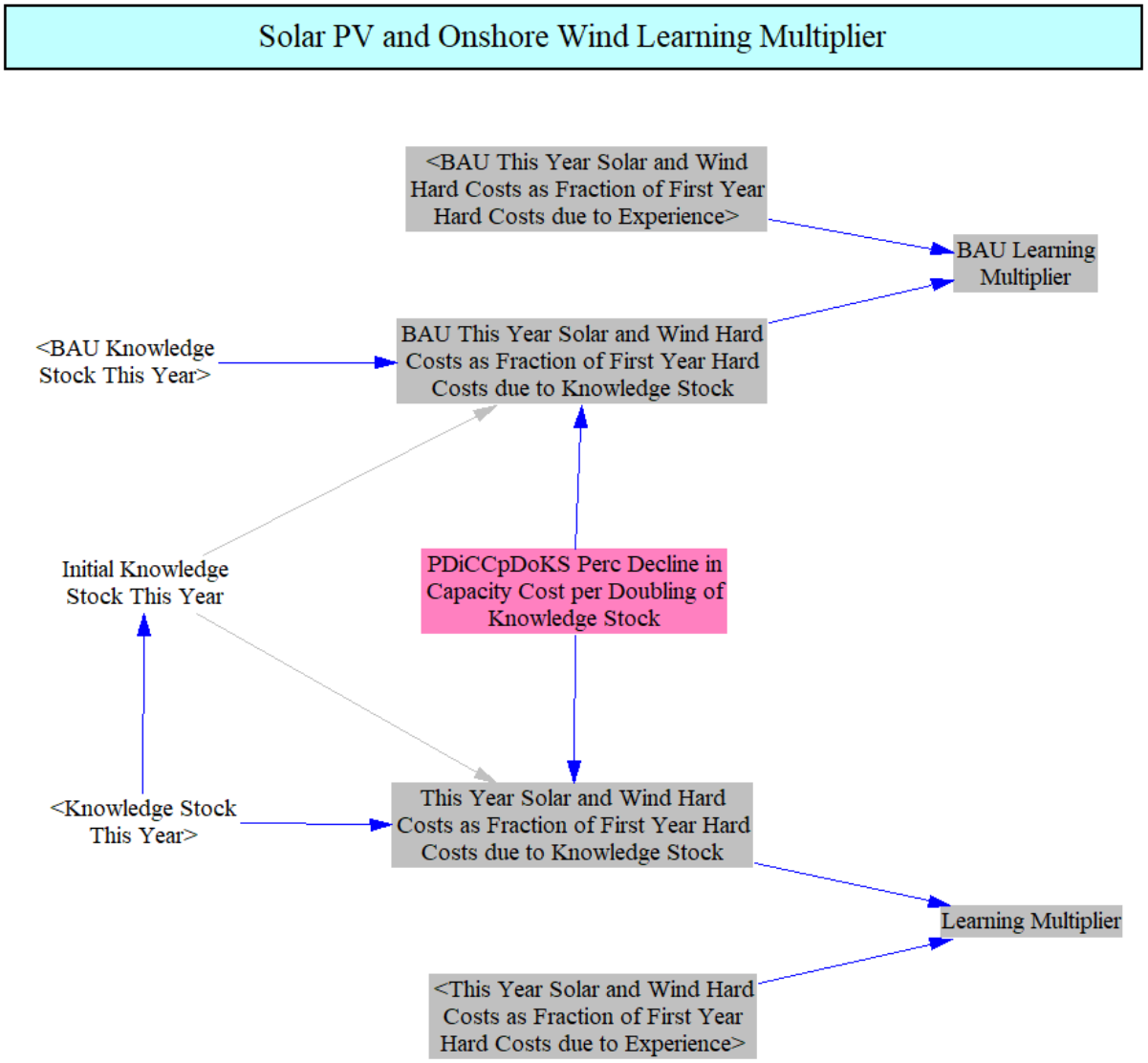


Fig. 9. Learning multiplier estimation for energy technologies selected. Description of coloured variables refer to (Source: (Energy Innovation 2021).

3.5. Simulation process

Input parameters in the EPS model undertake diverse data types (e.g. natural numbers, Booleans, real numbers divided into ten broad categories). Also, the EPS produces hundreds of output parameters within twelve broad categories (Energy Innovation 2021). Thus, the selection of inputs and outputs relevant to the analytical enquiry of this investigation represents a key task. The model's inputs, outputs, and calculation flow are presented in Fig. 10.

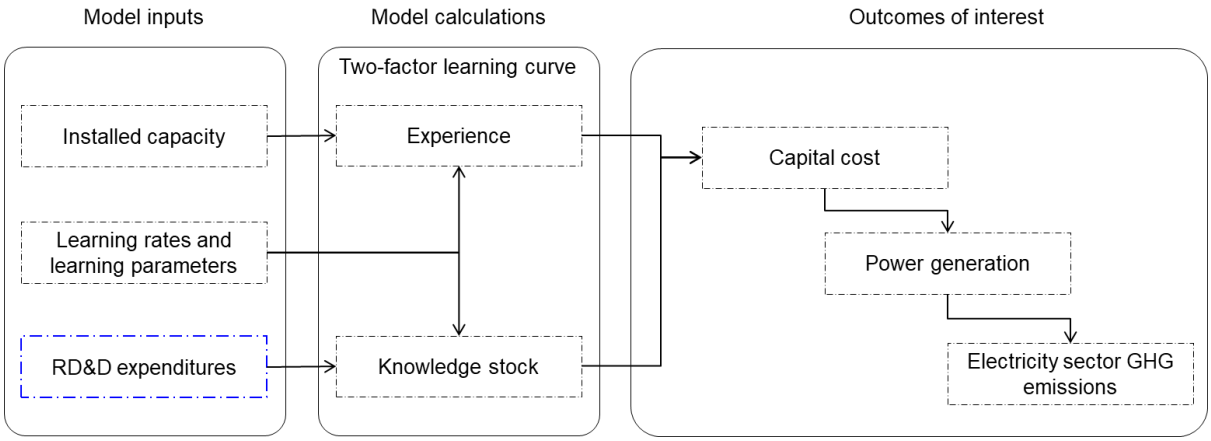


Fig. 10. Schematic diagram of the simulation process. Changes in RD&D investment as a policy lever is the focus of this investigation (blue dashed rectangle).

To explore the impacts of annual energy RD&D expenditures and knowledge accumulated, three scenarios were developed: business as usual (BAU) scenario, induced technological change (ITC) scenario, and low-innovation (LIN) scenario. Based on the 2FLC presented in (Castrejon-Campos, Aye & Hui 2022a), the BAU scenario is used to explore the impact of knowledge stock as a second source of learning (i.e. when public RD&D expenses are included in the model formulation) compared to the experience-only (1FLC) approach adopted in the original EPS model. The ITC scenario is used to explore the effects of additional government-financed RD&D expenditures on capital cost developments (compared to the BAU scenario). The LIN scenario is used to explore the impact of limited (under)investment (i.e. if policymakers would decide to reduce RD&D expenses) compared to the BAU scenario. Values on additional investment and limited (under)investment were set based on a basis of +/- 20% of cumulative investment under the BAU scenario from 2020 to 2050 (i.e. +/- 280 $ mil. and +/- 180 $ mil. for onshore wind and solar PV, respectively). The implementation of these (cumulative) investment strategies follows a S-curve shape along the simulation period.

4. Results and discussion

The aim of this article is to explore the potential effects of public energy RD&D expenditures on future technology cost developments, electricity generation, and electricity-sector GHG emissions. This section begins with a comparison between the BAU scenario applied by the original EPS model (1FLC approach) and the proposed BAU scenario which includes knowledge stock as a second source of learning (2FLC approach) to estimate future technology cost developments. It proceeds with exploring the effects of two RD&D-based innovation policy strategies on capital cost developments compared to the proposed BAU scenario: (1) if policymakers would decide to allocate additional RD&D investment to accelerate the speed of innovation processes (ITC scenario), and (2) if policymakers would decide to reduce investment in RD&D for renewable energy technologies (LIN scenario). Subsequently, the plausible effects of these innovation strategies on market dynamics (i.e. electricity generation) and environmental concerns (i.e. power-sector GHG emissions) are explored and discussed. Lastly, limitations and potential future research are presented and discussed.

4.1. The impact of RD&D public investment

The original EPS model adopted an experience-only approach to include endogenous learning within the simulation process. The data source used for defining learning rates for wind and solar PV is the 'state of the clean energy industry' keynote presented at the Bloomberg New

Energy Finance (BNEF)'s Future of Energy EMEA[24] Summit, held in London in 2017[25]. The document presented a learning-by-doing rate of 19% for wind (not distinguishing between onshore and offshore) and 24-28% for solar PV. However, how these learning rates were estimated is not clear within the document. Previous studies have suggested that the application of learning rates may result in misleading policy decision if sources of learning and learning parameters are not previously defined accordingly with the context of the study (Castrejon-Campos, Aye & Hui 2022a). Thus, we have estimated the learning rates (learning-by-deploying and learning-by-researching) for onshore wind and solar PV in the USA based on historical data as described in Section 3.3.

Total experience gained through technology deployment (learning-by-deploying) has been estimated accounting for learning sub-processes (i.e. learning-by-doing, learning-by-using, and international experience spillovers) as presented in (Castrejon-Campos, Aye & Hui 2022a). In the case of onshore wind, the learning-by-deploying (lbd) rate, estimated by using a 2FLC approach, is significantly higher than the learning-by-doing rate used in the original EPS model (i.e. 31.38% compared to 19%). On the other hand, the estimated lbd rate for solar PV resulted in a similar value used in the original EPS model (i.e. 27.56% compared to 24%). The empirical results obtained in this study (see Table 3) suggest that technological progress through technological experience (i.e. installed capacity additions) may play a more important role than knowledge stock (i.e. energy RD&D public investment) for these two renewable technologies (i.e. learning-by-deploying has a significantly larger impact than learning-by-researching). This finding is consistent with the technological maturity level of these technologies (i.e. mature technologies usually present high lbd rates and low lbr rates) as discussed in previous studies (see Castrejon-Campos et al., 2022a; Thomassen et al., 2020).

The estimated learning rates were used within the modified version of the EPS model to estimate the *annualised construction cost per unit capacity*. For onshore wind and solar PV, endogenous learning affects only a portion of the costs, known as technological-based costs (Castrejon-Campos, Aye & Hui 2022a). However, non-technological costs (e.g. soft costs such as permitting, transportation, and project management) also play an important role in the total technology capital cost. Although non-technological costs may follow different dynamics, they must be included in model-based energy policy analysis to explain the complete picture of capital cost developments. Thus, non-technological costs for technologies selected are handled via exogenous learning within the EPS model (Energy Innovation 2021). By integrating these two complementary methods (i.e. exogenous administrative processes and endogenous learning processes) technology capital cost developments over time were estimated using the original EPS model (1FLC approach) and the adaptation presented in Section 3.4 (2FLC approach). A graphical comparison between these approaches is presented in Fig. 11 for onshore wind and Fig. 12 for solar PV.

[24] Europe, the Middle East, and Africa (EMEA).

[25] The keynote may be found in https://about.bnef.com/blog/michael-liebreich-state-industry-keynote-bnef-emea-summit-2017/.

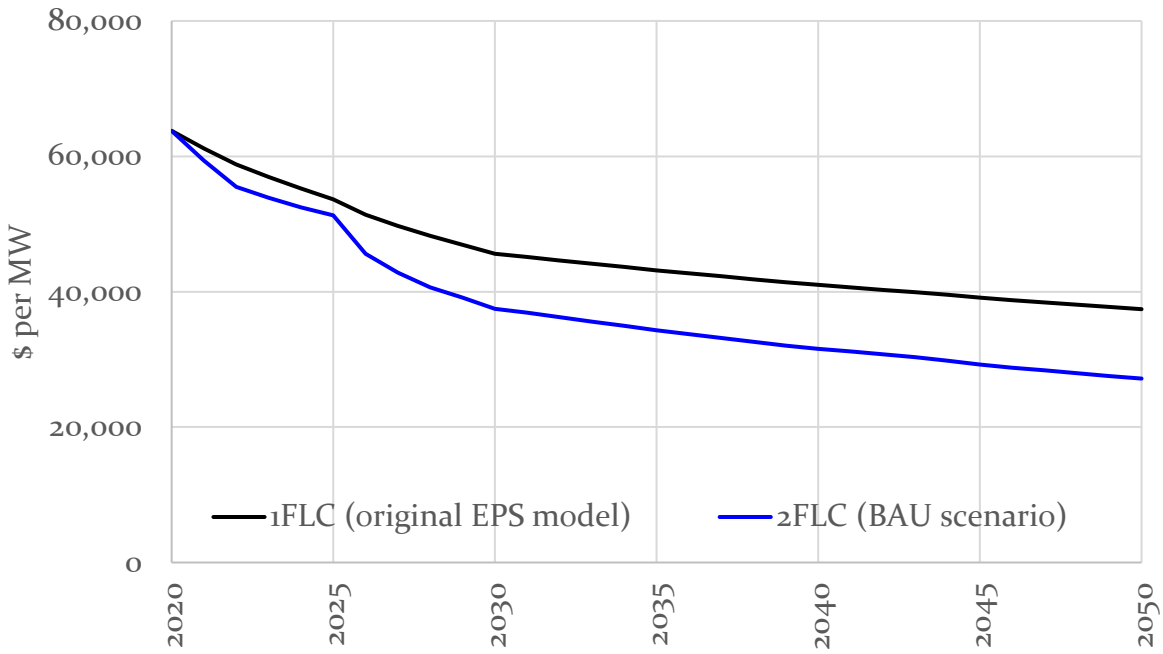


Fig. 11. Estimated annualised construction cost per unit capacity for onshore wind in the USA from 2020 to 2050.

When the 2FLC model formulation is applied to estimate technology capital cost developments from 2020 to 2050 for onshore wind and solar PV, a more accentuated reduction trend is observed for both technologies compared to the 1FLC approach. However, a larger gap can be observed for onshore wind (see Fig. 11) compared to solar PV (see Fig. 12). In the case of wind, the 2FLC approach shows a reduction of 57% by 2050 from the initial cost of 63,767 $ MW^{-1} in 2020 compared to a 41% reduction within the 1FLC approach. On the other hand, a reduction of 55% from the initial cost (50,390 $ MW^{-1}) is expected to occur for solar PV under the 2FLC approach, compared to a 47% under the original approach (1FLC). The difference between the two technologies may be explained by the relative contribution of local and global learning processes and the interaction between them. As previously discussed in (Castrejon-Campos, Aye & Hui 2022a), a dependent supply chain and a relatively weak domestic absorptive capacity may result in 'less' experience gained from learning-by-deploying processes and therefore less cost reduction in the case of solar PV, while a strong domestic manufacturing capacity and relatively strong domestic absorptive capacity may lead to 'more' experience for onshore wind.

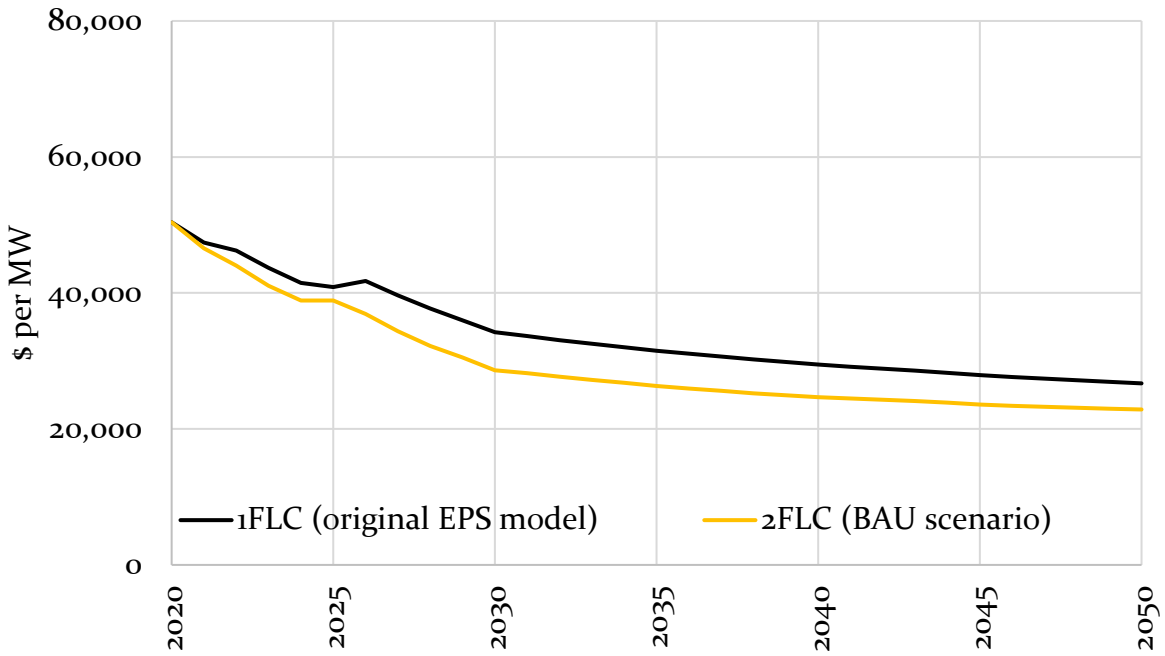


Fig. 12. Estimated annualised construction cost per unit capacity for solar PV in the USA from 2020 to 2050.

To decide how new capacity should be built to meet the total annual electricity demand, the model adopts a minimum cost approach by assigning priority to power plants based on the lowest cost (i.e. the power plant with lowest-cost is built first, then next-lowest cost plant, and so on). By representing the costs of each power plant type as a bell curve (i.e. normal probability distribution), the model finds the 'optimal' capacity to be built per technology (for details see Energy Innovation, 2021). Simultaneously, the cost of energy technologies modelled using an endogenous learning approach (i.e. wind and solar PV) depends on the installed capacity built (i.e. technological experience) over the simulation period, creating a feedback loop. By simulating future installed capacity developments (see Fig. 13), we have found that capacity construction for onshore wind and solar PV may be broadened under the 2FLC compared to the 1FLC approach. However, due to market dynamics and physical constraints some of the renewable energy capacity may not be dispatched to meet electricity demand (i.e. curtailment), as discussed in Section 4.4.

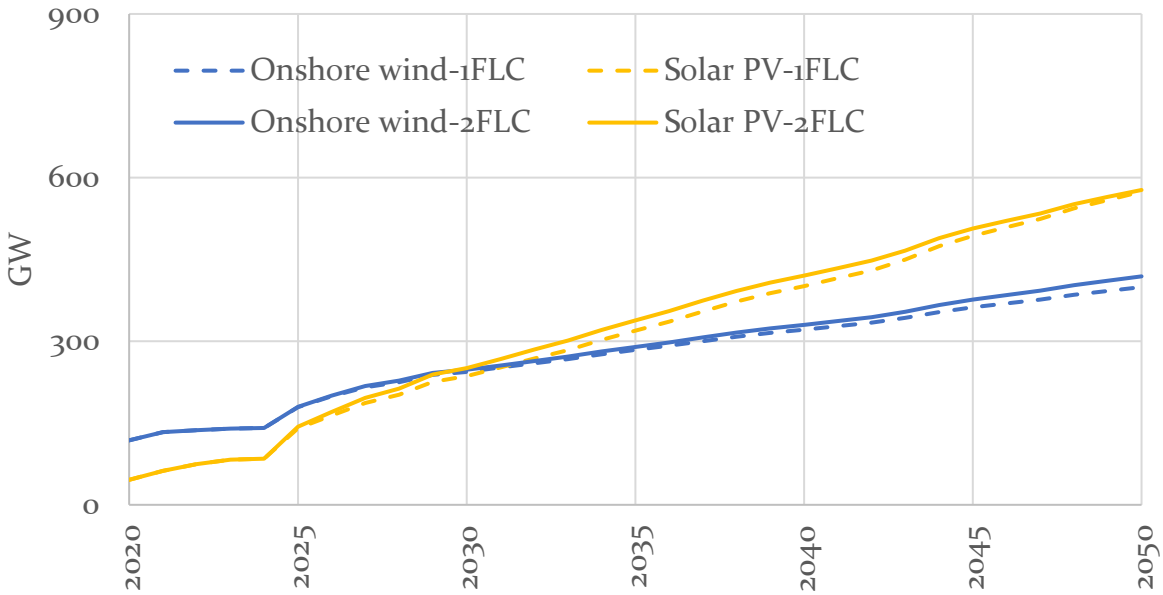


Fig. 13. Estimated installed capacity for wind and solar PV in the US from 2020 to 2050 under different approaches.

4.2. Additional RD&D public investment

By 2020 the USA government had spent around $3,000 and $5,400 mil. in RD&D for wind and solar PV, respectively (based on historical data). Following the logistic function approach described in Section 3.5, we have estimated that under the (2FLC) BAU scenario an additional $1,322 and $819 mil. dollars may be spent in RD&D by 2050 for onshore wind and solar PV, respectively. To explore the potential effects of additional RD&D public investment on technology capital cost developments, we have proposed the induced technological change (ITC) scenario (see Section 3.7). The ITC scenario assumes an additional $260 and $160 mil. dollars for onshore wind and solar PV respectively from the BAU scenario (around 20%). The implementation of this innovation policy strategy follows an S-shaped curve through the model run (as opposed to a linearly implementation schedule or a scheme of full implementation from the first years like other policy instruments within the EPS model). A comparison between the BAU and ITC scenarios is presented in Fig. 14 for wind and Fig. 15 for solar PV.

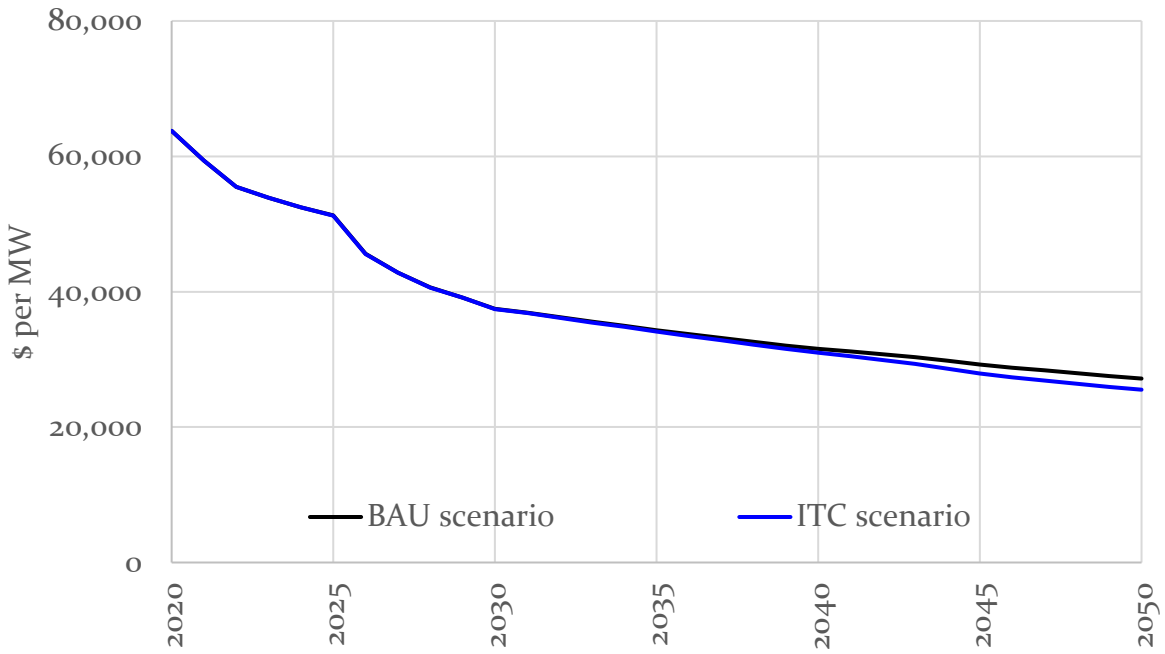


Fig. 14. Estimated annualised construction cost per unit capacity for onshore wind in the USA from 2020 to 2050.

We can observe that for both technologies capital costs may decline further if additional RD&D expenditures are allocated for these renewable technologies. In the case of onshore wind, the ITC scenario shows a reduction of 60% by 2050 from the initial cost (compared to a 57% reduction within the BAU scenario). Similarly, for solar PV a reduction of 58% by 2050 is expected from the initial cost in the ITC scenario (compared to a 55% reduction in the BAU scenario). However, the effects of these innovation efforts are not immediate; instead we can observe a long-term impact on capital cost reductions, reflected by a visually larger effect after 2040. This behaviour may be explained by the S-shape implementation schedule than follows the innovation policy. Thus, the exploration of different implementation schedule curves is proposed for future research.

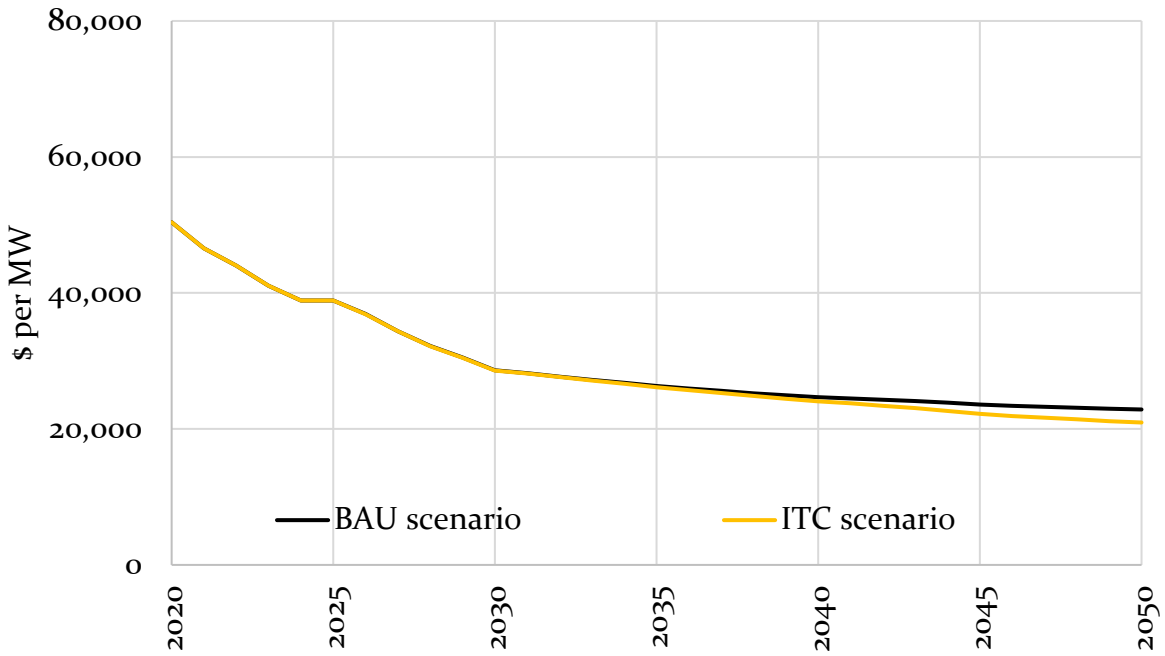


Fig. 15. Estimated annualised construction cost per unit capacity for solar PV in the USA from 2020 to 2050.

4.3. Limited RD&D public (under) investment

Following the same rationale of Section 4.2, we have proposed the limited innovation (LIN) scenario to explore the potential effects of RD&D underinvestment. The LIN scenario assumes a reduction of $260 and $160 mil. (around 20%) for onshore wind and solar respectively from the BAU scenario.

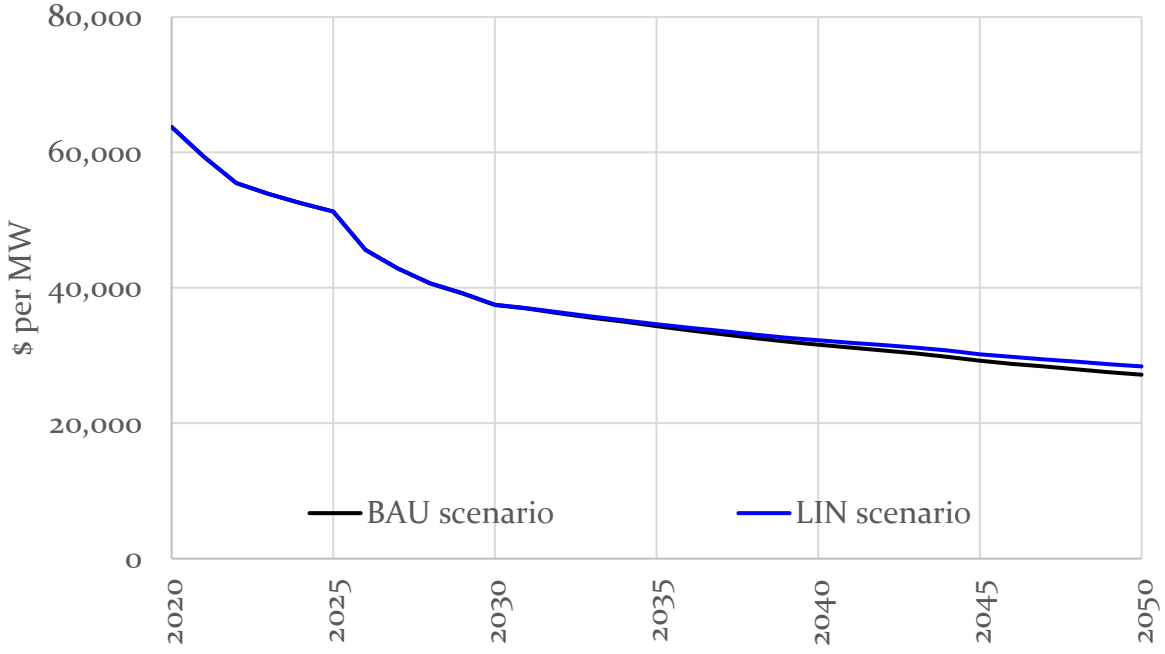


Fig. 16. Estimated annualised construction cost per unit capacity for onshore wind in the USA from 2020 to 2050.

As could be expected, cutting RD&D expenditures may have the opposite effect (in the long term) on capital cost developments as the ITC scenario. In the case of onshore wind, the LIN scenario shows a decrease of 55% by 2050 from the initial cost (compared to a 57% in the BAU scenario). Similarly, for solar PV a reduction of 52% by 2050 is expected from the initial cost in the LIN scenario (compared to a 55% reduction in the BAU scenario).

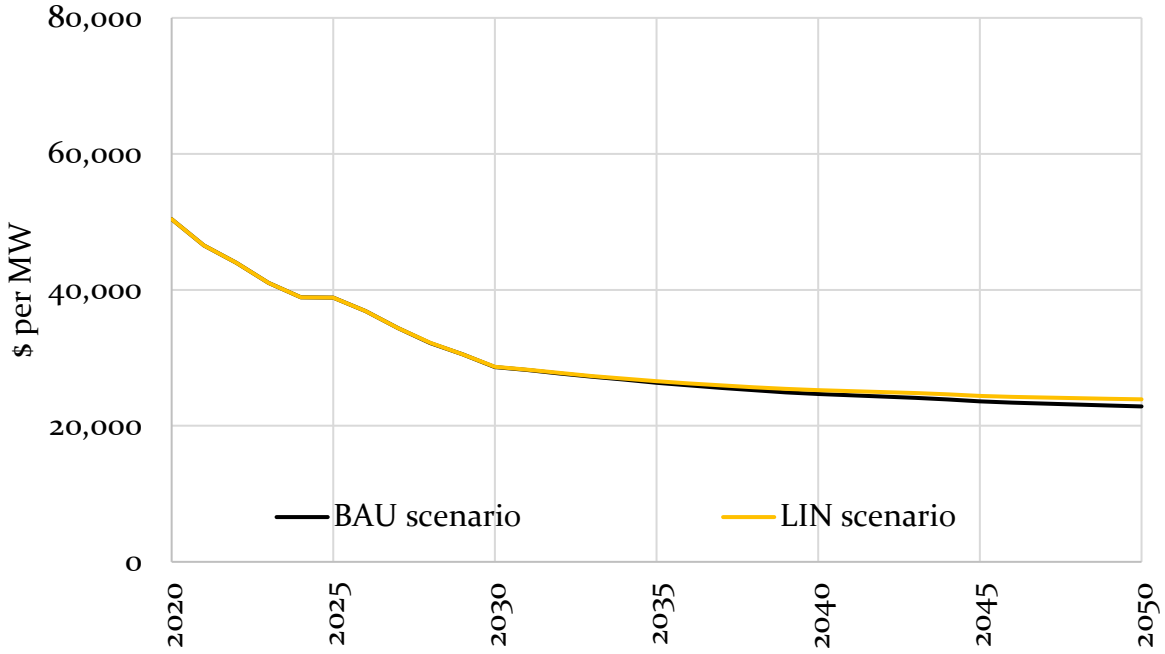


Fig. 17. Estimated annualised construction cost per unit capacity for solar PV in the USA from 2020 to 2050.

In addition, the effects of public RD&D on installed capacity developments under the three scenarios proposed are depicted in Fig. 18. Based on the simulation results for installed capacities, three aspects can be highlighted in this study. First, the market may favour the deployment of solar PV in the long term as this technology would be the cheapest technological option within the model runs. Second, although a relative difference on estimated annualised construction cost per unit capacity is observed between the BAU and LIN scenarios for onshore wind (see Fig. 16) and solar PV (see Fig. 17), no significant difference is perceived for predicted installed capacity for these technologies (see Fig. 18). This finding may be explained by the dynamic interaction between technology-push mechanisms (e.g. public investment in energy RD&D) and complementary market-pull policy strategies implemented within the model such as renewable portfolio standards, which requires a minimum share of electricity generation from renewable technologies (including onshore wind and solar PV). Third, following a 2FLC approach, learning-by-researching may have a large added value for renewable deployment in the long term as previously suggested in (Thomassen, Van Passel & Dewulf 2020; Castrejon-Campos, Aye & Hui 2022a).

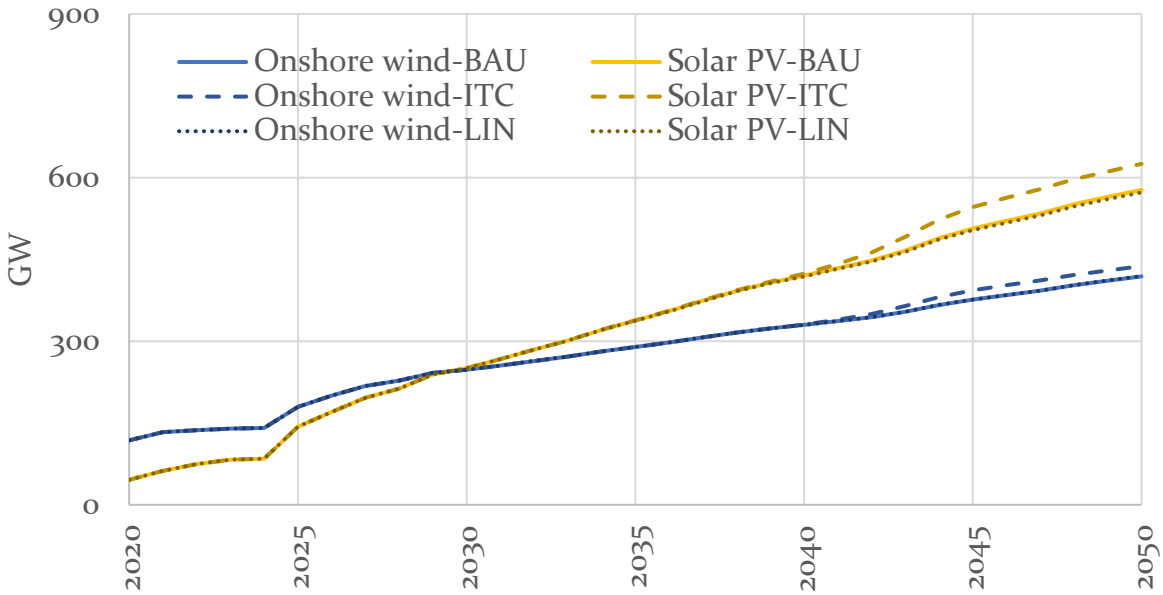


Fig. 18. Predicted installed capacity for wind and solar PV in the USA from 2020 to 2050 under diverse scenarios.

4.4. Effects of RD&D public investment on electricity generation

For energy technologies (as in many other sectors), cost is a key driver for increasing technology diffusion. As we have discussed in the previous sections, public investment in RD&D may influence capital cost developments for renewable energy technologies. However, this is not the only cost considered within the simulation process. Following the levelised cost of electricity (LCOE) approach, the model estimates the cost per unit output for all energy technologies (considering fixed and variable costs) and electricity is dispatched through two main mechanisms: guarantied dispatch mechanisms and least-cost dispatch mechanism (Energy Innovation 2021). Fig. 19 depicts the potential impacts on electricity generation of the two innovation policy strategies proposed in this study, compared to the BAU scenario. We can observe that under the ITC scenario, the market would favour the diffusion of solar PV and onshore wind in the long term. However, due to market dynamics in the electricity sector the behaviour of electricity generation may differ from the one observed for installed capacities of these technologies. This is, although more solar PV capacity is expected to be built in comparison to onshore wind capacity (see Fig. 18), the simulation results show that the market may favour the diffusion of onshore wind and constrain the penetration of solar PV in the long term (see Fig. 19). This may be explained due to renewable energy diffusion is heavily dependent on natural and physical constraints such as availability of natural resources or infrastructure. Thus, the variable aspect of these technologies and the not-yet-economically characteristic of energy storage as a complement for renewable generation, lead to curtailments. Even if solar PV and onshore wind reach high levels of deployment, electricity demand and market dynamics may guide the process of curtailment for these variable technologies.

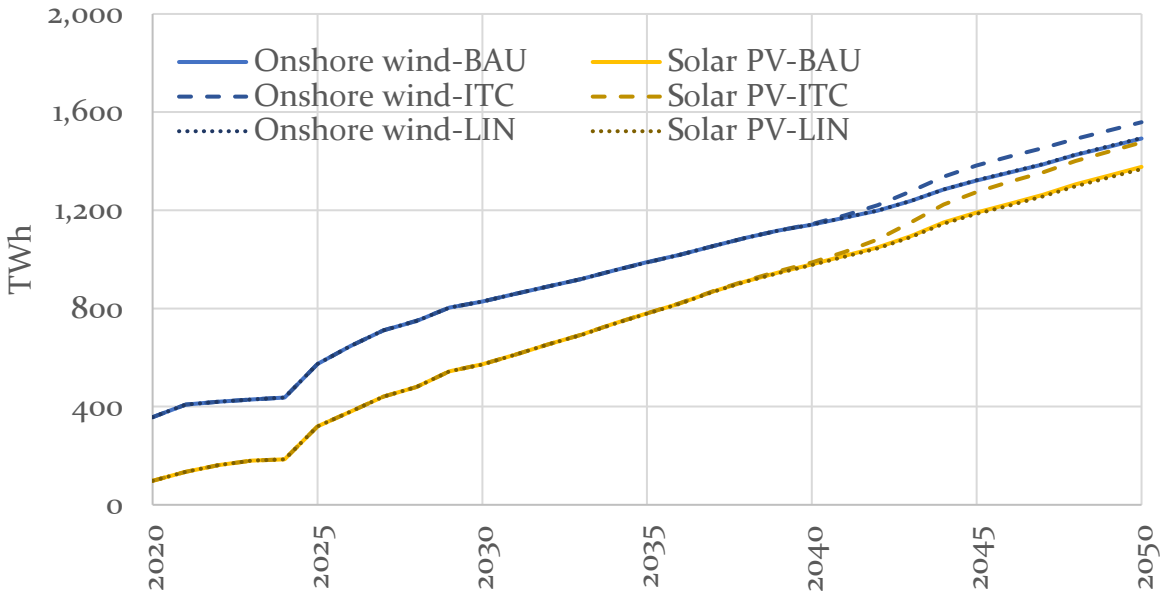


Fig. 19. Predicted electricity generation for wind and solar PV in the USA from 2020 to 2050 under diverse scenarios.

It is worth mentioning that under both scenarios, onshore wind may be the cheapest electricity generation technology with an average LCOE of $19.4 per MWh^{-1} (followed by solar PV with an average LCOE of $19.5 per MWh^{-1} and natural gas combined cycle with an average LCOE of $29.4 per MWh^{-1}).

4.5. Effects of RD&D public investment on GHG emissions

The model estimates pollutant emissions per MWh of electricity based on emissions indices (per unit energy in the fuel) and heat rates (energy units of fuel per MWh of electricity). Fig. 20 shows the total GHG emissions caused by the electricity sector. Although public investment in energy RD&D may play a significant role in reducing GHG emissions in the long term, little short-term effects can be seen from public RD&D efforts alone. This may be explained by multiple potential reasons. First, investment in electricity generation projects is costly and have a turnover rate of decades or more, thus a lock-in process may take place where incumbent companies for old technologies (e.g. natural gas or coal plants) may try to recover the costs by different means. Second, although a significant amount of additional electricity generation from renewable sources is expected during the model run, total electricity demand is expected to rise around 50% by 2050, highlighting the need for additional generation capacity from conventional sources. Third, the development and diffusion of variable renewable energy technologies (e.g. onshore wind and solar PV) may influence the development and diffusion of conventional energy technologies (e.g. natural gas) to ensure enough flexibility on the grid. For instance, if more solar PV and onshore wind are deployed, additional natural gas generation capacity (as a flexibility source for the system) may be needed to overcome the variable aspect of renewable energy generation. Fourth, public investment in energy RD&D may have a larger influence on technologies in the early stages of the innovation process (e.g. offshore wind, solar thermal, batteries) than on those technologies that have reached the full-commercialisation stage (e.g. onshore wind and solar PV), where market-pull policy instruments may have a larger effect on technology diffusion.

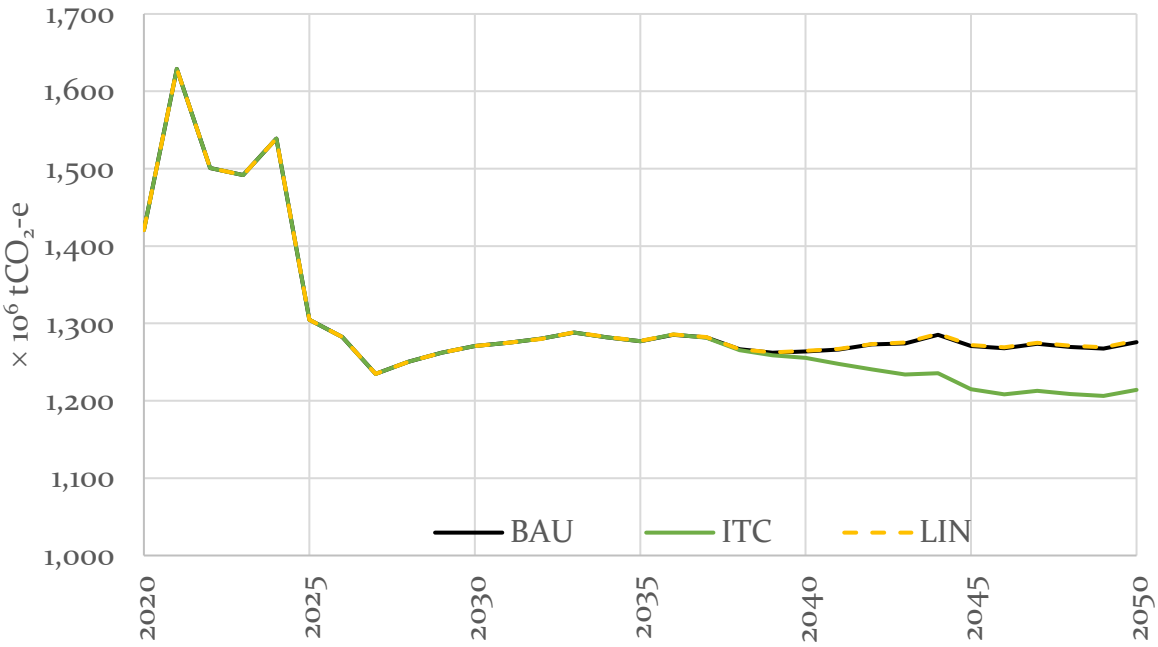


Fig. 20. Estimated GHG emission from the electricity sector in the USA from 2020 to 2050 under diverse scenarios.

4.6. Limitations and potential future research

While the 2FLC approach can improve the understanding of technological processes in energy systems, some limitations can be highlighted. First, data availability has been reported as one of the main issues when learning curves are used in energy models to inform policymaking (Rubin et al. 2015; Yeh & Rubin 2012; Samadi 2018; Castrejon-Campos, Aye & Hui 2022a). The 2FLC approach often encompasses public RD&D expenditures only, due to data on private investment in RD&D for energy technologies are usually not publicly available. Thus, including private RD&D investment within the model to investigate how (complementary) private and public RD&D expenditures affect technology costs projections is an important task for future research.

Second, the application of learning curves for model-based energy policymaking is context-dependent and how sources of learning are explicitly defined in energy models may have significantly different policy implications (i.e. different technology costs predictions based on alternative definitions of technological learning). Thus, analysing the role of alternative definitions of experience and knowledge stock is proposed for future research (e.g. including international spillover effects). Also, technological progress in energy systems is driven by complex dynamic interactions involving multiple factors. Apart from experience and knowledge stock, there may be other factors to include in energy models to inform policy-making decisions. Future research could be oriented to explore the potential effects of additional factors on energy systems (e.g. societal influences).

Third, in the process of knowledge development/creation and diffusion diverse actors may influence the pace and direction of innovation processes. In this article, we have focused on government actors who influence innovation through public investment in energy RD&D. However, other actors should be included in the analysis. For instance, universities or research institutes may influence innovation processes by focusing researching efforts on specific challenges. Also, interest groups may influence through lobbying. Similarly, end-users may play a key role in diffusion of innovations through social acceptance to capture market diffusion complexity (Bettin 2020). Although future technology progress may be estimated

using quantitative methods, such as the learning curve approach, complementary qualitative analyses may help to better explain the plausible effects of technological change on energy systems.

Fourth, we have investigated the role of a technology-push policy instrument (public investment in energy RD&D), however the dynamic interactions between this and complementary market-pull policy instruments focused on energy transitions should be further analysed. A promising mixed approach (quantitative and qualitative analyses) aiming at investigating policy mixes under deep uncertainty towards clean energy transitions may be found in (Castrejon-Campos, Aye & Hui 2020).

5. Conclusions and policy implications

Innovation policy focused on supporting clean energy development and diffusion plays a crucial role in reducing GHG emissions. The aim of this article was to explore the potential impacts of public investment in energy research, development, and demonstration (RD&D) on future technology cost developments by using a two-factor learning curve (2FLC) approach. We compared the 2FLC approach adopted in this investigation with a one-factor learning curve (1FLC) approach using a system dynamics model. Also, we explored the plausible long-term economic and environmental effects of diverse RD&D investment scenarios on electricity generation and GHG emissions. The focus was on onshore wind and solar photovoltaics (PV) in the United States of America (USA).

Learning rates were estimated based on empirical data by applying a 2FLC approach. Technological experience (using installed capacity as proxy) and knowledge stock (using public investment in energy RD&D as a proxy) were chosen as the main sources of learning. We found that the learning-by-deploying rates were 31.38% and 27.56%; and the learning-by-researching rates were 2.3% and 4.72% for onshore wind and solar PV, respectively. The estimated learning rates suggest that technological experience may have a significantly larger impact than knowledge stock, which is consistent with the maturity level of these renewable technologies. Following the logistic function approach described in Section 3.5, we have estimated that an additional $1,322 and $819 mil. are expected to be spent in RD&D for onshore wind and solar PV respectively by 2050 (BAU scenario). Using the estimated learning rates and predicted public investment in RD&D, we explored the potential impacts of changes in public (under)investment in energy RD&D on renewable energy cost developments, electricity generation, and GHG emissions. It was found that RD&D investment may play a critical role in the speed of capital cost reductions and technology diffusion. However, little effects can be seen on market dynamics and GHG emissions from RD&D efforts alone. Also, limitations of the investigation and potential future research were presented and discussed in Section 4.6.

Based on this analysis, some policy implications can be highlighted.

(1) The behaviour of innovation and diffusion of new energy technologies may be different from previous technologies or from other regions due to structural changes within the electricity system (e.g. different actors, different market dynamics, different institutions, infrastructure needs). Model-based investment decisions may vary significantly based on the stakeholder's definition of technological progress. The application of learning rates for model-based energy policymaking is context-dependent and may lead to significantly different technology costs predictions if sources of learning and parameters are not previously analysed and defined accordingly. The integration of public investment in energy RD&D adds a technology-push policy variable to the model and reduces somehow the problem of omitted variable bias. It has been found that incorporating learning through RD&D may accelerate or slow down the speed of costs reductions and technology diffusion compared to scenarios employing a one-factor learning curve approach.

(2) This article attempted to explain the economic and environmental benefits of public investment in energy RD&D. We have assumed no constraints to budget allocation for energy RD&D. However, public RD&D investment in energy technologies are restricted by several factors (e.g. financing constraints, finding an optimal RD&D resource allocation, market organisation, lack of information). Technology-oriented innovation policies may pose a danger in crowding out other relevant initiatives (e.g. investment in other promising technologies or market-pull policies). This is, other policy instruments may get less resources due to the nature of public limited resources. Although these limitations, energy RD&D has been recognised as a key policy tool for clean energy transitions in a cost-effective way by reducing technical issues, improving technology performance, and supporting technology niche markets.
(3) We found that public investment in energy RD&D alone may have little impact on GHG emissions (only evident in the long term). This finding highlights the importance of complementing technology-push mechanisms with market-pull policies throughout the innovation process. After the basic principles of a technology are proven (e.g. through demonstration plants) and market formation take place (i.e. early technology diffusion), complementary efforts are needed to drive the cost (and price) down to a competitive level and foster technology deployment.
(4) There is no simple policy instrument for reducing GHG emissions. The best approach would be to adopt a policy mix (i.e. diverse policy instruments) that reinforce policy strategies for tackling emissions. If they are designed properly, they could minimise the cost of transitioning to a low-carbon economy. Thus, the investigation of the potential effects of diverse policy mixes on clean energy transitions is suggested as a future research.

Data Availability

The data that support the findings of this article are available in Mendeley Data at https://doi.org/10.17632/82nfwvcgdz.2 (Castrejon-Campos, Aye & Hui 2022b).

CRediT authorship contribution statement

Omar Castrejon-Campos: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualisation. **Lu Aye:** Validation, Resources, Writing - review & editing, Visualisation, Supervision, Project administration, Funding acquisition. **Felix Kin Peng Hui:** Supervision, Writing - review & editing. **Paulo Vaz-Serra:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Sensitivity analysis with respect to alternative time lags and periods of analysis to estimate learning rates for onshore wind and solar PV in the USA

Table A1
Sensitivity analysis with respect to alternative time lags and periods of analysis for onshore wind

Time lag	Period	lbd[a] rate (%)	lbr[b] rate (%)	R-squared (-)	RMSE[c] ($ kW^{-1})
2	2008-2020	18.65	11.81	-0.19	334.31
	2009-2020	32.81	-10.20	0.87	110.52
	2010-2020	33.00	-3.74	0.93	73.18
3	2008-2020	12.11	29.74	0.39	239.28
	2009-2020	29.17	2.81	0.84	124.62
	2010-2020	31.38	2.30	0.91	85.02
4	2008-2020	13.19	29.31	0.40	237.10
	2009-2020	25.64	13.42	0.90	95.22
	2010-2020	28.42	10.44	0.93	74.26
5	2008-2020	13.60	29.06	0.40	237.32
	2009-2020	25.82	13.09	0.91	91.25
	2010-2020	28.75	9.33	0.95	63.93

[a] lbd = learning-by-deploying. [b] lbr = learning-by-researching. [c] RMSE = Root Mean Square Error.

Table A2
Sensitivity analysis with respect to alternative time lags and periods of analysis for solar PV

Time lag	Period	lbd[a] rate (%)	lbr[b] rate (%)	R-squared (-)	RMSE[c] ($ kW^{-1})
2	2008-2020	29.79	-66.11	0.97	195.68
	2009-2020	30.29	-60.57	0.98	126.25
	2010-2020	29.64	-67.69	0.99	76.61
3	2008-2020	31.73	-67.83	0.86	424.89
	2009-2020	32.93	-62.54	0.98	153.52
	2010-2020	33.19	-59.79	0.93	218.98
4	2008-2020	31.82	-48.11	0.75	559.35
	2009-2020	34.36	-57.08	0.88	346.03
	2010-2020	35.84	-57.20	0.82	352.05
5	2008-2020	27.56	4.72	0.81	484.44
	2009-2020	31.50	-13.67	0.86	384.88
	2010-2020	35.18	-31.46	0.65	484.80

[a] lbd = learning-by-deploying. [b] lbr = learning-by-researching. [c] RMSE = Root Mean Square Error.

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Chapter 5

Robust policy mixes for clean energy transitions in developing countries: An exploratory analysis for Mexico

In Chapter 2, a new integrated method for energy policy analysis was developed and presented. The stepwise implementation of the proposed method derived in the development and implementation of complementary analytical tools to improve its applicability. These tools include a new theoretical framework to qualitatively describe the evolution of energy systems at different scales (Chapter 3) and a new integrative technological learning model to explore the effects of learning processes on historical and future technological-based cost developments (Chapter 4). Chapter 3 contributes to improve the policy problem definition step within the integrated method (first step), and Chapter 4 contributes to enhance model development subprocess within the exploratory modelling and analysis process (third step). Thus, this chapter presents the full implementation of the integrated method by using the results and findings of previous chapters to explore the plausible consequences of adopting different policy mixes towards a clean energy transition in Mexico. Based on the stepwise implementation of the proposed method for policy analysis, this chapter presents and discusses policy recommendations to design and implement robust policy alternatives towards a clean energy transition in Mexico.

Chapter 5 empirically contributes to this study by answering Question #5:

- *What are the most robust policy alternatives to be implemented in the Mexican electricity sector to achieve long-term energy policy objectives?*
- *Considering deep uncertain conditions, what are the potential impacts of adopting different policy alternatives on the electricity sector in Mexico?*
- *What are the most influential policy instruments in achieving energy policy objectives in Mexico?*
- *What are plausible scenarios under which robust policy alternatives are vulnerable?*

Chapter 5 is based on a journal article with the same title, to be submitted to *Nature – Energy*. The format and numbering of the sections are according to the original publication style (see Appendix E).

Chapter 5

Robust policy mixes for clean energy transitions in developing countries: An exploratory analysis for Mexico

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ABSTRACT

Energy transitions to cleaner energy systems are required to fulfil international commitments on climate change mitigation. Energy policy instruments play a crucial role in influencing the direction and pace of clean energy transitions. Although the future is uncertain, an understanding of transition dynamics in the face of multiple plausible futures is needed. By implementing an integrated method to explore the potential impacts of robust energy policy mixes towards clean energy transitions, multiple energy transition pathways are simulated and analysed using statistical and data-mining techniques. The analysis reveals that policymakers in Mexico should focus on economic signals and performance standards to meet medium and long-term policy objectives on greenhouse gas emissions reduction strategies (i.e. clean energy development, energy efficiency improvement). In addition, the results illustrate the importance of considering deep uncertain factors for organising energy policy recommendations to achieve robust policy mixes towards clean energy transitions in developing countries.

***Keywords*:** energy policy mix, clean energy, energy transitions, robustness, Mexico, exploratory modelling and analysis.

Significant reductions in greenhouse gas (GHG) emissions are necessary to combat climate change and limit global temperature rise well below 2°C, preferably to 1.5°C above pre-industrial levels by the end of this century (Masson-Delmotte et al. 2019). Immediate policy action is needed for transitioning to more sustainable economies. Quantitative modelling on energy policy analysis is a useful tool for exploring the potential impacts of individual policy instruments (or a mix of instruments), particularly when a real-life test process is impractical. However, energy policymaking for clean energy transitions commonly deals with strategical, tactical, and operational challenges due to an extensive range of deep uncertainties such as fuel prices fluctuations, unpredictable energy demand, and climate change (Castrejon-Campos, Aye & Hui 2020). Ignoring deep uncertainty is attractive due to budget constraints, conflicting interests, and political instability. However, policy decisions that ignore deep uncertainty disregard reality (Marchau et al. 2019). Reductions in uncertainty might simplify choices in the short term by substituting assumptions for deep uncertainties but may limit the exploration of long-term options. Under deep uncertainty conditions, the policy learning process can be improved by applying model-based policy analysis with a robust approach to aid policymakers in exploring the consequences of implementing various policy alternatives towards clean energy transitions (Castrejon-Campos, Aye & Hui 2020).

Electricity consumption has contributed significantly to GHG emissions, especially in developing countries (Castrejon-Campos, Aye & Kin Peng Hui 2022). Mexico is an interesting case study as the 11th largest GHG emitter worldwide due to its fossil fuel-intensive energy mix (Castrejon-Campos, Aye & Kin Peng Hui 2022; Castrejon-Campos 2022). To fulfil international agreements on climate change mitigation, Mexico has set ambitious national GHG emissions reduction targets (22% by 2030 from business as usual and 50% from 2000 levels) with the electricity sector to be the largest contributor of these reductions (Castrejon-Campos 2022). Medium and long-term targets for electricity generation from clean energy sources aimed at reaching a share of 38.2% in total generation by 2030, and 50% by 2050

(Diario Oficial de la Federación (DOF) 2020). However, multiple socio-techno-economic challenges to put the country on a path to a low-carbon future have been identified (e.g. the ever-growing electricity demand) (Castrejon-Campos 2022; Castrejon-Campos, Aye & Kin Peng Hui 2022). Various policy instruments to overcome these barriers and allow a transition towards a clean energy system in Mexico have been identified and qualitatively discussed in (Castrejon-Campos 2022). However, clean energy development in Mexico may be affected by factors outside the control of policymakers such as fuel (mainly natural gas) prices for electricity production, technological progress, price-demand elasticities, and investment preference structures adopted by private generators. Based on the specific characteristics of Mexico's electricity system, the quantitative exploration of different policy mixes considering deep uncertain factors has been advocated recently (Castrejon-Campos 2022). Thus, an exploratory analysis on future transition pathways is conducted in this work to gain insights on what could be the most robust policy alternatives to efficiently meet the rapid growing electricity demand, reach the long-term target of generating 50% of electricity with clean energy technologies by 2050 (compared to 20% in 2019), and fulfil international climate change commitments.

By adopting an exploratory approach, a large number of experiments (i.e. energy transition pathways) were obtained and analysed using statistical and data-mining techniques. Our findings show that policymakers in Mexico should focus on economic signals and performance standards to meet long-term policy objectives. The application of the robust policy mixes obtained from the analysis could contribute to reduce up to 55% of GHG emissions from electricity production by 2050 (with respect to a business-as-usual scenario).

Exploring robust policy mixes towards clean energy transitions in Mexico

Traditional energy policymaking approaches attempt to predict what will happen in the future by using predictive energy models (Castrejon-Campos, Aye & Hui 2020). Many bottom-up, perfect-foresight cost-optimising models (e.g. NEMS in the US, or MARKAL in the UK)

produce energy scenarios based on thousands of structural and parametric assumptions to inform large-scale infrastructure planning decisions or to assess national-level policy strategies (Trutnevyte 2016). However, if changing conditions over time and multiple perspectives from stakeholders are considered, the application of traditional policy-making approaches to complex, evolving issues (e.g. energy transitions) is limited (Castrejon-Campos, Aye & Hui 2020). Thus, policy analysis with a robustness-based approach can be used as a systematic process for exploring the plausible consequences of adopting different policy instruments in a dynamic setting (Walker 2000).

An integrated method to explore the impact of robust energy policy strategies towards clean energy transitions is applied in this research (Castrejon-Campos, Aye & Hui 2020). The method is shaped by combining quantitative and qualitative approaches (i.e. mixed method): integrating sustainability and energy transitions concepts, analytical tools used by robustness-based approaches, quantitative simulation modelling techniques, and exploratory modelling and analysis (EMA) (see Methods section). A system dynamics model (Energy Policy Simulator (EPS) – Mexico version (Energy Innovation 2021)) has been adapted and used to explore the effects of energy-related policy instruments in future energy transitions (to 2050).

Using the EPS model as a simulation tool, we have found that without any interventions (BAU scenario) 907 million metric tonnes of carbon dioxide equivalent (Mt CO_2-e) may be emitted nationally by 2030 and 1,329 Mt CO_2-e by 2050 (considering the whole Mexican energy sector). GHG emissions from the electricity sector are expected to be around 167 Mt CO_2-e by 2030 (30% higher than the target set by the government of Mexico) and 224 Mt CO_2-e by 2050. Also, the expected share of clean energy technologies is 27% by 2030 and 37% by 2050 (below the targets of 38% and 50%, respectively). In addition, the expected electricity demand may reach 416 TWh by 2030 and 712 TWh by 2050 (well above the targets of 301 and 385, respectively). Thus, it is evident that further immediate policy action is needed to achieve

medium and long-term policy targets on mix diversification, climate change mitigation, and energy efficiency improvement.

There is no simple policy strategy to reduce complicated GHG emissions, increase the uptake of clean energy technologies, and reduce electricity demand. Various (complementary) technology-push (e.g. public investment in R&D) and market-pull (e.g. carbon tax, energy efficiency standards) policy instruments are needed. It is a matter of designing, adopting, and implementing the 'right' policy mix to achieve these medium and long-term targets. Thus, an exploratory process is required to investigate the potential consequences of implementing different policy alternatives.

There are three general approaches for conducting the exploration process: framed exploration, open exploration, and directed search (Marchau et al. 2019). While a framed exploration can be carried out based on policymakers' interest in specific policy instruments (i.e. using pre-specified policy instrument mixes), this work focuses on exploring alternative policy mixes not predefined by decision-makers (i.e. open exploration and directed search).

Open exploration

Exploratory analysis can be conducted following an open-ended approach if there is no agreement on the predefined set of policy instrument mixes to investigate (e.g. due to contested interests among stakeholders or the difficulty of choosing policy alternatives from a large range of options). For instance, there are more than 1,300 policy levers in the EPS model (considering separate subscripted elements of a policy), making it difficult to manually explore the effects of various policy alternatives. Thus, by exploring various policy alternatives we acknowledge that they are plausible based on various stakeholders' interests.

To gain insights about the impact of policy alternatives and uncertainties, the exploratory process was conducted by sampling five policy alternatives and 200 scenarios using the modified version of the EPS-Mexico model as a scenario generator. The decision space and

uncertainty space were sampled using Latin hypercube sampling (LHS). LHS is more beneficial than other sample techniques (e.g. Monte Carlo, full factorial design) for long running models when computational resources are limited (Agusdinata 2008). LHS forces the specified sample size to cover the whole experimental space (i.e. uncertainty space and decision space) by producing a sample that is random but relatively uniformly distributed over each dimension (Agusdinata 2008). To visualise the five sampled policy alternatives (i.e. the values of different policy instrument mixes) a series of parallel coordinate plots were generated and are presented in Fig. 1. Each coloured line represents a policy alternative.

Each policy alternative was evaluated over each plausible scenario (1,000 experiments in total). Energy transition pathways are explored with regard to the behaviour of the performance metrics (i.e. outcomes of interests) defined in the experiment setting (see Methods). Fig. 2 depicts the envelope plot of six performance metrics over time and Gaussian Kernel Density Estimates (KDEs) of their end state in 2050. Additional performance metrics can be explored by implementing the python code presented in Supplementary Information. Fig. 2 shows that Policy Alternative 1 (yellow lines) outperforms with respect to the share of clean energy, total electricity demand, and emissions from electricity generation (i.e. relatively lower electricity demand, higher share of clean energy sources, and less GHG emissions), which are directly related to the policy objectives of mix diversification, emissions mitigation, and energy efficiency set by the government of Mexico. However, the implementation of this policy alternative may result in a relatively higher cost (or less financial savings) in the long-term, compared to other policy alternatives (see KDEs of the *Policy cost curve* in Fig. 2). Thus, a more in-depth analysis is needed to understand the potential medium and long-term impacts of these policy alternatives under deep uncertainty conditions. In this section, the simulation results are interpreted and discussed in terms of medium-term policy objectives for 2030 (detailed descriptions in (Castrejon-Campos 2022)). Following a similar open

exploration approach, the analysis of results for long-term policy objectives for 2050 may be found in Supplementary Information.

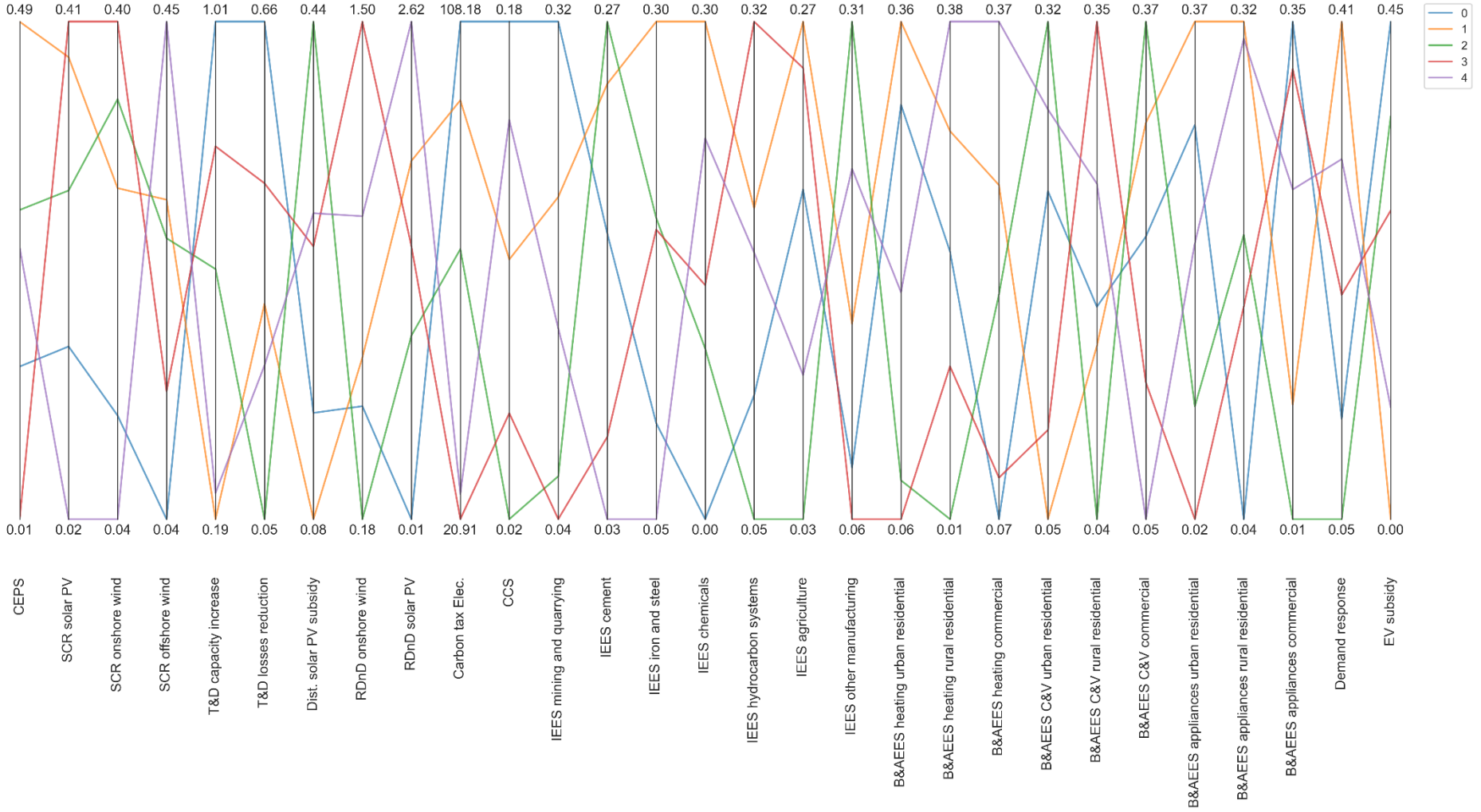


Fig 1. Policy alternatives generated using Latin hypercube sampling.

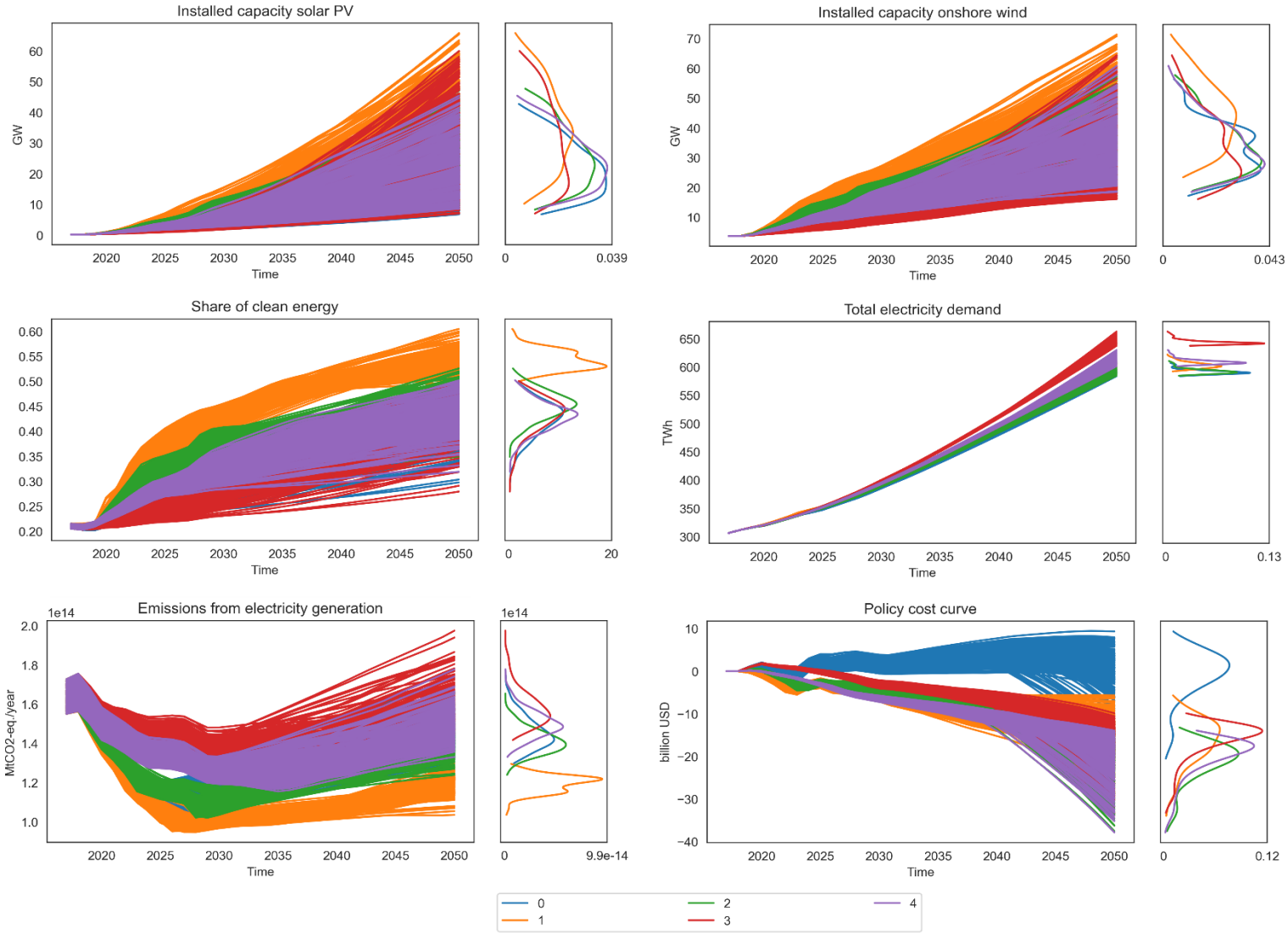


Fig 2. Behaviour over time of selected performance metrics and Gaussian Kernel Density Estimates of their end state in 2050.

Medium-term policy objectives analysis

To gain an understanding of the objective space, Fig. 3 shows a pairs plot where each policy objective is paired against every other policy objective to visualise the performance of policy alternatives in relation to 2030 policy objectives. Based on the results (see *Electricity emissions in 2030* v *Clean energy share in 2030* in Fig. 3), the deployment of clean energy technologies may result in lower emissions from electricity production (i.e. the higher the clean energy shares the lower the electricity emissions, as may be expected). However, emission reductions from electricity generation may result in a higher cost of policy mix by 2030 (see *Policy mix cost 2030* v *Electricity emissions in 2030* in Fig. 3).

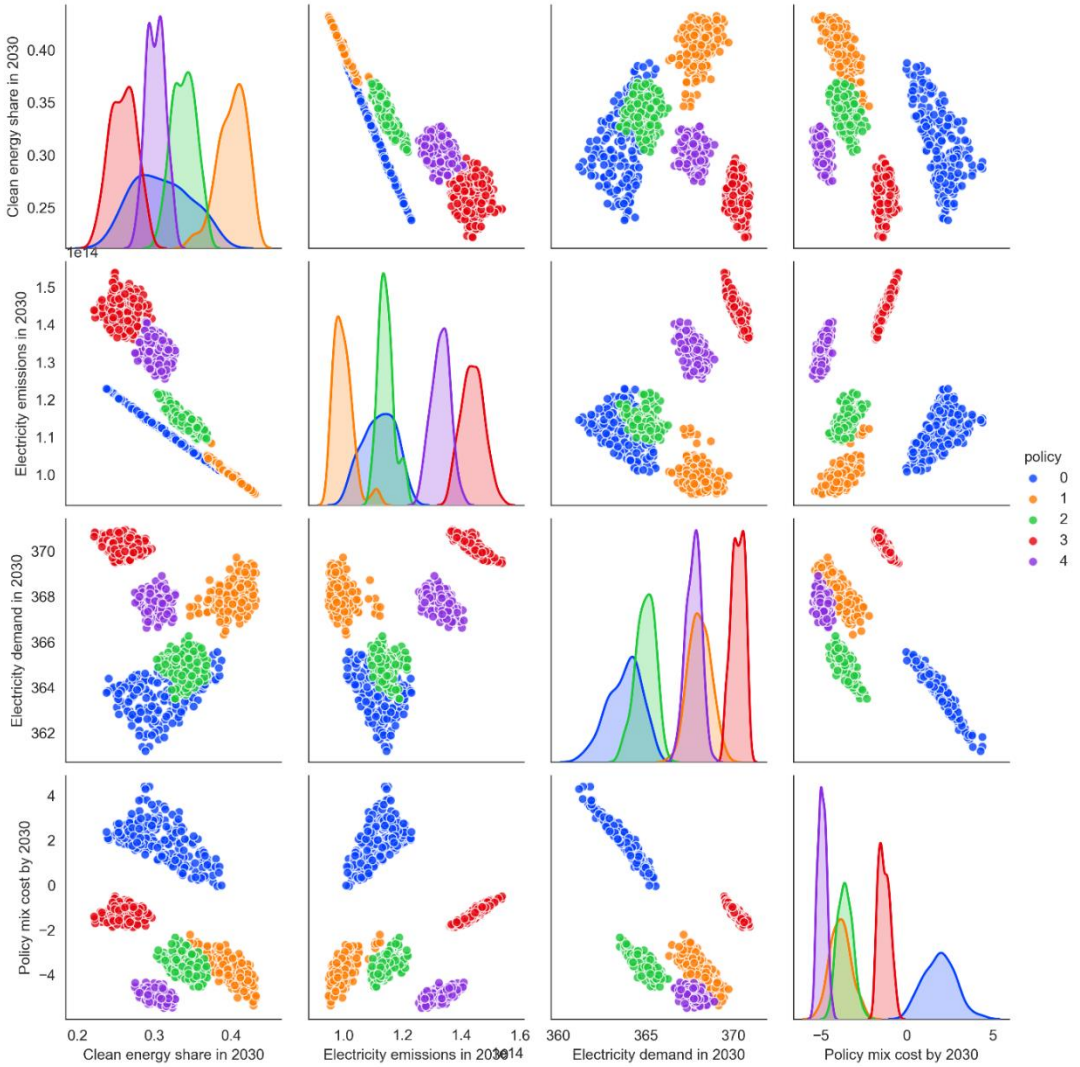


Fig. 3. Performance of policy alternatives with respect to policy objectives for 2030.

To understand what policy instruments may have a stronger influence in meeting medium-term policy objectives under deep uncertainty, we implemented a random forest-based feature scoring approach (Kwakkel 2017). Feature scoring is a family of techniques commonly used in machine learning for testing the effect that different regressors have on the target variable. The heatmap in Fig. 4 shows the policy instruments that have relatively stronger/weaker levels of influence in the policy objectives. From the results, we can observe that emissions from electricity generation are most influenced by the implementation of a carbon tax, followed by the intensification of energy efficiency standards for cooling and ventilation within the commercial sector, the implementation of energy efficiency standards for cement production, and public investment in RD&D for onshore wind. These four policy instruments may be responsible for more than 41% of the GHG emissions reduction within the electricity sector. Similarly, Fig. 4 shows that electricity generation from a clean source is most influenced by the additional clean energy portfolio standards to be implemented, and the total cost of policy mix by 2030 may be driven by the intensification of energy efficiency standards for buildings and appliances, particularly for heating within the commercial sector (accounting for 12%).

Robustness analysis

Robustness is defined in this research as the fraction of sampled scenarios in which a policy alternative meets policymakers' performance requirements in one or more objectives. Based on this definition, policy alternatives can be ranked based on their robustness scores (see Methods). For instance, for Policy Alternative 1 around 87% of the experiments meet the policy target of at least 38.2% of total electricity generation from clean energy sources; the target of emitting no more than 128 Mt CO_2-e in 2030 is met in 100% of all plausible scenarios (100% compliance); and 0% of the time the target of not exceeding 301 TWh of electricity consumption is met (0% compliance). By assigning equal weight to all the objectives, a robustness score of 62% is assigned to Policy Alternative 1. On the contrary, based on the results obtained, a robustness score of 0% was assigned to Policy Alternative 3, being the least

robust alternative. Fig. 5 shows that Policy Alternative 1 is the most robust alternative with regard to 2030 policy objectives (considering the three explicit policy targets presented in the experiment setting), followed by Policy Alternative 0. Supplementary Table 1 depicts the characterisation of Policy Alternative 1 with respect to each policy instrument.



Fig. 4. Feature scoring for 2030 policy objectives. (*B&AEES* = buildings and appliances energy efficiency standards, *C&V* = cooling and ventilation, *CCS* = carbon capture and storage, *CEPS* = clean energy portfolio standard, *PV* = photovoltaics, *EV* = electric vehicle, *IEES* = industry energy efficiency standards, *RDnD* = research, development, and demonstration, *SCR* = soft cost reductions, *T&D* = transmission and distribution).

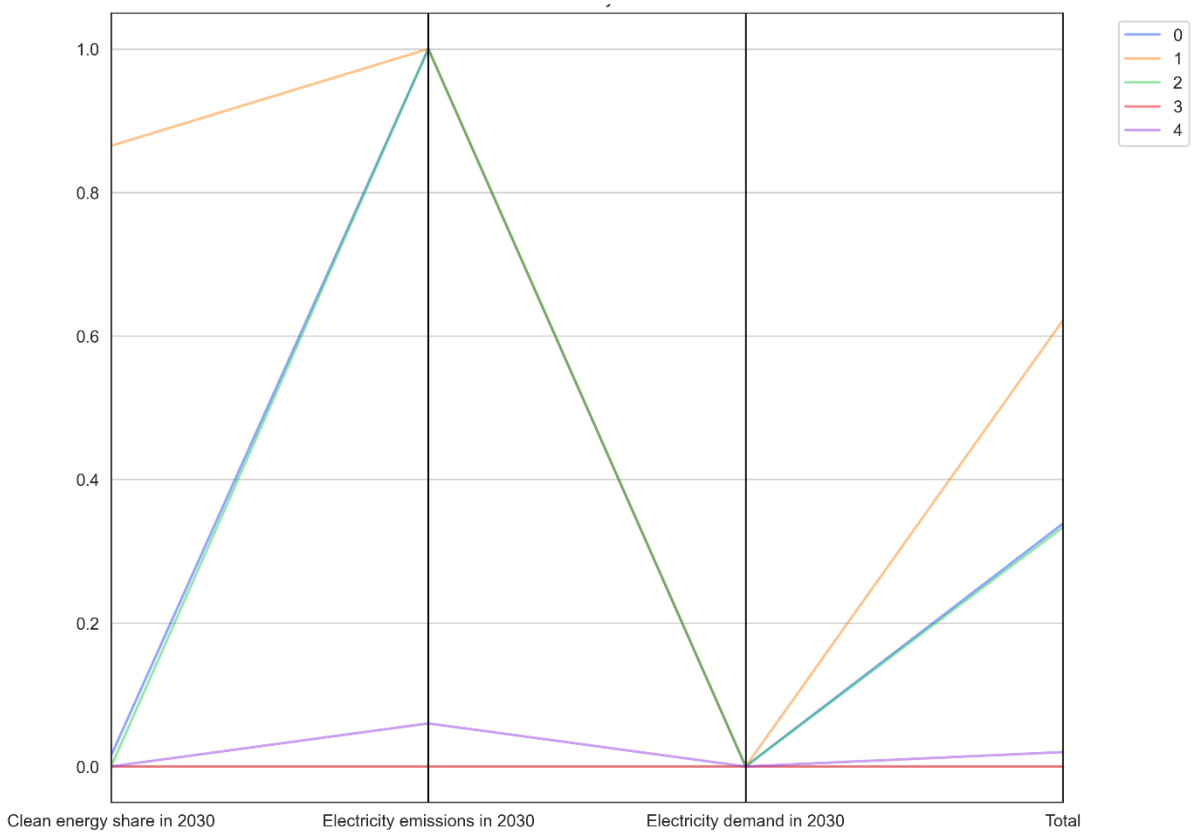


Fig. 5. Robustness analysis of different policy alternatives with respect to 2030 policy objectives.

Vulnerability analysis

Poor performance is defined in this work as situations when policy alternatives fail to meet the performance threshold set by policymakers. By implementing scenario discovery (see Methods) we can explore the most relevant uncertainties that may produce poor performance. Taking emissions mitigation as an example, we have found that the most important uncertainties are investment preference structure (based on the plausible values for the discount rate that generation companies might choose) and the implementation of energy efficiency standards for cooling and ventilation in the commercial sector (see Fig. 6). In other words, the higher the discount rate, the smaller the present value of future costs and benefits (higher risk) for investors that could be explained by political uncertainty as previously discussed in (Castrejon-Campos, Aye & Kin Peng Hui 2022; Castrejon-Campos 2022). Also, a

rapidly developing heating, ventilation, and air conditioning industry, coupled with brisk capacity additions in both the power and hydrocarbons sectors, may significantly affect the demand for heat exchangers in Mexico.

Trade-off analysis

Although Policy Alternative 1 may be the most robust option based on our analysis, it may not be the most inexpensive in the middle-term (see Fig. 3). Thus, policymakers should consider trade-offs between specific policy targets and costs. Fig. 7 shows three visualisation techniques (three-dimensional scatter plot, parallel axis plot, and KDEs) aimed at comparing policy alternatives and thus revealing potential trade-offs between them. Based on the robustness score and the policy mix cost, policymakers may be able to choose between different policy alternatives (for instance between Policy Alternative 4 that represents the policy mix with highest savings –based on the mean of all plausible scenarios– or Policy Alternative 1 that is the most robust policy mix). However, contested stakeholders' preferences may challenge the decision process when a myriad of policy alternatives is considered. A potential solution is the use of optimisation processes to find Pareto-optimal policy alternatives with reference to policy objectives and conduct the EMA process for a second time, adopting a directed search approach. Following the iterative approach adopted within the method applied in this work, the following section presents the main findings of a directed search approach.

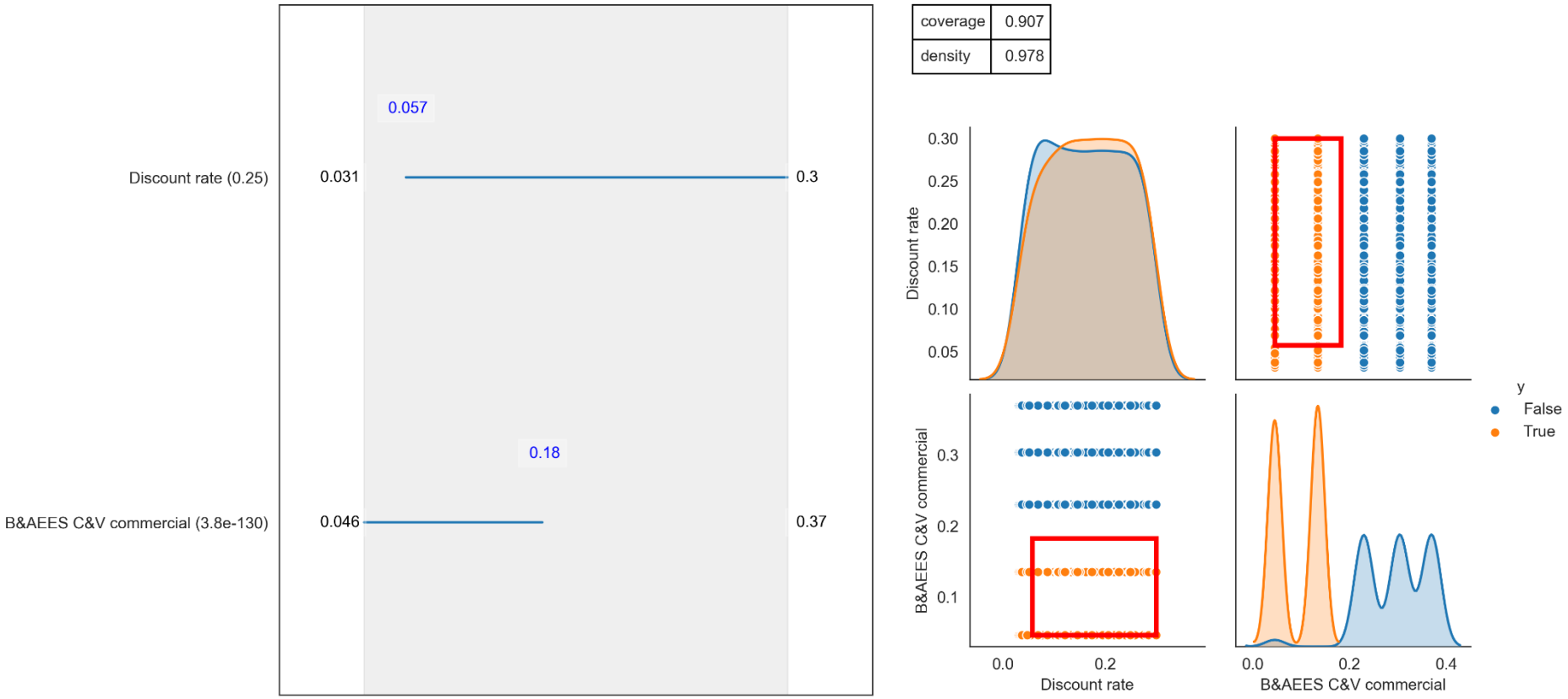
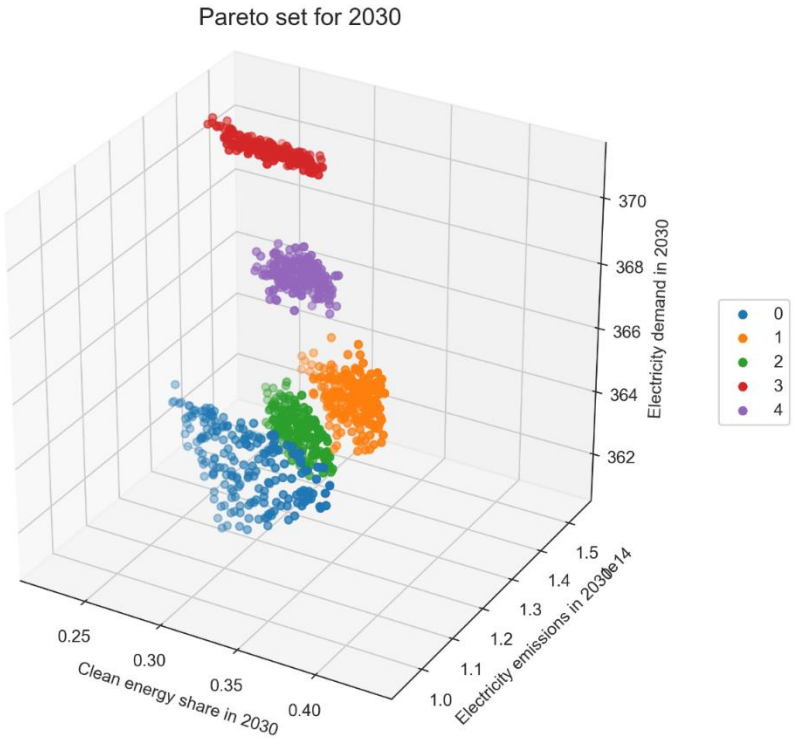
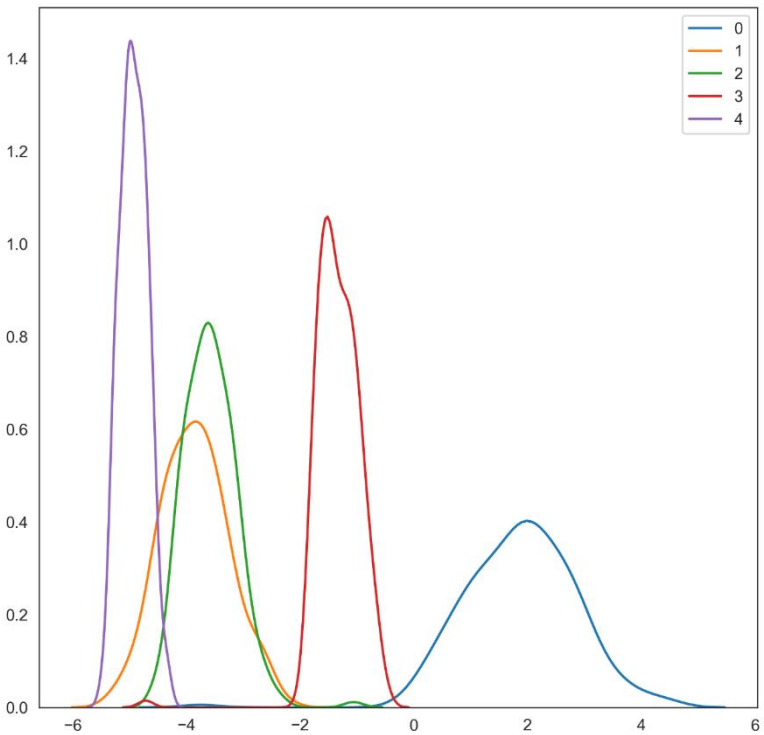


Fig. 6. Vulnerability analysis for 2030 using scenario discovery.

a)


Pareto set for 2030
370
368
366
364
362
Electricity demand in 2030
1.5
1.4
1.3
1.2
1.1
1.0
1e14
Electricity emissions in 2030
0.25
0.30
0.35
0.40
Clean energy share in 2030
0
1
2
3
4

b)


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−6
−4
−2
0
2
4
6
0
1
2
3
4

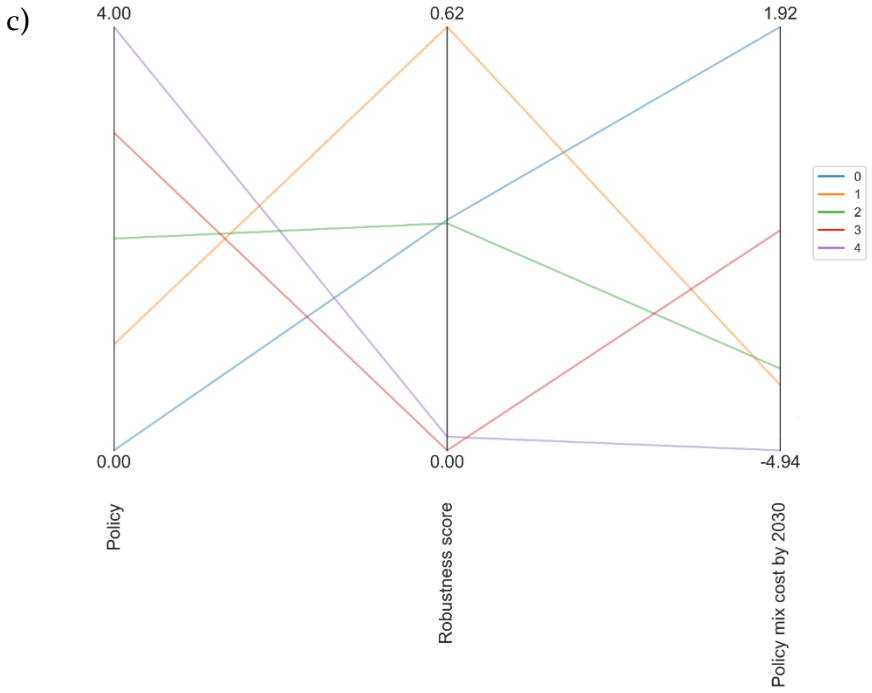


Fig. 7. Trade-off analysis based on explicit medium-term policy targets and policy mix cost by 2030. a) three-dimensional scatter plot (including the full Pareto set in relation to the objective space with specific thresholds); b) Kernel Density Estimates (KDE) for non-constrained policy objectives (i.e. policy mix cost); c) a parallel axis plot (to depict the robustness ranking of policy alternatives according to each policy objective).

Directed search

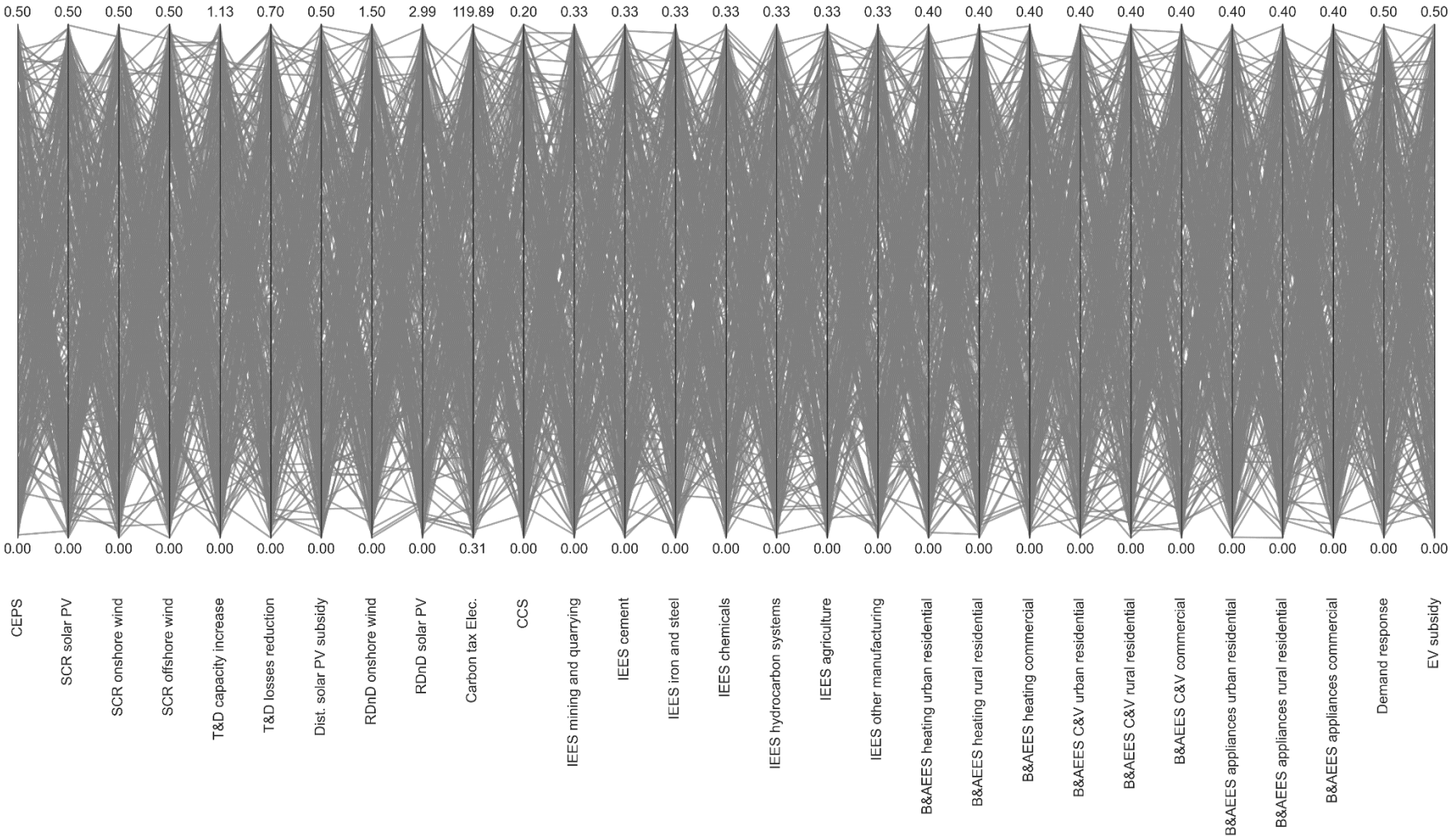
In the previous section, a set of policy alternatives was generated using common sampling techniques. Within this section, a directed search approach was adopted where a potentially high-performing set of policy alternatives were generated using a many-objective evolutionary algorithm (MOEA) known as non-dominated sorting generic algorithm II (NSGA-II) (Yusoff, Ngadiman & Zain 2011). A total of 304 policy alternatives close to the pareto-optimal front were found from the optimisation process (see Fig. 8). Then, these promising policy alternatives were evaluated over 200 plausible scenarios (a total of 60,800 experiments). Following a similar rationale presented in the previous section, policy-relevant information concerning long-term policy objectives (by 2050) was generated by implementing the EMA process described in Methods (including feature scoring, robustness analysis, vulnerability

analysis, and trade-off analysis) and results are analysed and presented using visualisation techniques described in the previous section (see Supplementary Figures 1 to 3). Fig. 8 depicts the eight most robust policy alternatives based on our analysis. The implications of adopting these policy mixes are discussed in the next section.

Discussion and policy recommendations

There is no simple policy strategy to reduce GHG emissions. Some economists have argued that carbon pricing is the 'best' solution for reducing GHG emissions (Baranzini et al. 2017), but it may be ineffective in parts of the economy prone to market failures (e.g. it may be ineffective for a sector that is low price sensitive and for which there are few low-carbon alternatives at near competitive prices) (Harvey, Orvis & Rissman 2018; Stevens 2020). As shown in Fig. 8, implementing a carbon tax for the electricity sector is just one policy instrument that policymakers could include in the policy agenda. However, the design and implementation of a carbon price strategy may depend on complementary policy instruments (e.g. energy efficiency standards) and the interactions between them (i.e. energy policy mixes) (Castrejon-Campos, Aye & Hui 2020). Thus, developing economies like Mexico should focus, first and most intensively, on the highest-potential opportunities to achieve medium and long-term performance targets. Based on the analysis presented within this work, policymakers in Mexico should focus on performance standards (e.g. clean energy portfolio standards, industry energy efficiency standards for 'other manufacturing' activities, and reductions in T&D losses) and economic signals (e.g. carbon tax, clean energy certificates, feed-in tariffs) to meet long-term policy objectives (see Supplementary Figure 2). Results obtained from the direct search, suggest that the application of the most robust policy mixes could contribute to reduce up to 55% of GHG emissions from electricity production by 2050 (compared to the BAU scenario).

a)


0.50 0.50 0.50 0.50 1.13 0.70 0.50 1.50 2.99 119.89 0.20 0.33 0.33 0.33 0.33 0.33 0.33 0.33 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.50 0.50
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.31 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
CEPS
SCR solar PV
SCR onshore wind
SCR offshore wind
T&D capacity increase
T&D losses reduction
Dist. solar PV subsidy
RDnD onshore wind
RDnD solar PV
Carbon tax Elec.
CCS
IEES mining and quarrying
IEES cement
IEES iron and steel
IEES chemicals
IEES hydrocarbon systems
IEES agriculture
IEES other manufacturing
B&AEES heating urban residential
B&AEES heating rural residential
B&AEES heating commercial
B&AEES C&V urban residential
B&AEES C&V rural residential
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Demand response
EV subsidy

b)

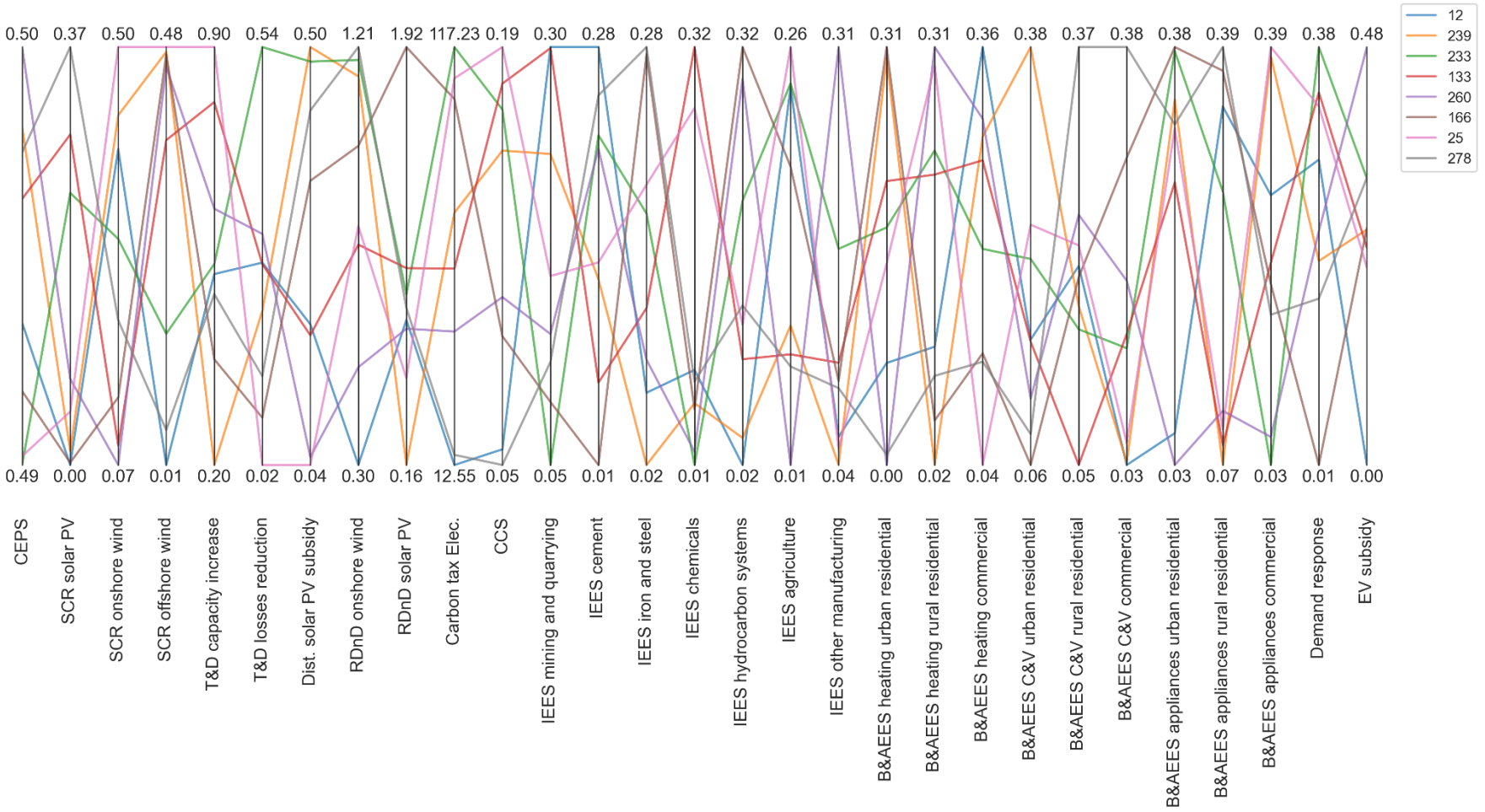


Fig. 8. a) Pareto-optimal (304) and b) most robust (8) policy alternatives for long-term policy objectives based on a directed search approach.

The two most common policy instruments for promoting clean energy generation are renewable (or clean energy) portfolio standards and feed-in tariffs (Harvey, Orvis & Rissman 2018). Mexico implemented a target-based clean energy standard to stimulate the market for electricity generation from clean energy technologies. To meet these targets, a price-finding mechanism (power auctions) and a compliance system (CECs) were developed (Castrejon-Campos 2022). Feed-in tariffs (and premiums) are particularly valuable for emerging technologies (e.g. thermal solar, offshore wind, biomass) and clean energy portfolio standards (CEPS) work best for promoting more developed technologies (e.g. solar PV and onshore wind) (Harvey, Orvis & Rissman 2018). Mexico should consider implementing a two-step process for emerging technologies where feed-in tariffs are created first and then transition to a CEPS as technologies and renewable markets mature. In addition, if clean energy certificates (renewable energy credits) are to be tradable across borders (e.g. in cross-border carbon markets), policymakers should verify that they have similar (legal) definitions of clean energy and a clear tracking system (e.g. unique ID number). Although Mexico has implemented a carbon tax (around 3 USD/tonC), it has not been enough to reflect the social cost of carbon and therefore reduce carbon emissions from the electricity sector. Thus, considering a decreasing domestic production and high dependence on imported natural gas, our results suggest that an increase in carbon tax level (USD 13–117/t CO_2-e by 2050) should be implemented by the government of Mexico.

Mexico's energy policy design has historically focused on the supply side rather than the demand side. However, increasing the efficiency of industrial equipment through performance standards (e.g. fostering efficiency improvement in electric motors, pumps, and commercial boilers) should be prioritised in the policy agenda, as energy-intensity industries are expected to rise in the coming years (Castrejon-Campos 2022). In addition, Mexico's electricity losses are significantly higher than other OECD countries. More than 21% of the electricity generated is not charged derived from technical (e.g. network infrastructure in a poor state) and non-

technical (e.g. non-payment, theft) losses, which results in higher transmission and distribution costs (IEA 2017). Smart grid infrastructure should be considered within the policy mix to reduce network losses. Bringing down electricity losses may help improve operational efficiency and reduce the investment required for building new capacity (IEA 2017). In addition, to support the uptake of electricity generation from variable energy technologies (e.g. onshore wind and solar PV), improvements in the National Transmission Grid and the General Distribution Grids will be needed.

Developing countries share some characteristics. For instance, due to rapid economic growth and urbanisation processes, new infrastructure is needed to meet societal demands (e.g. new schools, new roads, new buildings). To cover these societal requirements, carbon-intense industries (e.g. iron and steel, cement, construction) need to produce more, increasing (primary and secondary) energy demand (oil, natural gas, and electricity) and thus rising GHG emissions. Also, more vehicles may be seen on the road (including private and public transportation because more people need to commute), increasing the demand for fossil fuels. Based on our analysis, the long-term energy target on electricity demand reduction may not be achievable (see Supplementary Fig. 3). Thus, policymakers should consider setting more realistic targets based on the Mexican context. For instance, based on the simulations generated from the direct search, a more realistic target for electricity demand would be 575 TWh by 2050 (based on the mean of 60,800 experiments). Similarly, a target of 140 Mt CO_2-e emitted from electricity production by 2050 would be considered as a realistic target for GHG emissions mitigation. An interactive approach with stakeholder consultation is beyond the scope of this work, however, it is suggested for future research.

Methods

An integrated method for energy policy analysis towards clean energy transitions (Castrejon-Campos, Aye & Hui 2020) has been implemented in this article. The applied method is an integration of energy transitions concepts, quantitative simulation modelling techniques,

robustness-based approaches, and exploratory thinking. The operationalisation of the analytical method was proposed at a national level, with a special interest in developing countries members of the Organisation for Economic Co-operation and Development (OECD). Mexico was selected as the case study as the 11th largest GHG emitter worldwide due to its fossil fuel-intensive energy mix (Castrejon-Campos 2022). The implementation of the method involves a series of interdependent analytical processes aimed at analysing policy-relevant information and designing robust policy mixes in line with clean energy transitions (see Supplementary Fig. 4). These processes are briefly described in the following subsections.

Policy problem definition

The conceptualisation and contextualisation of the policy system follow a two-phase process. First, based on policy research and relevant literature review, historical energy transitions are described by using a multi-perspective theoretical framework, developed and implemented in (Castrejon-Campos, Aye & Kin Peng Hui 2022). Key concepts from sustainability transitions, policy mixes for energy transitions, and interactive governance literature are used to describe historical structural transformations within energy systems and then to identify potential drivers and barriers for future energy transitions (Castrejon-Campos, Aye & Kin Peng Hui 2022; Castrejon-Campos 2022). The multi-perspective theoretical framework used within this article has been applied to Mexico by describing the evolution of the national electricity system in general (Castrejon-Campos, Aye & Kin Peng Hui 2022) and clean energy technologies in particular (Castrejon-Campos 2022).

Second, the two studies described above were used to guide an elicitation process by applying a structured policy analysis framework labelled as COPRIEMD, as proposed in (Castrejon-Campos, Aye & Hui 2020) (see Supplementary Fig. 5). These studies (Castrejon-Campos, Aye & Kin Peng Hui 2022; Castrejon-Campos 2022) represent the policy problem context (C). Policy objectives (O), relevant policy alternatives (P), potential external factors (E), and performance metrics (M) towards a clean energy transition in Mexico have been identified and

discussed in (Castrejon-Campos 2022). In the context of this research, a policy alternative refers to a mix of policy instruments with specific values (selected from a range) and a particular implementation schedule. In addition, external factors are variables outside the control of policymakers that are of special interest in the development of future transitions (i.e. uncertainties). The characterisation of these uncertain factors is described in more detail in the next step of the method used for policy analysis (i.e. deep uncertainty characterisation). Regarding relationships (R) and internal factors (I), we used the EPS model to represent the interactions of relevant elements in a co-evolving dynamic setting (Energy Innovation 2021). Finally, the decision rule (D) for policy acceptance of different alternatives was set based on (Herman et al. 2015; Castrejon-Campos, Aye & Hui 2020). The aim of the elicitation process is to identify and select relevant elements to be included within an EMA process. The schematic integration of these elements is presented in Supplementary Fig. 6.

Deep uncertainty characterisation

Uncertainty may be defined simply as *limited knowledge* about current, past, or future events (Walker, Lempert & Kwakkel 2013). In policymaking, uncertainty refers to the gap between available knowledge and the knowledge policymakers would need to select or design the 'best' policy strategy (Marchau et al. 2019). The identification and characterisation of external factors depend on the research enquiry. For instance, for many decisions, the development of policy mixes would be considered as an external factor. However, this would not be the case for analyses in which policymakers play the decision-making role (Marchau et al. 2019).

Uncertainty is traditionally accounted for by assigning an expected value from an established probability distribution. However, agreement on the likelihood of particular uncertain factors (e.g. fuel prices, technological progress) is challenging under situations of deep uncertainty. Deep uncertainty refers to the condition in which decision-makers or analysts do not know or cannot agree on: (a) the appropriate models to describe interactions among different variables of a system, (b) the probability distributions to represent uncertainty about key parameters,

and/or (c) how to assess the desirability of different outcomes of interest (Lempert, Popper & Bankes 2003). Deep uncertainty also emerges from actions taken over time in response to unpredictable evolving situations (Haasnoot et al. 2013). Thus, an alternative approach to deal with (deep) uncertainty is to explore the performance of multiple policy alternatives against a wide range of potential values for these uncertain factors.

The identification of deep uncertain factors was carried out based on literature. A narrative review approach, also called the semi-systematic review process (Snyder 2019), was adopted to identify key uncertain factors within electricity systems. The research design (i.e. series of steps followed) to identify, screen, and select relevant documents for analysis may be found in Supplementary Information. Deep uncertain factors, common in various studies (see Supplementary Table 2), were classified in four main categories for conducting this research: fuel prices, technological progress, price-demand response, and investment preference structures (see Supplementary Table 3).

Although methodological, structural, and parametric uncertainties can be explored using an EMA process, we focused mainly on parametric uncertainty. Multiple models can be used to explore structural uncertainty (based on stakeholders' perception of the system). However, we have adopted a comprehensive perspective aimed at including elements within the model relevant to different stakeholders (e.g. policymakers, industry, academia). Different approaches have been used to define the range of deep uncertainties (i.e. parametric uncertainty) for exploratory analysis. For instance, a range of minus-plus 50% of the estimated base value for each uncertain parameter was assigned in (Moallemi et al. 2017). Similarly, key uncertainties (e.g. investment costs and fuel prices) were set to vary to a maximum of plus/minus 33% of their initial projection in (Cieplinski, D'Alessandro & Marghella 2021). In addition, some studies (Kwakkel & Yücel 2014; Kwakkel & Pruyt 2013) have assigned multiplier factors, based on literature review, to explore the plausible effects of parametric uncertainty. On the other hand, model input uncertainties were characterised through expert

consultation and literature review (e.g. policy documents) in (Pye, Sabio & Strachan 2015). Also, sensitivity analyses have been applied to explore potential ranges of uncertain factors (Pruyt et al. 2011; Yue et al. 2020).

Potential uncertainties, relevant to our analysis, and their estimated initial values were identified through literature review and model analysis. Parametric uncertainty (i.e. range of possible values for uncertain parameters) were selected based on literature review and are presented using the deep uncertainty characterisation matrix proposed in (Castrejon-Campos, Aye & Hui 2020). Additionally to the three possible locations of uncertainty initially proposed in (Castrejon-Campos, Aye & Hui 2020) (i.e. model structure, future conditions, and outcomes of interest), we have included policy planning elements (i.e. policy objectives and instruments) for completeness in the experiment setting for conducting the EMA process. A total of 29 external factors, 29 policy instruments, 15 outcomes of interest, and 8 policy objectives are included for EMA, using the EPS model as a scenario generator. The deep uncertainty characterisation matrix is presented in Supplementary Information.

Exploratory modelling and analysis (EMA)

EMA refers to the systematic exploration of the impacts of multiple uncertainties within highly complex systems (e.g. energy systems), using computational experimentation (Marchau et al. 2019). By simulating one set of hypotheses, one computational experiment is obtained. The assumption is that if various hypotheses (or assumptions) about the system are correct, one computational experiment represents how the system would behave according to those various hypotheses encapsulated in one single model (Castrejon-Campos, Aye & Hui 2020). Following (Castrejon-Campos, Aye & Hui 2020), the EMA process encompasses a series of phases: experiment setting, model development, robustness analysis, vulnerability analysis, and trade-off analysis. The two previous steps within the integrated analytical method (i.e. policy problem definition and deep uncertainty characterisation) craft the 'experiment setting'

phase within the EMA process. The following sections describe the rest of the phases within the EMA process.

Model development

Exploratory modelling uses simulation models as scenario generators to systematically explore the potential effects of different parametric and non-parametric uncertainties (Moallemi & Malekpour 2018). This article used a modified configuration of the latest version (v1.4.2) of the Mexico EPS developed by Energy Innovation LLC (Energy Innovation 2021). A public web-based version of the original model may be available at https://us.energypolicy.solutions/. The EPS is an open-source and peer-reviewed system dynamics (SD) computer model aiming at quantifying the plausible effects of energy and climate policies on GHG emissions at a national or regional level. SD is a methodology that aid analysts and decision-makers to map the interaction of multiple variables in complex systems and explore their behaviour in time by the use of simulation models (Sterman 2000). The EPS allows users to control multiple parameters that affect energy use and production, as well as GHG emissions (Austin & Denzinger 2020). The EPS model has been used to explore the impact of different policy mixes in diverse regions such as Indonesia (Chandra Setiawan, Indarto & Deendarlianto 2021), China (Gallagher et al. 2019), Mexico (Stevens 2020), and Alberta, Canada (Austin & Denzinger 2020).

Although the EPS model integrates a myriad of variables for the energy system (more than 380,000), the modelling approach adopted to model technological progress was identified as a key limitation for policy analysis (e.g. technological knowledge stock was not included) (Castrejon-Campos et al., Under Review). The EPS model uses a combination of exogenous and endogenous learning approaches to estimate technology cost developments depending on the maturity level of each technology (Energy Innovation 2021). In the case of endogenous learning, the EPS model adopts the one-factor learning curve (1FLC) approach being installed capacity the only driver for future cost developments in the case of wind and solar PV. We

extended the approach by explicitly including technological experience and knowledge stock as the sources of learning based on comprehensive analysis of how technological learning is modelled for policy analysis (Castrejon-Campos, Aye & Hui 2022a). Thus, some modifications to the EPS model were needed. The main structural modifications within the EPS model were made in the *Endogenous learning sheet* following (Castrejon-Campos et al., Under Review). The model was implemented in Vensim DSS, and simulations were run for the period from 2017 to 2050.

Exploratory analysis

Based on the experimenting setting discussed in the previous sections and using the EPS model as a scenario generator, a series of prospective transition pathways can be generated (i.e. computational experiments). The analysis of extensive simulation results was conducted using an exploratory thinking approach. Exploratory thinking aims at systematically exploring alternative perspectives to policymaking through creative thinking and deliberate exploration of vulnerabilities (Moallemi & Malekpour 2018). By adopting an exploratory approach more realistic insights may be obtained using statistical techniques (e.g. envelop plotting and Kernel Density Estimates (KDE)) and data-mining techniques (e.g. feature scoring and scenario discovery) over a large number of experiments (Moallemi & Malekpour 2018). We used the EMA Workbench (Kwakkel 2017) to conduct the exploration process. EMA Workbench is an open source Python library aimed at providing support for designing experiments, performing the experiments, and analysing the results (Kwakkel 2017). The python code is presented in Supplementary Information.

Based on (Castrejon-Campos, Aye & Hui 2020), an exploratory analysis includes three analytical sub-processes: robustness analysis, vulnerability analysis, and trade-off analysis.

Robustness analysis

In the face of deep uncertainty, policy decisions may be made using the principle of satisficing rather than optimising (Trutnevyte 2016). Robustness analysis was performed based on the satisficing measure adopted from (Herman et al. 2015). Thus, robustness is defined in this work as the fraction of sampled scenarios (i.e. uncertainty space) in which a policy alternative meets policymakers' performance requirements in one or more objectives. Based on the performance thresholds established by policymakers to 'accept' a robust solution, policy alternatives can be ranked. When a policy alternative is ranked with 100%, the alternative satisfies the policy objective threshold in all plausible scenarios. On the other hand, a rank of 0% is assigned when a policy alternative fails to meet the established performance criteria in all plausible scenarios. The aim of using a robustness metric is to identify policy mixes that are both high-performing, in terms of policy objectives, and relatively insensitive to future external changes (i.e. different scenarios) (Marchau et al. 2019).

Vulnerability analysis

To identify regions of the large, multi-dimensional uncertainty space where robust policy alternatives are vulnerable to poor performance, we used the patient induction method (PRIM) (Friedman & Fisher 1999) as the algorithm to conduct scenario discovery (Bryant & Lempert 2010). PRIM is a factor mapping approach aiming at identifying sensitive ranges of uncertainties that are likely to cause a particular behaviour. It works by peeling away layers of the uncertainty space by constraining one dimension at a time, then evaluating how well those constraints capture the points of interest based on two metrics: coverage (the fraction of poor-performing scenarios that fall within the box) and density (the fraction of scenarios within the box that perform poorly) (Kasprzyk et al. 2013; Herman et al. 2015). In this work, poor performance is defied to be situations when policy alternatives fail to meet the performance threshold set by policymakers (i.e. policy objectives).

Trade-off analysis

Visualisation techniques are required to communicate policy-relevant insights and to provide a clear understanding of trade-offs and potential consequences of each policy alternative (Castrejon-Campos, Aye & Hui 2020). Thus, to present the performance of different policy alternatives we use a three-dimensional scatter plot (including the full Pareto set in relation to the objective space with specific thresholds), a parallel axis plot (to show the robustness ranking of policy alternatives according to each policy objective), and Kernel Density Estimates (KDE) for non-constrained policy objectives (i.e. policy mix cost in this case).

Policy recommendations

The aim of implementing the integrated analytical method adopted within this article is to analyse policy-relevant information and to reach a consensus about the selection of robust policy alternatives rather than specifying a single best policy mix. Thus, the development of policy alternatives should be considered as an iterative process where policy learning may be facilitated by revealing possible trade-offs among alternative problem definitions and solutions. Based on this iterative scheme and considering specific characteristics of Mexico's electricity system, policy recommendations are systematically generated, presented, and discussed.

Data Availability

The data that support the figures and findings of this article are provided in Supplementary Information. Source data are provided with this paper.

Code Availability

Computer code related to this article can be found in Supplementary Information.

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Author contributions

Omar Castrejon-Campos: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualisation. **Lu Aye:** Validation, Resources, Writing - review & editing, Visualisation, Supervision, Project administration, Funding acquisition. **Felix Kin Peng Hui:** Supervision, Writing - review & editing. **Paulo Vaz Serra:** Supervision, Writing - review & editing.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Additional information

Supplementary information for this paper is available.

Chapter 6

Conclusions and recommendations for future research

6.1 Introduction

In the previous chapters, a new integrated method for energy policy analysis towards clean energy transitions was developed (Chapter 2) and implemented (Chapter 5) by using insights from complementary analytical tools developed and applied through the stepwise implementation process (Chapters 3 and 4). This closing chapter concludes the study by summarising the main findings within previous chapters and appraising the value and contributions thereof. It also reports the limitations of the study and proposes recommendations for future research avenues.

6.2 Conclusions of the thesis

Understanding how energy-related policy alternatives have affected electricity transitions and how they can influence future transitions may aid policymakers in developing more robust policy alternatives. This study aimed at exploring the effects of robust energy policy mixes towards clean energy transitions in Mexico. This thesis presented the background and relevance of the study in Chapter 1. Then, based on a comprehensive literature review, an integrated method for supporting policymakers with the design of robust energy-related policy alternatives towards clean energy transitions was developed and presented in Chapter 2. The proposed method was developed and implemented by combining the strengths of various analytical tools found in sustainability transitions literature, policy mixes for energy transitions, interactive governability, robustness-based frameworks, dynamic modelling techniques, and exploratory thinking. Thus, policy-relevant information about clean energy transitions was generated and analysed by carrying out a series of interdependent analytical processes including policy problem definition, deep uncertainty characterisation, exploratory modelling and analysis, and (the development of) policy recommendations. To improve the applicability of these processes, complementary analytical tools were developed and applied through the stepwise implementation process (Chapters 3 and 4).

Based on policy research and relevant literature review, the evolution of energy systems was described by using a new multi-perspective theoretical framework. The developed framework was applied to Mexico by describing the evolution of the national electricity system in general and clean energy technologies in particular in Chapter 3. Key concepts from sustainability transitions, policy mixes for energy transitions, and interactive governance literatures were used to describe historical structural transformations within energy systems and then to identify potential drivers and barriers for future energy transitions, generating a series of 'micro-logics'. By using interactive governance theory, this study synthesised these micro-logics into a broader theoretical construct. Thus, interactive governance theory and governability have enabled an analytical framework for exploring the role of social actors, technological change, policy mixes, and the interactions among them in national energy transitions. By integrating a new multi-perspective theoretical framework and a new analytical framework for policy analysis, a more comprehensive policy problem definition was obtained.

Based on the historical evolution of the Mexican electricity sector, different drivers were identified in shaping electricity transitions in Mexico. First, governance decisions have depended on specific paradigms that relevant actors have adopted. Second, available indigenous resources have played a key role in directing the path and pace of electricity

production technologies. Third, increasing environmental and climate change concerns have modified the way electricity is produced and used. Building on the developed theoretical framework and extending its application, the energy transitions governability framework was also applied to describe the development of clean energy technologies in Mexico. The empirical application of the framework to clean energy technologies revealed that the ever-growing electricity demand in Mexico has called for exploring different technologies and available energy sources over time. The decline in fossil fuels domestic production, increasing environmental concerns, and international agreements on climate change mitigation have been the main drivers for deploying clean technologies and adopting energy efficiency measures in Mexico. However, clean energy technologies have faced important barriers. For instance, although Mexico has a remarkable potential for renewable energy sources (e.g. wind, solar, geothermal, bioenergy), the lack of investment in research, development, and demonstration (RD&D) and innovation for clean energy technologies have limited their development.

Technological learning was identified as a key driver for electricity transitions in Mexico. Thus, a new integrative technological learning model was developed in Chapter 4 to explore the effects of learning processes on technological-based cost developments. By choosing how different sources of learning and key parameters are defined, the influence of alternative approaches was explored. Also, a new definition of experience was developed and presented in Chapter 4 to account for the interaction between global and local experience. This new definition of experience also accounts for learning sub-processes (i.e. learning-by-doing, learning-by-using, and international experience spillovers) to estimate total experience gained through technology deployment.

The findings presented in Chapter 4 suggested that the application of learning rates for model-based energy planning is context-dependent and how technological factors are explicitly defined may have significantly different policy implications (i.e. different technology costs predictions based on alternative model formulations). Thus, when learning curves are used for policy analysis, it is paramount to explicitly establish what sources of learning are to be included and how they are formulated. Also, empirical findings based on historical data suggest that, when data are available, experience and knowledge stock should be explicitly included as sources of learning to explore the effects of learning processes on future technological-based cost developments. Thus, the impact of technological progress on cost reductions can be explored by accounting for different learning sub-processes, global and local experience, and domestic public investment in RD&D for energy technologies.

The results presented in Chapter 4 suggest that learning through researching is of critical relevance for innovation policymakers when the effects of energy RD&D are to be investigated. Thus, by applying the developed integrative model, the potential economic and environmental impacts of multiple RD&D investment scenarios on future technology cost developments, electricity generation, and GHG emissions were explored. It was found that RD&D investment may play a critical role in the speed of capital cost reductions (or increases) and technology diffusion. However, little effects would be seen on market dynamics and GHG emissions from RD&D efforts alone, highlighting the importance of complementing technology-push mechanisms with market-pull policies to fulfill long-term energy policy objectives on clean energy diversification, energy efficiency, and GHG emissions reduction.

The development and application of an integrative model for technological learning have contributed to the (exploratory) modelling process within the integrated method developed in Chapter 2. Thus, consideration of public investment in RD&D for energy technologies adds a controllable policy variable to the model and reduces, to some extent, the issue of bias due to omitted variables compared to one-factor learning curve models.

By using the insights of the previous chapters and adopting an exploratory approach, Chapter 5 quantitatively explored the plausible consequences of adopting different policy mixes towards a clean energy transition in Mexico. Exploratory modelling uses simulation models as scenario generators to explore the potential effects of different parametric and non-parametric uncertainties systematically. Using publicly available data for Mexico, this study used a modified configuration of the latest available version (v1.4.2) of the Mexico energy policy simulator (EPS) developed by Energy Innovation LLC. The EPS model served as scenario generator for exploratory analysis to obtain policy-relevant information upon: (1) under what conditions a plausible future can take place and what combinations of uncertainties could trigger undesirable outcomes, (2) the estimation of the robustness of policy alternatives under key deep uncertainty conditions, and (3) possible trade-offs among policy alternatives.

By adopting an exploratory approach, a large number of experiments (i.e. energy transition pathways) were obtained and analysed using statistical and data-mining techniques. The analysis revealed that policymakers in Mexico should focus on economic signals and performance standards to meet medium and long-term policy objectives on clean energy development, energy efficiency improvement, and GHG emissions reduction. Based on the empirical findings, the most influential policy instruments towards a clean energy transition in Mexico may be: (1) implementation of a two-step process of feed-in tariffs and clean energy portfolio standards for emerging technologies; (2) application of a more effective carbon pricing mechanism for electricity generation; (3) efficiency improvement of industrial equipment through performance standards; and (4) implementation of mechanisms to reduce technical and non-technical electricity losses (e.g. smart grid infrastructure) to improve operational efficiency of transmission and distribution lines. The application of the robust policy mixes obtained from the analysis could contribute to reduce up to 55% of GHG emissions from electricity production by 2050 (regarding a business-as-usual scenario).

6.3 Limitations and recommendations for future research

Although the integrated method developed and implemented in this study has demonstrated its applicability in exploring the potential effects of implementing robust energy policy mixes towards clean energy transitions in Mexico, the method proposed has some limitations. These limitations have been extensively discussed within each chapter. Thus, a summary and potential research avenues are listed as follows:

- This study is a complementary analytical exercise to previous work focused on explaining electricity transitions in Mexico. This study has used concepts from literature on policy mixes for sustainability transitions, energy/sustainability transitions, and interactive governance theory to describe changes in socio-techno-economic systems. Based on the selection of relevant energy transitions concepts to explain the dynamics of energy transitions, the perception of future electricity transitions could be different and, therefore, influence the definition of the policy

problem. Future research could use complementary concepts to explain transformation processes not covered in this thesis. These may include concepts found within the same disciplinary roots (e.g. technology costs, voters' preference, international competition, public opinion, corporatism) or relevant concepts/processes derived from complementary literature (e.g. geography, political ecology, energy justice).

- Data availability and reliability have been identified as important limitations for the applicability of the proposed integrated method to developing countries (e.g. outdated information available from public organisations or data inconsistency from different sources). The procedures involved in conducting research or collecting data (i.e. methods) usually exclude and privileges diverse social actors. Thus, complementary sources (not covered in this study) may provide additional information regarding structural transformations in the electricity system in Mexico (e.g. including sources in other languages or using different keywords). Also, the research method applied in this study may be improved by diversifying sources, comparing findings with other studies, and triangulating research methods (e.g. on-site interviews or expert elicitation). To increase the reliability of policy recommendations, it is highly recommended to involve stakeholders and policymakers in all phases of the process.
- This study has revealed the relative effects of different learning sources and explanatory variables on technological-based cost developments by exploring alternative approaches to model technological progress. Experience and knowledge stock were chosen as the sources of learning to be explored. However, there may be other factors to be considered when informing policy-making decisions (e.g. social influences). Future research could investigate the possible impact of those factors on energy systems. In addition, by untangling learning-by-deploying sub-processes (i.e. learning-by-doing, learning-by-using, and experience spillovers), valuable insights on technological experience were found. However, the new definition of experience proposed in this study integrated the three sub-processes to estimate total experience and then estimate learning rates quantitatively. Future research can focus on investigating the relative contribution of each one of these sub-processes in cost developments.
- The operationalisation of the integrated method developed in this study was proposed at a national level, with special interest in developing countries members of the Organisation for Economic Co-operation and Development (OECD). Mexico was selected as the case study as the 11th largest GHG emitter worldwide due to its fossil fuel-intensive energy mix. However, the approach adopted in this study may be used as an analytical tool to conduct comparative research between countries, technologies, and periods to extend its applicability and improve the generalisability of the findings.
- The exploratory results presented in this study illustrated the importance of considering deep uncertain factors for organising energy policy recommendations to achieve robust policy mixes towards clean energy transitions in developing countries. For instance, developing countries share some common characteristics affecting their electricity systems, such as increasing electricity demand and thus the need for infrastructure expansion. However, the framework may also be applied to other developed countries (e.g. Australia) by explicitly establishing the key

energy/sustainability concepts and periods of analysis to be used for the investigation. In addition, by implementing this integrated method, policy recommendations can be structured to support policymakers in the development of more robust policy mixes in other societal dynamic systems, such as transportation or waste management.

Appendices

Appendix A Declaration for Publications

Declaration for publications incorporated in thesis

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Graduate researchers may incorporate their own published material, or material in progress towards publication in their thesis if:

- The graduate researcher contributed greater than 50% of the content in the publication and is the "primary author", ie. the graduate researcher was responsible primarily for the planning, execution and preparation of the work for publication
- The graduate researcher has approval to include the publication in their thesis from their Advisory Committee
- It is a primary publication that reports on original research conducted by the graduate researcher during their enrolment
- The initial draft of the work was written by the graduate researcher and any subsequent editing in response to co-authors and editors reviews was performed by the graduate researcher
- The publication is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in the thesis

You must submit this form, along with *Co-author authorisation forms* completed by each co-author (combined as a single file), when you submit your thesis to the Thesis Examination System: *https://tes.app.unimelb.edu.au/*. If you are incorporating material from multiple publications in your thesis you will need to list each publication on this form. Further information is available at: *gradresearch.unimelb.edu.au/preparing-my-thesis/thesis-with-publication*

A. GRADUATE RESEARCHER'S DECLARATION

I declare that:

- the information below is accurate
- the publications below meet the requirements to be incorporated in the thesis
- my advisory committee has met and agreed to the material incorporated in my thesis
- all co-authors of the publications have reviewed the information below and have agreed to its veracity.

Co-Author Authorisation forms for each co-author are attached.

Graduate researcher's name	Graduate researcher's signature	Date *(dd/mm/yy)*
Omar Castrejon Campos		30/07/22

PRINCIPAL SUPERVISOR'S DECLARATION

Supervisor's name	Supervisor's signature	Date *(dd/mm/yy)*
Lu Aye		02/08/22

B. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Making policy mixes more robust: An integrative and interdisciplinary approach for clean energy transitions
Authors	Omar Castrejon-Campos Lu Aye

	Felix Kin Peng Hui		
Graduate Researcher's contribution (%)	75	Status	☒Published ☐ Accepted and in-press ☐ In progress
Journal or book name	Energy Research & Social Science		
Volume and page numbers (if published)	64/101425	Date accepted/ published (if relevant)	Available online 16 January 2020

B. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Competition, coordination, or institutional change? A multi-perspective analysis of historical electricity transitions in Mexico		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate Researcher's contribution (%)	75	Status	☒Published ☐ Accepted and in-press ☐ In progress
Journal or book name	Energy Research & Social Science		
Volume and page numbers (if published)	84/102362	Date accepted/ published (if relevant)	Available online 12 November 2021

B. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Evolution of clean energy technologies in Mexico: A multi-perspective analysis		
Authors	Omar Castrejon-Campos		
Graduate Researcher's contribution (%)	100	Status	☒Published ☐ Accepted and in-press ☐ In progress
Journal or book name	Energy for Sustainable Development		
Volume and page numbers (if published)	67/29-53	Date accepted/ published (if relevant)	Available online 25 January 2022

B. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Effects of learning curve models on onshore wind and solar PV cost developments in the USA

Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate Researcher's contribution (%)	75	Status	☒Published ☐ Accepted and in-press ☐ In progress
Journal or book name	Renewable and Sustainable Energy Reviews		
Volume and page numbers (if published)	160/112278	Date accepted/ published (if relevant)	Available online 1 March 2022

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Full title	Dataset on effects of learning curve models on onshore wind and solar PV cost developments in the USA (Version 2)		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate Researcher's contribution (%)	75	Status	☒Published ☐ Accepted and in-press ☐ In progress
Journal or book name	Mendeley Data		
Volume and page numbers (if published)	V2	Date accepted/ published (if relevant)	Available online 21 February 2022

B. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Economic and environmental impacts of public investment in clean energy RD&D		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui Paulo Vaz-Serra		
Graduate Researcher's contribution (%)	65	Status	☒Published ☐ Accepted and in-press ☐ In progress
Journal or book name	Energy Policy		

Volume and page numbers (if published)	168/113134	Date accepted/ published (if relevant)	Available online 01 July 2022

B. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Robust policy mixes for clean energy transitions in developing countries: An exploratory analysis for Mexico		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui Paulo Vaz-Serra		
Graduate Researcher's contribution (%)	65	Status	☐ Published ☐ Accepted and in-press ☒ In progress
Journal or book name	Nature Energy		
Volume and page numbers (if published)	Enter Volume/Page numbers here.	Date accepted/ published (if relevant)	Enter Date

Appendix B Publication related to Chapter 2

Co-author authorisation form

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All co-authors must complete this form. By signing below co-authors agree to material from the listed publication being included in the graduate researcher's thesis and that the graduate researcher contributed greater than 50% of the content of the publication and is the "primary author" ie. the graduate researcher was responsible primarily for the planning, execution and preparation of the work for publication.

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A. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Full title	Making policy mixes more robust: An integrative and interdisciplinary approach for clean energy transitions		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate researcher's contribution (%)	75		
Status	☒ Published ☐ Accepted and In-press ☐ In progress		
Journal or book name	Energy Research & Social Science		
Volume/page numbers (if published)	64/101425	Date accepted/ published (if relevant)	Available online 16 January 2020

B. CO-AUTHOR'S DECLARATION *(to be completed by the collaborator)*

I authorise the inclusion of material from this publication in the graduate researcher's thesis and certify that:

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A. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

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Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate researcher's contribution (%)	75		
Status	☒ Published ☐ Accepted and In-press ☐ In progress		
Journal or book name	Energy Research & Social Science		
Volume/page numbers (if published)	64/101425	Date accepted/ published (if relevant)	Available online 16 January 2020

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Original research article

Making policy mixes more robust: An integrative and interdisciplinary approach for clean energy transitions

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ABSTRACT

Energy transitions from a fossil fuel-based to a clean-energy economy are required to meet international commitments on climate change mitigation. Energy-related policies play a paramount role to influence the pace of clean energy transitions. Energy policy makers must deal with operational, tactical, and strategic challenges due to an extensive range of deep uncertainties such as fuel price fluctuations, unpredictable demand behaviour, and climate change. Even though the future is uncertain, policy makers must design strategies to meet diverse long-term energy goals in line with changing societal needs. Analyses of the dynamics of policy decisions, economic development, technological innovation, social changes, and environmental impacts enable designing robust policy mixes consistent with clean energy transitions. A policy mix is considered robust, if the system of interest performs satisfactorily under a broad range of plausible futures. Thus, an integrated method is developed for organising energy policy recommendations to achieve robust policy mixes towards clean energy transitions. The method presented is an integration of energy transitions concepts, robustness-based approaches, quantitative simulation modelling techniques, and exploratory modelling and analysis.

1. Introduction

Every single day we make decisions around our lives that may have positive or negative impacts in the future. Policy decisions (e.g. R&D public investment, infrastructure expansion strategies, urbanisation plans) have long-term effects [1]. Current public policies may support regional, sectoral, and/or national development in long timeframes. Public policies are understood as the set of objectives, decisions, and actions carried out by the government to solve practical problems that both the citizens and the government consider paramount at the point of time [2]. These decisions involve multiple actors, sectors, and government levels. Policymakers develop policy strategies to solve practical problems based on the analysis and interpretation of available information. However, conditions throughout time may change rapidly making current strategies not suited for new conditions. Thus, policymakers may formulate policies capable of withstanding variations of the initial designed conditions [3].

The trends of the performance of energy systems could be different in the future due to incorrect predicted changes in economic, technological, social, political, and environmental conditions. There is no agreement among both decision-makers and scholars about what the exact future of clean energy technologies will be and the impact on the development of the electricity sector. Electricity transitions are conceptualised as co-evolutionary, multi-actor, long-term dynamic processes of structural change in the way electricity is produced and used [4,5]. Multiple barriers to electricity transitions have been identified, including lock-in into fossil fuel-based technological trajectories, resistance to change from incumbent regimes, and path dependency and inertia due to organisational commitments and vested interests within energy systems [5]. Thus, energy-related policymaking plays a key role in overcoming these challenges and promoting electricity transitions to reach national energy objectives (e.g. use of clean energy technologies for decarbonisation).

Choosing and implementing an energy policy instrument, or a mix of instruments, from a range of options may affect different from the intended performance in the future. Analyses of policy mixes for energy transitions consider not only the interaction among policy instruments but also a strategic component (including policy objectives and plans), the dynamic policy processes, and the analysis of actors and institutions involved in developing and implementing such policy mixes [5,6]. Electricity transition processes involve various key actors with diverse interests and roles within energy systems. Thus, when diverse stakeholders are considered in energy policy development identifying suitable policy instruments for clean energy transitions turns out to be

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difficult. Priorities set to meet the requirements of electricity systems vary among institutions, targeting different (sometimes contradictory) intended outcomes. Considering different perceptions and diverse possible electricity transitions pathways that can unfold in a range of plausible futures, policymaking for clean energy transitions is considered a 'wicked' problem [7]. For a wicked problem the selection of a solution depends upon the interaction among a variety of decision-makers and stakeholders with conflicting values and diverging viewpoints [8].

Traditional energy policy-making approaches aim to answer the question 'What will happen in the future?' by using suited predictive energy models. In general, these models rely on various assumptions to aid policymakers in designing an optimal policy instrument mix based on the system's likely evolution. An optimal policy instrument mix is defined to be one that reach the best results based on a particular perspective and considering well-defined and narrowed future conditions. However, if various perspectives and changing conditions over time are considered, the application of traditional policy-making approaches to wicked problems is limited. Energy policymaking for clean energy transitions must deal with operational, tactical, and strategic challenges due to an extensive range of deep uncertainties such as unpredictable energy demand, fuel prices fluctuations, and climate change [9]. Deep uncertainty is the condition in which analysists do not know or the parties to a decision cannot agree on: (a) the appropriate models to describe interactions among different variables of a system, (b) the probability distributions to represent uncertainty about key parameters, and/or (c) how to assess the desirability of alternative outcomes [10].

Various approaches have been proposed to deal with deep uncertainty in policy-making processes [11]. Policymakers can choose a strategy among various options: (1) plan for the worst-case scenario (i.e. resistance), (2) regardless of the conditions in the future, select a policy mix that allow the system to recover rapidly (i.e. resilience), (3) seek a strategy that will be able to perform reasonably well in almost all plausible futures (i.e. static robustness), and (4) in case of a change in conditions, be prepared to change the policy mix (i.e. adaptive robustness) [11].

Robust policy mixes aim to answer, 'knowing the fact that the future is uncertain, what available policy instruments are likely to perform well in multiple plausible futures?' [12]. 'Robustness-based approaches' are considered useful when decision-makers are trying to find policy alternatives that perform satisfactorily across multiple plausible future conditions. To reach this, there is a need for tools that allow policymakers to develop and evaluate robust policy mixes while coping with deep uncertainty. Policy analysis with a robustness-based approach can be used as a systematic process for analysing the plausible consequences of adopting different policy instruments in a dynamic setting [13]. By estimating these plausible consequences, a dataset is generated. Then, the dataset is analysed based on intended performance outcomes. As a result of the analysis, information relevant to the policy-making process is obtained, hereafter referred as *policy-relevant information*. Policy-relevant information can be obtained by using different research paradigms: quantitative, qualitative, or a combination of both (integrated methods) [14].

The aim of this paper is to develop an integrated method to explore environmental impacts of robust energy policy mixes towards clean energy transitions. The proposed method is developed in the context of electricity transitions at a national level. In the frame of decarbonisation processes by using clean energy technologies, this integrated method mainly focuses on environmental impacts (e.g. greenhouse gas emissions mitigation). The developed method was formulated by integrating various analytical tools to take their advantages for energy policy analysis. To demonstrate the practical applicability, we introduce and discuss some successful examples of these tools applied to energy and electricity transitions.

The rest of the paper is organised as follows. Section 2 presents the background of this paper by describing diverse analytical tools used in policy analysis for energy transitions. Also, some challenges to energy transitions policy analysis are presented and discussed. An integrated method for model-based policy analysis towards clean energy transitions is developed and presented in Section 3. In Section 4 the advantages and limitations of the method presented are discussed. Conclusions are exhibited in Section 5.

2. Model-based policy analysis for energy transitions

Dunn [15] defined policy problems as "… *unrealized needs, values, or opportunities for improvement attainable through public action.*". When policy problems formulation becomes challenging due to contradicting decision-makers' standpoints, investigating diverse policy alternatives becomes crucial. Policy analysis supports policymakers in selecting lines of action by identifying stakeholders' preferences, possible policy alternatives, deep uncertainties, and outcomes of interest [13]. Thus, the aim of a policy analysis process is to analyse information relevant to the parties involved within the policy-making process about the consequences of adopting different policy instruments [13].

The concept of policy instrument mix (a combination of policy instruments and the interaction among instruments) is considered just as one element within the policy mix framework proposed by Rogge and Reichardt [6]. In the context of sustainability transitions, a policy mix should incorporate policy-making processes and a strategic component in order to evaluate the impact of energy policy instruments aimed at achieving sustainability-oriented objectives in a dynamic setting [6]. Policymaking for clean energy transitions can be seen as a policy learning process based on a cycle of problem-solving attempts with a focus on repeated analysis of energy policy problems and experimentation with solutions [16]. To facilitate the policy learning process, the exploration of the plausible impacts of policy instruments under deep uncertainty conditions is necessary.

Aiming at supporting policymakers in addressing energy-related policy problems, various approaches can be applied to analyse policy-relevant information. Model-based policy analysis is one approach that systematically explores the effect of policy mixes on different contexts (e.g. current or future transformation processes) and, thus, the degree to which policy instruments can aid to meet specific (long-term) targets [17]. This systematic exploration may be carried out through a structured analytical process (see Fig. 1). A detailed description of the set of steps considered within the policy analysis process may be found in [18, 19]. Thus, using models, policy-relevant information not easily apparent for policymakers can be analysed to improve energy policy-making towards clean energy transitions. Various analytical tools have been applied for model-based policy analysis to support decision-making for energy transitions. This research focusses on analytical tools used for policy problem identification and policy alternatives analysis (see Fig. 1).

Several model approaches have been developed for energy systems [20]. The analysis of energy-economy models is mainly based on the theoretical paradigm of following the normative neoclassical assumptions of rational choice, perfect information, and profit and utility maximisation [21]. Thus, traditional quantitative modelling approaches (i.e. integrated energy assessment and optimisation models) tend to depend on economic optimisation and equilibrium assumptions [22]. This type of quantitative energy models narrows its scope by linking only techno-economic factors to understand energy systems and their plausible future development. Therefore, the behaviour of individual actors and organisations, policies, regulations, and social aspects are framed exogenously within formal energy-economic models for energy policy analysis [21]. Reviews of this category of energy models and their application to energy policy analysis may be found in [23, 24].

To capture key societal actors and the co-evolutionary aspects of policy, technology, and behavioural aspects within formal quantitative

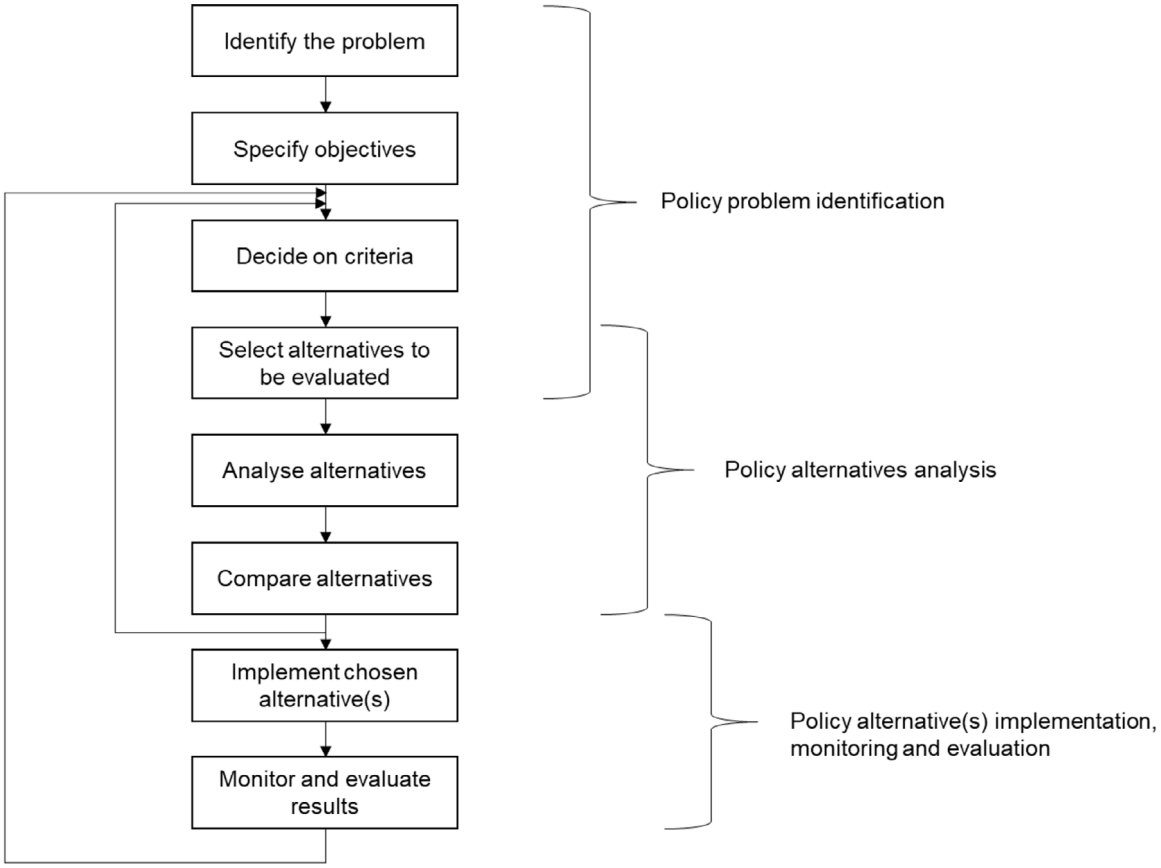


Fig. 1. Steps in a policy analysis study. Source: Walker [13].

energy models, 'Socio-Technical Energy Transition' (STET) models were proposed [21]. STET models aim at improving the understanding of the plausible impact of policy design and implementation on normative futures for energy transitions. They integrate techno-economic details, actor heterogeneity, and transition pathway dynamics to capture the elements of socio-technical transitions [21]. Thus, qualitative insights regarding the dynamics of societal actors, socio-technical change, and policy interventions can be included within quantitative energy models to analyse energy transitions.

2.1. Understanding energy transitions for policy problem identification

Ackoff [25] pointed out that "*Successful problem solving requires finding the right solution to the right problem. We fail more often because we solve the wrong problem than because we get the wrong solution to the right problem.*". When even the task of defining policy problems is contested and uncertain due to diverse stakeholders' preferences and viewpoints, the use of different tools for framing the policy system turns crucial. Various problem structuring methods (PSMs) have been proposed to deal with the conceptualisation of complex problem situations characterised by multiple actors, multiple perceptions, contradictory interest, important intangibles, and key uncertainties [26]. Aiming at conceptualising and delimiting the system of interest, PSMs use diverse analytical techniques based on different theoretical bases. A summary of most widely applied PSMs may be found in [26–28]. Though one single method can be applied to conceptualise particular problems, there are several case studies where analysts combine parts of methods together (considering qualitative, quantitative, and integrated methods) to deal with their limitations and to improve the problem identification [28]. In order to identify the policy problem, this research focuses on two frameworks: energy transitions concepts for policy analysis and policy problem structuring frameworks.

Several transition theories, with different roots (e.g. economics, social studies, history of technology, political science) have been used for (qualitatively) understanding societal transitions in general and energy transitions in particular [29,30]. Turnheim et al. [29] set out a suggestion for linking three theoretical approaches to the analysis of sustainable transition pathways: quantitative systems modelling, socio-technical transition analysis, and initiative-based learning. On the other hand, Cherp et al. [30] analysed existing approaches focused on energy transition studies and categorised them in three main perspectives: techno-economic, socio-technical, and political. At the view of this framework, long-term changes occur within three major co-evolving sub-systems: (1) techno-economic sub-system, explained by energy flows associated with energy supply and demand coordinated through energy markets; (2) socio-technical sub-system, defined by energy technologies; and (3) sub-system of political actions, influencing energy systems by adopting and implementing energy-related policy instruments. The concept of co-evolution systems (or sub-systems) refers to the idea of systems with their own elements, boundaries, and dynamics but interacting among them [30]. In addition, various definitions of core concepts to policy mixes for energy transitions have been proposed. Examples of these concepts and how policy mixes are addressed by three key disciplinary foundations (environmental economics, innovation studies, and policy sciences) are synthesised in [5].

A complementary approach to energy policy problem identification is the use of policy analysis frameworks. For instance, Moallemi et al. [31] used energy-related examples to illustrate the applicability of the XLRM (exogenous uncertainties, policy levers, relationships, and measures) framework from robust decision making [10] to problem formulation for multi-objective decision making under deep uncertainty. Similarly, Agusdinata and DeLaurentis [32] presented a policy problem formulation framework to study how policy intervention could aid in reducing greenhouse gas emissions in the Dutch household sector. A

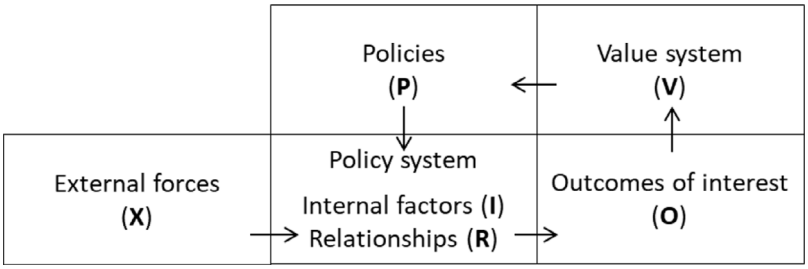


Fig. 2. Policy analysis approach with XPIROV structure. Source: Agusdinata and DeLaurentis [32].

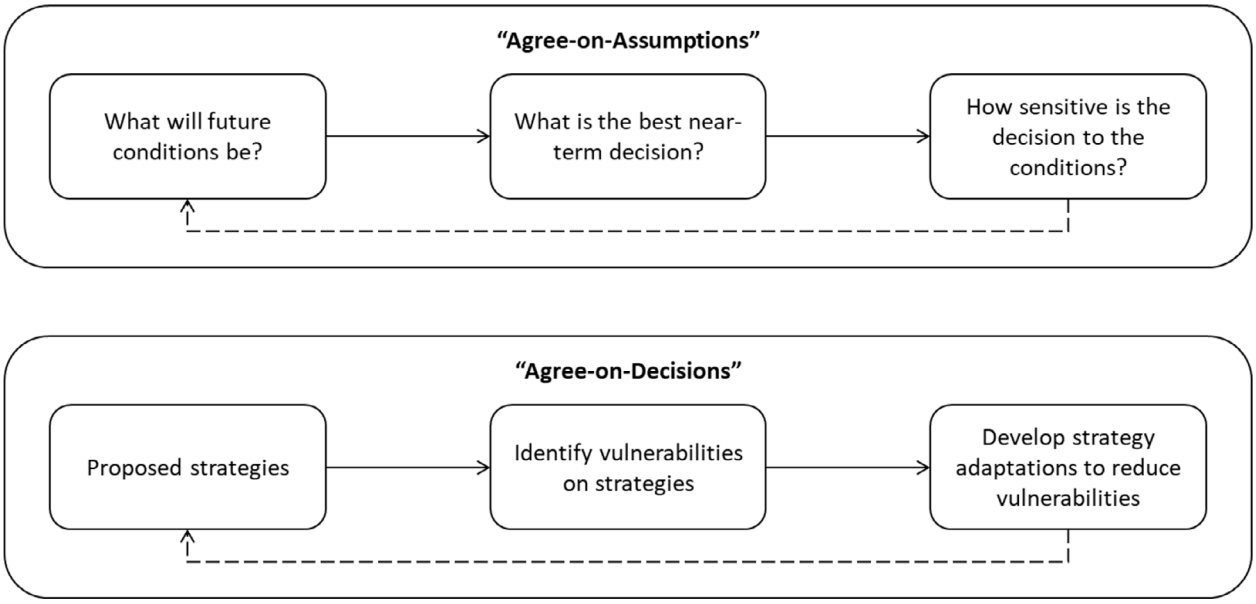


Fig. 3. 'Agree-on-assumptions' and 'Agree-on-decisions' processes. Source: Kalra et al. [1].

policy problem structuring framework called 'policy analysis XPIROV framework' (Fig. 2) informs the exploratory modelling and analysis process by identifying key elements for the system-of-systems (SoS) model. The framework is an expanded version of Walker's public policy analysis [13] and XLRM [10] frameworks.

In Fig. 2, external forces (X) are exogenous factors beyond the control of policymakers (e.g. cost of conventional fuels, renewable access to power grid, technological progress). Policies (P) are the policy instruments (e.g. incentives and regulations for renewable energy) which seek to influence system's behaviour towards the achievement of stated objectives. Internal factors (I) are the endogenous components of the system which may be influenced by policies and external forces (e.g. stock of renewables within the Dutch Renewable Energy System). Relationships (R) refer to the linkages among internal factors, external forces, and policies which produce the outcomes of interest (O). These relationships can be classified into (1) relationships between the system and external forces, (2) relationships among internal factors, and (3) relationships between internal factors and outcomes of interest. The outcomes of interest (O) are considered as a relevant set of characteristics of the system for the evaluation of various policies (e.g. share of renewables in the energy supply). Based on stakeholders' preferences and policymakers' objectives, the value system (V) contains the criteria to identify the desirability of different policy outcomes (e.g. energy security, protection of the environment) [32,33]. Unlike Walker's [13] and XLRM [10] frameworks, XPIROV framework [32] makes an explicit consideration of internal factors within the system of interest with the aim of better explaining the structural change in the policy system [33].

2.2. A robustness-based approach to policy alternatives analysis

Traditional policymaking aims to agree on assumptions about current and future conditions to reduce uncertainty. This 'Agree-on-assumptions' approach (also called 'predict-then-act' [1]) explores how sensitive is the 'best' near-term decision to assumed conditions of the future. A 'best' solution can perform well according to a specific set of assumptions but perform poorly if the assumptions are incorrect. Decision making under deep uncertainty (DMUDU) approaches follow an inverted process known as 'Agree-on-decisions' to encourage consensus about robust solutions (i.e. to perform 'satisfactorily' regardless of uncertain future) by analysing options first and then seeking agreement. This process considers the identification of vulnerabilities and opportunities of proposed solutions with the aim of developing solution adaptations to reduce the vulnerabilities and focus decision-makers' attention on trade-offs among decision alternatives [10]. In this research, we consider policy alternatives as those policy instrument mixes whose impact on electricity transitions are of interest to policymakers (e.g. energy R&D public investment, clean energy certificates, tax incentives) [34]. The identification of specific conditions in which each alternative does not meet its goals can be revealed using analytical tools [1].

Thus, the focus in 'Agree-on-decision' processes is on testing the available options (policy alternatives in the case of policymaking) under an extensive range of plausible conditions, considering diverse set of uncertainties (see Fig. 3).

Recently a variety of exploratory model-based frameworks have been proposed. They consider deep uncertainty and aim at designing robust policy strategies as opposite to optimal. These approaches

include (but are not limited to) Information-gap Decision Theory (Info-gap) [35,36], Robust Decision Making (RDM) [10], Decision Scaling or Climate Informed Decision Analysis (CIDA) [37], Dynamic Adaptive Policy Pathways (DAPP) [38], and Many-Objective Robust Decision Making (MORDM) [39]. See [40] for a review of DMUDU approaches.

DMUDU approaches (or robustness-based frameworks) provide a structured framework for planning complex systems [41]. They encompass diverse interdependent steps to obtain relevant information through simulations. Nevertheless, model-based policy analysis under conditions of deep uncertainty is problematic due to the complexity of strict model validation. A limitation of DMUDU approaches, pointed out by Kwakkel et al. [42], is that analysts commonly rely on the importance of using existing (energy-economy) models that are accepted by the parties for a decision. Exploratory modelling and analysis (EMA) can be useful when policy-relevant information is to be obtained and analysed by constructing models but is not possible to identify a single model which accurately describes the system behaviour. Thus, models are built in line with available information, but they are not unique [43,44].

EMA uses computational experiments to explore several possible futures shaped by the impact of diverse methodological, structural, and parametric uncertainties [10,44]. By running computer simulations many times, a large dataset of cases is generated and then analysed using different algorithms and techniques to determine vulnerabilities of the proposed policy alternatives. EMA is commonly applied for three main purposes: (1) to identify under what conditions a plausible future can take place and what combination of uncertainties could trigger undesirable outcomes; (2) to assess strategies performance under uncertain conditions; and (3) to identify vulnerabilities and possible trade-offs among policy alternatives [45].

2.3. Challenges to model-based policy analysis for energy transitions

Multiple analytical approaches with different theoretical roots have been applied in isolation to study energy transitions. However, how they can be integrated in order to complement each other for policy analysis is seldom addressed in the literature [34]. Thus, in this section some key challenges for policy analysis towards clean energy transitions are discussed and some lines of action to address them are proposed.

First, although problem definition is highly emphasised within policy analysis literature [13,15], modelling techniques such as system dynamics [46], exploratory modelling and analysis [33,44,47], and robustness-based approaches [10,35,37–39], there is little discussion regarding what methods to use when defining the boundaries of a policy system. As stated by Rogge and Reichardt [6], the definition of these boundaries should be seen as an iterative process, improving the policy learning process. Thus, the co-evolution patterns of policy mixes for clean energy transitions and technological innovation can only be revealed through dynamic analyses covering long-term timeframes [6]. Model-based policy analysis with a robust approach may aid policymakers to improve the learning process by exploring the consequences of implementing different policy alternatives towards energy transitions under deep uncertainty conditions.

Second, when models are applied to study complex societal challenges, such as electricity transitions, the concepts of ‘dynamic complexity’ and ‘deep uncertainty’ emerge [43]. Deep uncertainty refers to the situation in which the parties to a decision do not know or cannot agree on: (1) models that relate relevant variables and parameters, (2) probability distributions of the model elements, and/or (3) the desirability of outcomes of interest [10]. Dynamic complexity implies that the system is dynamic, non-linear, adaptive, self-organised, history dependent, governed by feedback, policy resistant, counterintuitive, and characterised by trade-offs [46].

To cope with the dynamic complexity of energy systems, non-linear dynamics models can be used such as STET models. They aid analysts and decision-makers to understand the behaviour of complex energy systems by combining the formal rigor of mathematical models with the wealth of verbal models. Several STET models have been applied as a tool to aid policy analysis in energy transitions. However, how they deal with uncertainty analysis is a key limitation pointed out by Li et al. [21]. Usually STET models depend on deterministic sensitivity analysis to provide insights regarding long-run changes to energy systems. This limitation could be overcome by applying an exploratory thinking approach to explore the behaviour of complex energy systems characterised by deep uncertainty conditions.

To deal with deep uncertainty, policymakers seek to develop and implement alternatives to achieve multiple performance goals across a wide range of plausible futures while withstanding modifications in the conditions for which they were designed [3]. Considering changing conditions, the concept of robustness plays an important role in energy policymaking under deep uncertainty. A policy alternative is assumed to be robust if the outcomes of interest perform ‘satisfactorily’ under a broad range of plausible conditions in future [11]. To capture decision-makers’ stance about uncertainty (pessimistic/optimistic attitude), a large number of formal (mathematical) definitions of robustness have been proposed [48–50]. The different ways of quantifying the robustness of a policy alternative is referred by Schneller and Sphicas [51] as ‘the meta-problem of deciding how to decide’. For instance, a recent study by McPhail et al. [50] categorised and compared several robustness metrics to illustrate the difference of choosing one from the others. Eleven robustness metrics, categorised in four main classes, were applied to three case studies to provide understandings regarding the ranking of alternatives. They concluded by stating that the decision of robustness metrics should consider: (1) the decision-context, (2) the preferred level of risk aversion, and (3) the decision-makers’ preferences regarding performance, variance or some higher-order moment. To overcome this challenge, explicit decision rules should be included within the policy problem formulation as a normative criterion to ‘accept’ robust policy alternatives.

Third, based on multiple conceptual and empirical contributions on policy mixes for energy transitions, some key implications for future work were identified [5]. We focus on two of them: methodological and geographical limitations. First, many studies on the field rest on qualitative research methods uncovering partial relevant information to policymakers. However, an integrated method for energy policy analysis towards clean energy transitions may contribute to a better-informed policy advise. Second, the majority of empirical policy mix research has focused on the European Union only. To overcome this limitation, we propose to expand the geopolitical coverage by applying the proposed method to developing countries members of the Organisation for Economic Co-operation and Development (OECD). Developing countries within the OECD have some common features in their electricity systems. The need for expansion of infrastructure is due to rapid growth in the electricity demand, continuous structural changes, and greater uncertainties regarding future conditions for energy system transition. The operationalisation of the proposed method may consider available public documents and databases of policy instruments, outcomes of interest, and key parameters encompassed within the electricity system (usually presented at a national level).

To gain insights to overcome these challenges in a holistic manner, this research focuses on answering the following research question: how can quantitative and qualitative methods for policy analysis be integrated to explore the plausible consequences of adopting different policy instruments towards clean energy transitions? With the aim of analysing these potential consequences considering many plausible futures, simulations combined with large data, computational capability, and visualisation tools are required [52]. Thus, an integrated method for policy analysis towards clean energy transitions is developed and presented in Section 3.

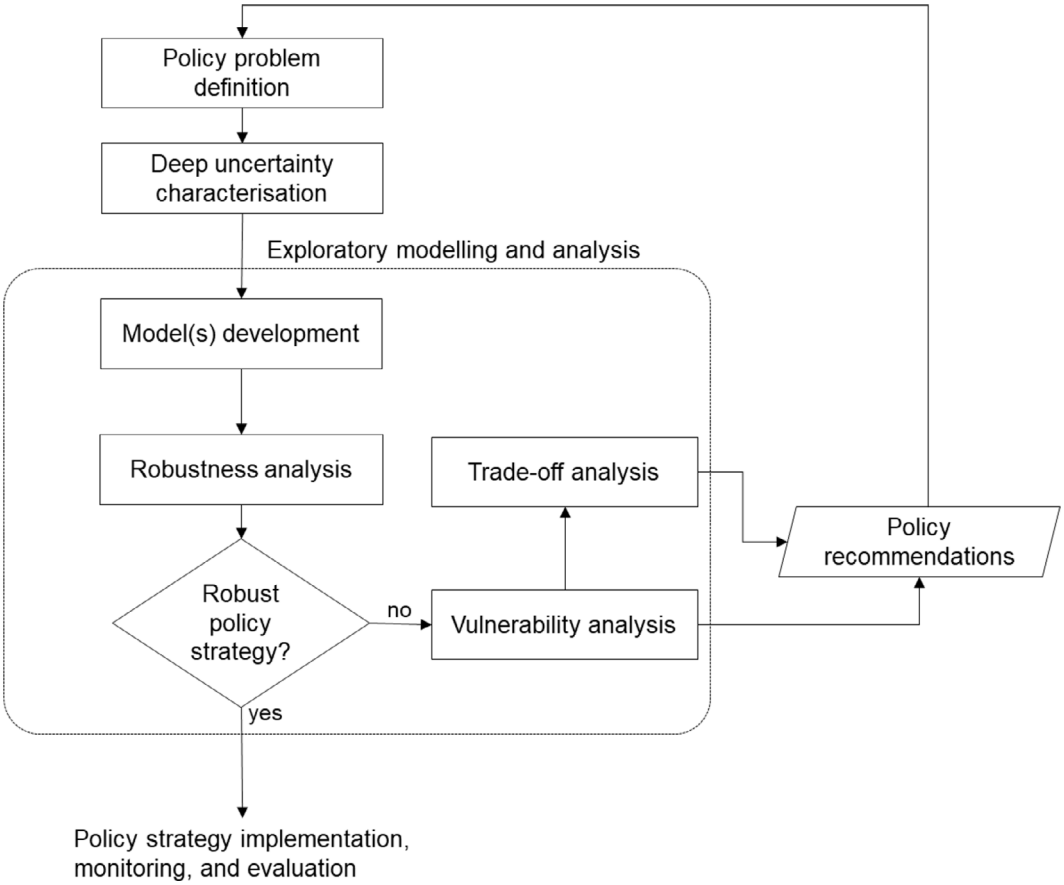


Fig. 4. Stepwise processes considered within the integrated method for energy policy analysis towards clean energy transitions.

3. Introducing an integrated method for policy analysis

In this paper, an integrated method has been developed for policy analysis based on the robustness of energy policy mixes for clean energy transitions. This method integrates diverse quantitative and qualitative analytical tools used for policy design. It aims at analysing policy-relevant information by carrying out a series of interdependent analytical processes (see Fig. 4). Each process is explained in the following sections. By applying the method proposed we expect to aid policymakers in redirecting and accelerating innovation towards clean energy transitions.

3.1. Policy problem definition

The notion of conceptualising the system of interest to formulate model(s) structure(s) and to define the corresponding policy system boundaries is known with various terms: problem identification, problem definition, problem formulation, problem conceptualisation. In this paper, problem definition is used in lieu of problem identification within the policy analysis approach [13]. This first step within the integrated method is critical for obtaining and analysing 'the right' policy information relevant to policymakers.

Based on the understanding and definition of the policy system, model(s) development is carried out by different approaches. Thus, policy-relevant information is analysed differently to support policy-making decisions. Different conceptual framings have been applied to understand energy transitions, and then inform model development for exploratory analysis. For instance, Moallemi et al. [53,54] used qualitative storylines (historical narratives) to understand the dynamics of energy transition pathways in India. Based on a historically-informed review of energy transitions, they pointed out that narratives (i.e. structured storylines) frame the exploratory modelling and analysis process, serving as a conceptual framework to develop the system dynamics model. Kwakkel and Yücel [55] described historical trajectories to explain the internal dynamics within the Dutch electricity system and identify actors' preferences to shape plausible development pathways (i.e. energy transitions). Based on these historical trajectories and actors' decisions, an agent-based simulation model was developed for exploratory analysis.

The examples mentioned above were applied to the electricity sector using different approaches to inform the exploratory modelling and analysis process (structured historical narratives based on a socio-technical perspective and historical actors' behaviour). We argue that an integrated framework for policy systems conceptualisation and contextualisation is needed. Conceptualisation refers to the identification of the policy system boundaries, as well as identifying the key elements of the system of interest. Contextualisation calls for understanding the policy system within a geographical, sectoral, historical, and social context. Thus, to explain historical electricity transitions and their context, and then, define the policy problem, two complementary analytical phases are proposed.

First, based on literature review and policy research, the analyst describes historical electricity transitions to contextualise the current state of the system. The adoption of energy transitions concepts using a multi-perspective analytic framework [30] and core concepts from policy mixes for energy transitions literature [5,6] are suggested for this phase. In a second phase, an elicitation process is carried out with policymakers. This process uses a policy analysis framework labelled as 'COPRIEMD' to explicitly define the boundaries of the policy system to be analysed. The outcome of the first phase is used as starting point to lead the elicitation process towards the identification of key system elements and to inform the development of the model(s) to be used in

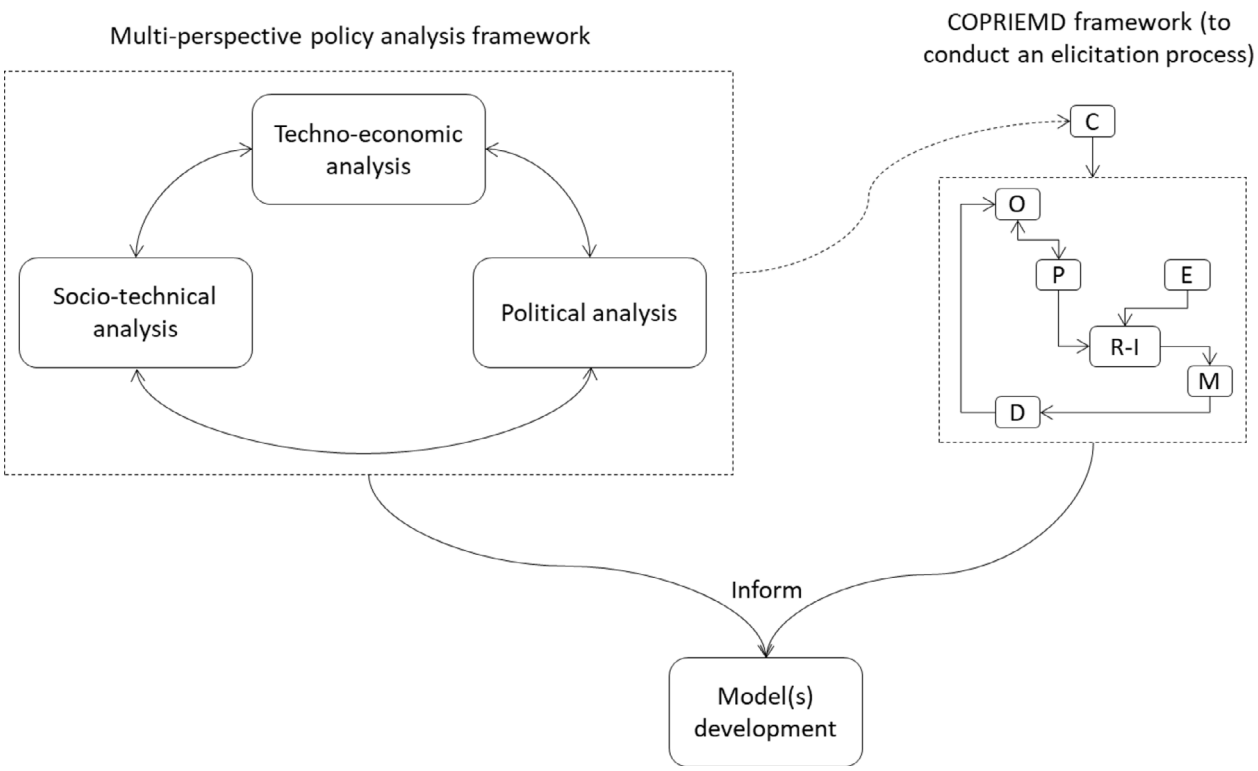


Fig. 5. Integrated framework for policy problem definition. (C = policy problem context, O = objectives values, P = policy alternatives, R = relationships, I = internal components, E = external factors, M = performance metrics, D = decision rules).

an exploratory modelling and analysis process (see Fig. 5).

Sustainability transitions concepts have been used to describe historical electricity transitions and the role of diverse policy mixes in future transitions. For instance, a multi-perspective analytic framework (based on the interaction of techno-economic, socio-technical, and political processes) was applied to analyse national low-carbon electricity transitions by comparing the evolution of nuclear, solar, and wind power generation technologies in Germany and Japan [56]. In addition, concepts from the emerging literature on policy mixes for sustainability transitions have been applied to study and assess the impact of policy mixes on electricity transitions in Europe (see, for instance, [57–60]).

A more comprehensive contextualisation of the policy system is sought, by applying a multi-perspective approach in the first phase, reflecting different perceptions of relevant elements of the system. The outcome of this phase is a structured storyline describing historical electricity transitions and the current situation of the policy system. Within this framework, diverse complementary sustainability transitions concepts are used (see Fig. 6) to describe and understand relevant long-term changes within energy systems. In addition, concepts from the policy mixes for energy transitions literature are integrated to explain the impact of policy instruments on historical electricity transitions. The main reason for using different (yet complementary) analyses of energy transitions is due to changes in the system can take place as a result of different contextual driving forces from one episode to another [30]. Aiming at identifying driving forces and main barriers in electricity transitions, that is used for the next phase of the policy problem definition process.

An elicitation process is proposed as the second phase to identify and to select the relevant elements to be included within the model(s) for exploratory modelling and analysis. To carry out this participatory technique a structured framework is needed to capture relevant information. Taking previous policy analysis frameworks as a basis [10,13] (see Section 2.1), a new framework for conducting an elicitation process is proposed. It aims to capture system perceptions from different stakeholders (e.g. industry, academia, and policymakers) (Fig. 7). Three key elements are added within this framework: policy problem context (C), objectives values (O), and decision rules (D), which are explained in the following section. For the rest of the elements within 'COPRIEMD' framework we use conventional terminologies within model-based policy analysis and robust decision-making domains: policy alternatives (P), external factors (E), internal components (I), and performance metrics (M) instead of policies, external forces, internal factors, and outcomes of interest, used in 'XPIROV' framework [32,33].

3.1.1. Policy problem context (C)

Aiming at identifying policy-relevant information regarding the nature, scope, stakeholders, boundaries, and possible impacts of policy mixes, the context within which different policy alternatives are to be assessed is established explicitly. The explicit policy problem context allows decision-makers to have a preliminary understanding of the policy problem, the context in which the system of interest is immerse, and the purpose of the analysis. For this paper, 'C' corresponds to the structured storyline generated using energy transitions concepts (see Fig. 5).

3.1.2. Objectives values (O)

In line with the policy problem context, and based on usually contested stakeholders' preferences, multiple objectives are involved in public policy problems [13]. To express a set of minimum acceptable performance requirements (i.e. performance thresholds) defined by decision-makers [61], the objectives values are encompassed in the proposed framework. These values are different from the value system proposed by Agusdinata and DeLaurentis [32]: similar to policies, the value system is taken as given within XPIROV framework, while objectives values in the framework proposed here consider possible trade-offs; setting thresholds based on stakeholders' preferences and priorities. The set of requirements can be evaluated in two ways: where all criteria must be met (as an intersection) or where any of the criteria are

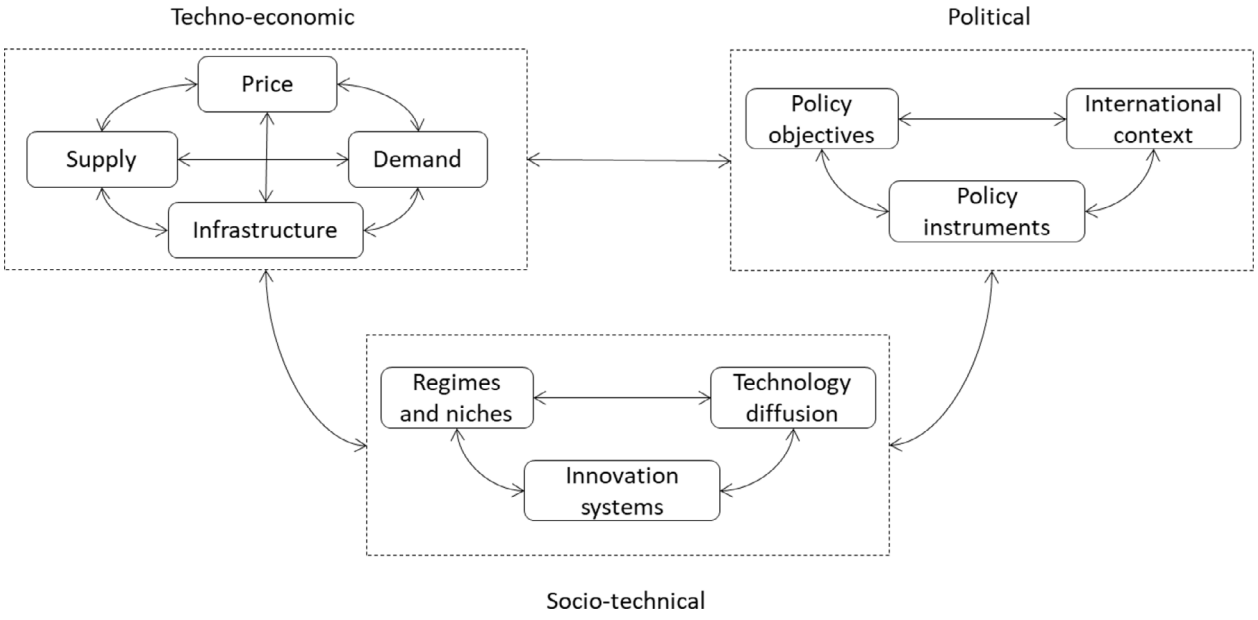


Fig. 6. Energy transitions concepts associated with the three perspectives on national energy transitions. Sources: Own elaboration based on [5,6,30,56].

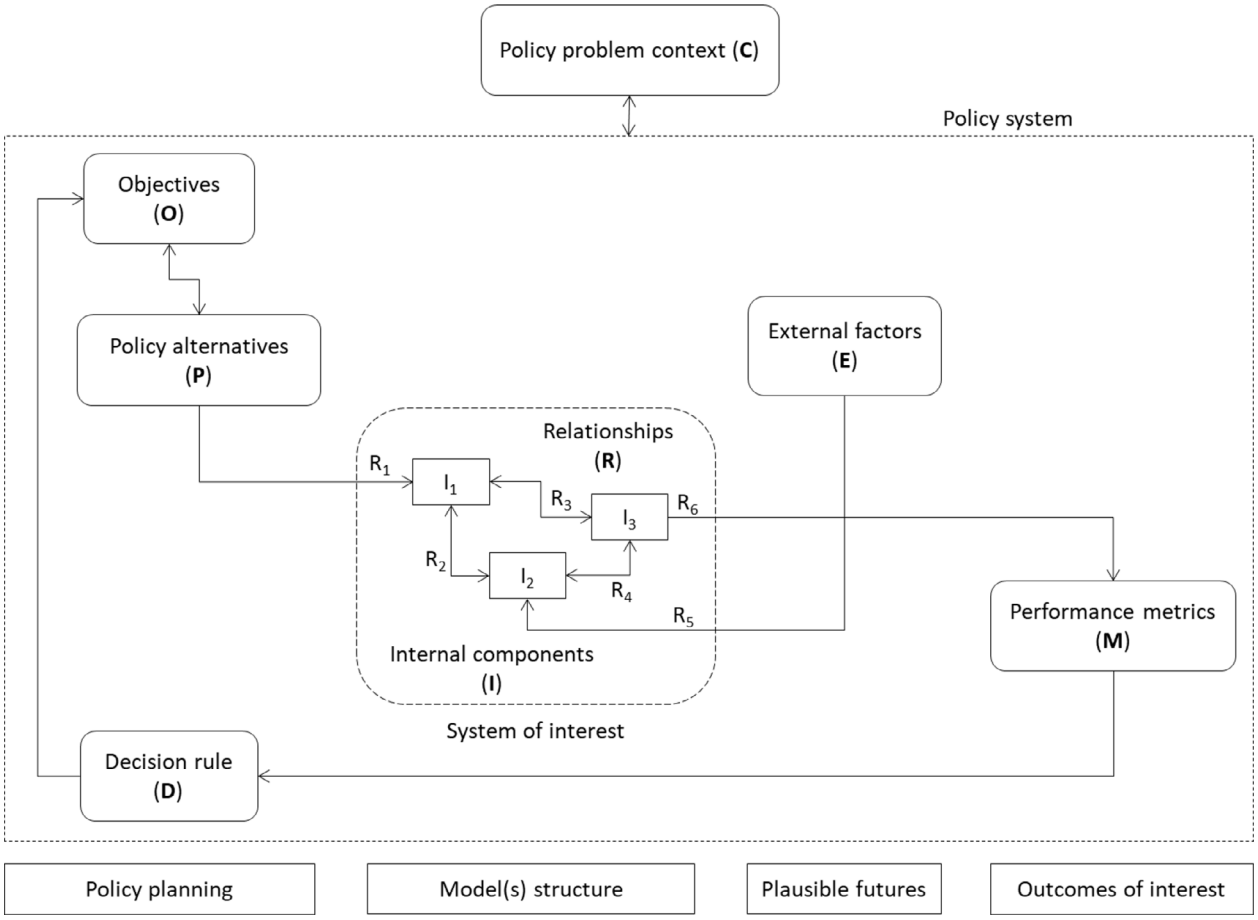


Fig. 7. Policy problem definition through COPRIEMD framework.

met (as a union) [61].

3.1.3. Decision rules (D) for robustness assessment

Specifying the decision rules within the policy problem definition process is paramount for analysing and communicating policy-relevant information to decision-makers. The definition of robustness in this phase is proposed within the framework as a normative criterion for decision-making. Based on alternative robustness requirements, choosing an energy policy alternative among others could vary significantly. Thus, we argue that the policy problem definition process should include the selection of robustness requirements based on policymakers' preferences and system perceptions. The robustness

identification can be explicitly established by policymakers or initially proposed by the analyst. Bearing in mind that the method presented is an iterative set of processes, the impact of alternative robustness requirements can be explored in following iterations.

3.2. Deep uncertainty characterisation

The representation of uncertainty has been conceptualised through diverse typologies in the literature [11,62]. Multiple types of uncertainty are presented in complex energy problems [63,64]. For instance, Kwakkel and Yücel [55] assessed the impact of technological, political, and socio-economic uncertainty factors on the development path for the Dutch electricity system. They stated investment and operational costs for various generation technologies, the demand development, decision making by generator companies, and carbon prices as the main uncertainties affecting electricity transitions. On the other hand, Moallemi et al. [53] identified five key deep uncertainties in the future transition pathways of the Indian electricity sector. Using standard sensitivity analysis in Vensim DSS and policy research they found that the learning curve of renewable generation technologies, electricity losses in grids, the potential installed capacity of renewables, the stability of policy supports, and the capacity factor of fossil fuel power plants are the main uncertainty factors in future electricity transitions.

To aid with the definition of what to be considered inside or outside the policy systems, we propose a *deep uncertainty characterisation matrix* (see Table 1) for leading the identification of deep uncertainties. To carry out the deep uncertainty characterisation a series of steps are proposed. First, all the internal components, relationships, external factors, and performance metrics obtained from the elicitation process are listed within the deep uncertainty characterisation matrix. Then, based on different perceptions of the policy system, the matrix is filled out specifying what elements are relevant for the analysis (model structure definition) and the range of possible values to be analysed (parametric definition). By filling the matrix considering different perspectives, diverse (complementary) model structures can be formulated. These models (considering different perceptions) serve as scenario generators for exploratory analysis.

In a single exploratory modelling and analysis approach, is technically feasible to deal with multiple alternative models (i.e. system perceptions) to analyse policy-relevant information [42]. By carrying out an exploratory modelling and analysis process, employing different but complementary models, the focus is on improving the process of learning about stakeholders' preferences and possible trade-offs.

The deep uncertainty characterisation matrix shown in Table 1 is proposed as an analytic tool to systematically obtain information about the elements that should be included within the policy system based on different perspectives. Thus, analysts and users of the model(s) can explicitly identify uncertain factors that may shape the future of clean energy transitions.

Table 1
Deep uncertainty characterisation matrix.

System perception (e.g. policymakers' perception of the system)				
Location		Relevant for analysis?	Initial value	Range
Model structure	Internal components (I)	–	–	–
	Relationships (R)	–	–	–
Future conditions	External factors (E)	–	–	–
Outcomes of interest	Performance metrics (M)	–	–	–

3.3. Exploratory modelling and analysis

3.3.1. Model(s) development and simulation

According to relativism, models are naturally relative, incomplete, and partly subjective [33]. Electricity transitions are characterised by dynamic complexities such as non-linearities among variables of the system, time delays, inter-temporal interactions, and side-effects between system variables. Electricity transitions have been analysed employing different modelling approaches for exploratory analysis (for example, Agent-Based Modelling (ABM) in [55], SoS in [32,33], System Dynamics Modelling (SDM) in [53,54,65]). These model-based analyses apply exploratory analysis to seek robust (policy) alternatives.

According to Bolwig et al. [22], energy transitions should be analysed through an endogenous approach. They pointed out that "*A more realistic representation of energy transition(s) requires consideration of a disequilibrium energy-economy-social system with delays in perception and adjustment, endogenous technological change, feedback effects and explicit behavioural rules, rather than optimization while assuming complete information and instantaneous equilibration of factor inputs to optimal levels.*" [22]. Following an endogenous approach, we propose System Dynamics (SD) [46] as the simulation modelling approach for implementing out the exploratory modelling and analysis process. SDM allow us to integrate socio-technical factors and explicit behavioural rules via information feedback loops and delays in perception and adjustment [22]. Although alternative modelling techniques such as ABM or Discrete Event Modelling (DEM) can be applied to energy policymaking, they require a vast amount of historical or empirical data to simulate the behaviour of individual entities [22].

SD is used to formulate and test structural policies. It is performed by modelling and simulating complex systems and analysing their resulting non-linear behaviour over time [44]. The focus of SD is on the use of simulation models to explore the relationship between a specific system structure and the dynamic behaviour of the system, based on established assumptions [43]. By formulating a dynamic hypothesis, the behaviour of the system can be explained [46]. By changing the system structure (e.g. alternative energy policy mixes), the resulting system behaviour may change over time (e.g. electricity transition pathways).

Koul et al. [64] pointed out that SD methodology had not been able to cope with deep uncertainties in energy systems. However, Kwakkel and Pruyt [43] proposed EMA as a complementary approach to SD to address this limitation by focusing on how policy analysis should be carried out despite multiple plausible models. When available policy-relevant information is not sufficient to choose a single model to explain the system behaviour, multiple (interrelated) models can be analysed using an exploratory approach. Thus, systems can be analysed considering diverse hypotheses around the structure of the system, parameter values, relationships among variables, external factors that affect the system behaviour, and diverse outcomes of interest (i.e. different models created based on different perceptions). By simulating one set of hypotheses, one computational experiment is obtained. The assumption is that if various hypotheses (or assumptions) about the system are correct, one computational experiment represents how the system would behave according to those various hypotheses encapsulated in one single model [43].

3.3.2. Robustness analysis

Using computer simulations, the performance of policy alternatives is systematically explored across the range of uncertainties identified. Then, these alternatives are assessed according to the requirements of robustness set up during the problem definition process. Based on the performance criteria established by policymakers to 'accept' a policy alternative as satisfactory from the robustness aspect, policy alternatives can be ranked. Herman et al. [61] defined robustness as "… *the fraction of sampled states of the world in which a solution satisfies all performance requirements.*". Based on this definition, energy policy

alternatives can be ranked between 0 and 100%. When a policy alternative is ranked with 0%, the alternative fails to meet the objectives thresholds in all plausible futures. On the other hand, a rank of 100% is assigned when a policy alternative satisfies the established performance criteria in all plausible futures. When several objectives thresholds are specified to accept a policy alternative, the analysis can be carried out focusing on each objective; allowing to underline those alternatives which could be of interest for policymakers for further analysis. If a policy alternative is considered robust based on the information analysed using the method presented, policymakers could justify the implementation of a policy instrument mix. If the potential policy alternatives are not robust enough, they can be redesigned aiming at increasing their robustness. A vulnerability analysis is proposed to identify the conditions in which policy alternatives perform poorly (i.e. vulnerabilities), and then propose new or modified policy alternatives to overcome these vulnerabilities.

3.3.3. Vulnerability analysis

In order to explore under what conditions an energy policy would perform well or would fail, an open exploration using EMA can be carried out. The exploration is to be done by generating a set of computational experiments that cover the complete uncertainty space [43]. Then, a large number of scenarios (plausible futures) can be analysed considering an extensive selection of uncertainties by using data-mining techniques. To identify key uncertainties that lead cases where policy alternatives fail in future conditions, scenario discovery [66,67] uses data-mining and statistical methods to generate computational experiments. The analysis of model simulation results is used for explaining specific future behaviours based on a range of uncertainties. This approach assesses the quality of these ranges based on two metrics: (1) coverage, to measure if the ranges of uncertainty in input parameters completely explain the behaviour of interest (i.e. universality of ranges); and (2) density, to measure the number of cases with irrelevant behaviours within the selected range of uncertainties (i.e. purity of ranges). Then, by making an appropriate trade-off between coverage and density, the result is the best combination of uncertain inputs parameters that explain the vulnerability of policy alternatives in future conditions [45]. Once vulnerabilities of proposed policy alternatives are identified (i.e. key uncertainties influencing system behaviour), new or modified policy alternatives can be proposed to evaluate the robustness.

Scenario discovery has been applied to identify the conditions in which a renewable-dominated transition pathway is more likely to occur and to identify the long-run vulnerabilities of policy instrument mixes [34]. By performing 3000 computational experiments using the EMA Workbench [68], Moallemi et al. [54] demonstrated that solar and wind technologies could gain popular over a coal-dominated system in India if three conditions are met: (1) if the government sets ambitious targets and mobilising public funding and giving facilities to foreign investors to meet these targets, (2) if solar and wind potential available installed capacity outplays the existing estimates, and (3) if the price volatility of fossil fuels is not protected by government subsidies. Another example regarding the use of scenario discovery to identify the conditions where a subsidy policy could fail in meeting its long-term objectives is found in [69]. Eker and van Daalen [69] studied subsidies as a candidate policy to achieve the minimisation of emissions and costs while maximising the biomethane production in the Netherlands. They found that the uncertain behaviour of producers' investment is the main uncertainty associated with the vulnerability of the subsidy policy investigated.

3.3.4. Trade-off analysis

By applying EMA for analysing clean energy transitions, a large set of computational experiments is generated, holding a vast amount of information regarding plausible transition pathways. Communication (visualisation, presentation) of policy-relevant information to policymakers is critical for successful implementation of policy alternatives in the system of interest [44]. Thus, visualisation techniques are required to aid policymakers with understanding insights obtained through computational experiments within the analytical method proposed. Diverse visual analytic techniques have been analysed to communicate these insights [33,39]. We propose to use Pareto sets of policy alternatives to compare them and to provide a clear understanding of trade-offs and possible consequences of each alternative [3]. However, depending on decision-makers' requirements and limitations, different techniques can be applied to explore trade-offs among policy alternatives.

3.4. Policy recommendations

By carrying out the proposed integrated analytical method, the aim is to analyse policy-relevant information and to create consensus about the selection of robust policy alternatives rather than specifying a single best policy mix. The selection, implementation, monitoring, and post-evaluation of policy alternatives is beyond the scope of this method. Policymaking in wicked conditions may be conceptualised as a learning process. When the policy problem definition, the development of policy alternatives, and the expected outcomes emerge from a collaborative process among stakeholders, policymakers, and analysts, an iterative approach is needed. Thus, learning may be facilitated by this iterative scheme revealing stakeholders' preferences and possible trade-offs among alternative problem definitions and solutions [3]. The method presented can aid in discovering robust policy alternatives based on stakeholders' priorities and preferences, making the possible trade-offs more evident and transparent within the policy-making process.

4. Discussion

The method developed and presented integrates quantitative and qualitative approaches to better understand the dynamics of historical electricity transitions and to explore the impact of energy-related policy instruments in future clean energy transitions. By integrating diverse analytical tools used for model-based policy analysis, it can bring several benefits for energy policymaking under deep uncertainty.

First: by understanding historical electricity transitions and the current state of electricity systems, the exploration of how different policy alternatives can influence clean energy transitions would be clearer to policymakers. That is, by using concepts of the policy mixes research and a multi-perspective analytical framework (via techno-economic, socio-technical, and political analyses) the dynamics of historical electricity transitions can be explained; highlighting the role of policy mixes as a major focus of analysis [30]. Then, to systematically define the boundaries of the policy system (objectives, policy alternatives, internal components, external factors, etc.), we proposed a new analytical framework for model-based policy analysis. This framework, explained in Section 3.1, differs from earlier frameworks in making explicit the context of the policy system, the objectives values, and the decision rules (i.e. robustness) to choose robust policy alternatives. By integrating these two analytic frameworks a more comprehensive policy problem definition is sought.

Second: energy-related policy decisions for clean energy transitions occur under deep uncertainty conditions. To make an explicit effort to characterise deep uncertain factors, a deep uncertainty characterisation matrix was proposed. This matrix serves as an analytic tool to develop different model structures (according to different perceptions about the system), which can be analysed using an exploratory thinking approach, and thus, to obtain information about the influence of energy policy mixes on clean energy transitions. To deal with deep uncertainty, a robustness-based approach is adopted in the method presented. Though several robustness requirements have been proposed a priori with different impacts on policy decisions, we argue that the decision rules (i.e. robustness) should be clear based on decision-makers' preferences and their pessimistic/optimistic attitude about uncertain

future conditions.

Third: once the elements of the model(s) have been defined and deep uncertainties are characterised, we proposed System Dynamics (SD) as an approach to develop the clean energy transition model(s). Although different quantitative modelling techniques have been applied for understanding energy transitions, system dynamics outstands from others due to its endogenous approach (i.e. focused on the system structure as the responsible of its dynamic behaviour). Following the notions of scenario discovery, multiple analyses are carried out within the exploratory process: (1) robustness analysis, (2) vulnerability analysis, and (3) trade-off analysis. These complementary analyses seek to obtain policy-relevant information regarding under what conditions a plausible future can take place and what combinations of uncertainties could trigger undesirable outcomes; to assess the robustness of policy alternatives under key deep uncertainty conditions; and identify possible trade-offs among alternatives.

A coordinated policy mix should combine technology-push and demand-pull policy instruments to address policy objectives such as GHG mitigation. By implementing this integrated method, policy recommendations can be structured to support policymakers in the development of more robust energy-related policy mixes towards clean energy transitions. However, following the stepwise interdependent analyses proposed in this paper, the method may be applied to other societal transitions such as transportation and water management.

The method proposed has some limitations. Based on the selection of relevant energy transitions concepts (from sustainable transitions literature and policy mixes for energy transitions research) to explain the dynamics of historical energy transitions, the perception of future electricity transitions could be different and, thus, influence the definition of the policy problem. Future research can be made by using additional complementary concepts to generate alternative narratives about electricity transitions. Model-based decision support under conditions of deep uncertainty is challenging due to the complexity in model validation. To increase the reliability of policy recommendations, we highly recommend involving stakeholders and policymakers in all phases of the process. The analytical tools presented in this paper are suggested in a conceptual basis to operationalise an exploratory thinking approach for policy analysis. The lack of empirical validation about the integration of these tools is perceived as a key limitation. Future research can be oriented towards applying the integrated method to case studies to verify its applicability. Some other limitations may exist during the application of the method to empirical case studies. Thus, depending on the types of policy problem, stakeholders, available information, and resources limitations complementary analytical tools and energy transitions concepts can be employed to address diverse energy policy issues.

5. Conclusions

Understanding how energy-related policy alternatives have affected electricity transitions and how they can influence future transitions aids policymakers in developing more robust policy alternatives. An integrated method for supporting policymakers with the design of robust energy-related policy alternatives towards clean energy transitions has been developed and presented. The method integrates quantitative and qualitative approaches to better understand the dynamics of historical energy transitions and explore the impact of energy-related policy mixes in future transitions. Policy-relevant information about clean energy transitions can be analysed by carrying out the interdependent analytical processes presented in Section 3.

The proposed method was formulated by combining the strengths of various analytical tools found in sustainability transitions literature [30], policy mixes for energy transitions [5,6], robustness-based frameworks [10,39], dynamic modelling techniques [46], and exploratory thinking [33,44,47]. First, by integrating a multi-perspective analytic framework [30], concepts from policy mixes for energy transitions literature [5,6], and a new analytical framework for policy analysis, a more comprehensive policy problem definition was sought. Based on the main economic, technological, social, and political drivers for historical energy transitions, the boundaries of the policy system can be defined aiming at analysing the possible consequences of implementing different policy instruments. Second, to make an explicit effort to characterise deep uncertain factors, a deep uncertainty characterisation matrix was proposed. This matrix serves as an analytic tool to systematically elicit information about what set of elements should be included in the model, based on different perspectives about the system (e.g. when there are different parties deciding). Thus, different model structures can be formulated (structural uncertainty) with diverse parameter values to be analysed (parametric uncertainty). By characterising deep uncertainty factors, diverse models and parameters can be analysed using an exploratory thinking approach to obtain information about clean energy transitions for policy analysis. Third, we propose System Dynamics (SD) [46] as the simulation modelling approach to build a clean energy transition model(s). That is due to its focus on the system structure as the responsible of its dynamic behaviour (endogenous). Models created serve as scenario generators for exploratory analysis to obtain policy-relevant information upon: (1) under what conditions a plausible future can take place and what combinations of uncertainties could trigger undesirable outcomes, (2) the estimation of the robustness of policy alternatives under key deep uncertainty conditions, and (3) possible trade-offs among policy alternatives.

Declaration of Competing Interest

None.

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Appendix C Publications related to Chapter 3

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A. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Full title	Competition, coordination, or institutional change? A multi-perspective analysis of historical electricity transitions in Mexico		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate researcher's contribution (%)	75		
Status	☒ Published ☐ Accepted and In-press ☐ In progress		
Journal or book name	Energy Research & Social Science		
Volume/page numbers (if published)	84/102362	Date accepted/ published (if relevant)	Available online 12 November 2021

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Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Felix Kin Peng Hui		18 March 2022

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Original research article

Competition, coordination, or institutional change? A multi-perspective analysis of historical electricity transitions in Mexico

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ABSTRACT

The electricity sector is a complex dynamic system that has experienced continuous changes since its beginning. The aim of this article is to explore the evolution of historical electricity transitions in Mexico from 1879 to 2012 under the interactive governance approach. Governability provides an analytical framework for investigating the role of actors, technologies, and policies in national energy transitions. By integrating a multi-perspective analytical framework, we applied concepts from energy transitions and policy mixes for sustainability transitions to qualitatively describe social, economic, and technological changes and their relative role in historical transitions. The case study revealed that governability of national energy transitions may vary considerably from one episode to another depending on how governance systems have handled national societal needs and international cooperation agreements. Additionally, different drivers have been identified in shaping electricity transitions in Mexico. First, governance decisions have depended on specific (policy) paradigms that relevant actors have adopted. Second, the article highlights the key role that available (indigenous) energy resources have played in directing the path and pace of electricity production technologies. Third, increasing environmental and climate change concerns have improved the way electricity is produced and used. The analysis conducted

Abbreviations: CFE, Federal Electricity Commission (Comisión Federal de Electricidad); CIDE, Centre for Economic Research and Teaching (Centro de Investigación y Docencia Económicas); CLyF, Mexican Light and Power Company (Compañía de Luz y Fuerza); CNEN, National Nuclear Energy Commission (Comisión Nacional de Energía Nuclear); CNFM, National Power Commission (Comisión Nacional de Fuerza Motriz); CNSNS, National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias); CO_2-e, carbon dioxide equivalent; CONACYT, National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología); CONAE, National Energy Saving Commission (Comisión Nacional para el Ahorro de Energía); CONUEE, National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía); CPP, cogeneration power producer; CRE, Energy Regulatory Commission (Comisión Reguladora de Energía); CSS, continuous self-supply; CUF, Committee for the Unification of Frequencies (Comité de Unificación de Frecuencia); FH, Hydrocarbons Fund (Fondo de Hidrocarburos); FIDE, Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica); FSE, Energy Sustainability Fund (Fondo de Sustentabilidad Energética); GDP, gross domestic product; GHG, greenhouse gas; GI, governing interactions; GS, governance system; IER, Institute of Renewable Energy (Instituto de Energías Renovables); IIE, Electricity Research Institute (Instituto de Investigaciones Eléctricas); IINGEN, Institute of Engineering (Instituto de Ingeniería); INECC, National Institute of Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático); INEEL, National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias); ININ, National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares); IPP, independent power producer; kW, kilowatts; LAERFTE, Use of Renewable Energy and the Financing of the Energy Transition Law (Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética); LASE, Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía); LGCC, General Climate Change Law (Ley General sobre Cambio Climático); LGEEPA, General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente); LUCF, land use change and forestry; MW, megawatts; NAFTA, North American Free Trade Agreement; NGCC, natural gas combined cycle; NGT, natural gas turbine; NO_x, oxides of nitrogen; OECD, Organisation for Economic Co-operation and Development; PAESE, Energy Saving Program for the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico); PE, power exports; PEMEX, Mexican Petroleum (Petróleos Mexicanos); PI, power imports; PPA, power purchase agreement; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; PSS, power self-supply; PV, photovoltaic; R&D, research and development; RD&D, Research, development, and demonstration; SE, Secretariat of Economy (Secretaría de Economía); SEMIP, Secretariat of Energy, Mining and Parastatic Industry (Secretaría de Energía, Minas e Industria Paraestatal); SEN, National Electricity System (Sistema Eléctrico Nacional); SENER, Secretariat of Energy (Secretaría de Energía); SG, system-to-be-governed; SME, Mexican Electricity Labour Union (Sindicato Mexicano de Electricistas); SO_x, oxides of sulphur; SPP, small power producer; UAM, Metropolitan Autonomous University (Universidad Autónoma Metropolitana); UK, United Kingdom; UNAM, National Autonomous University of Mexico (Universidad Nacional Autónoma de México); UNFCCC, United Nations Framework Convention on Climate Change; US, United States.

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suggests that energy transitions governability may be improved by fostering communication and cooperation among actors and institutions to define policy mixes in line with societal needs.

1. Introduction

Electricity is vital for supporting economic development. The electricity sector has been experiencing deep-structural changes worldwide since the 19th century. These changes in electricity system configurations are the result of complex, dynamic interactions between multiple actors (e.g. policymakers, generation companies, consumers) and societal systems (including infrastructure, markets, policies). Electricity transitions have been conceptualised as multi-actor, long-term dynamic processes of structural change in the way electricity is produced and consumed [1]. These processes are the result of the interactions between a set of interconnected transformations at different sublevels and scales that take place over long periods of time. Although there is no universal agreement on how large these changes would establish a transition, relationships between the scale, the depth, the speed, and the complexity of change have been discussed to gain better understanding on energy transitions [2–5].

Electricity generation and consumption has contributed considerably to greenhouse gas (GHG) emissions and thus to anthropogenic climate change, especially in developing countries. Transitions towards low-carbon economies require the understanding of past structural transformations within electricity systems and the role that governance systems have played in those transitions. Interactive governance theory and governability provide a conceptual basis for exploring changes in governance of dynamic societal systems, such as electricity transitions [6]. Mexico is an appealing case study due to its fossil fuel-intensive energy mix which has positioned the country as the 11th largest GHG emitter worldwide [7,8]. To comply with international agreements on climate change mitigation, Mexico has set ambitious targets on GHG emission reductions with the electricity sector to be the largest contributor of these reductions [9]. However, the (ever-growing) electricity demand in Mexico may exhibit significant challenges for future transitions if previous structural system transformations and their drivers are not fully understood. To improve the in-depth understanding of historical structural changes in the electricity system in Mexico, this work focuses on answering the following research questions: how governing structures in the electricity sector have evolved over time? What role have these governing structures played in shaping electricity transitions? What have been the main drivers for structural change within the Mexican electricity system?

The aim of this article is to explore the governability of historical electricity transitions in Mexico from 1879 to 2012. By integrating energy transitions concepts with interactive governance theory, we seek a more comprehensive qualitative explanation of historical national energy transitions in developing countries. This work builds on previous energy transitions literature by integrating the interactive governance approach as an analytical framework for describing the co-evolution of techno-socio-economic systems. Simultaneously, a national energy system is conceptualised by using complementary perspectives (i.e. socio-political, techno-economic, and socio-technical) to explore governing interactions over time. This adds to interactive governance literature by integrating a multi-perspective framework for conceptualising the system-to-be-governed and expanding its application to electricity transitions. Also, concepts from energy transitions, policy mixes for sustainability transitions, and interactive governance theory are integrated and applied (i.e. theoretical synthesis [10]) to describe historical electricity transitions in Mexico, expanding their relative application to developing countries (i.e. empirical contribution).

The rest of this article is organised as follows. Section 2 sets the theoretical framework for analysing energy transitions governability. An empirical application of the framework to Mexican historical electricity transitions from 1879 to 2012 is presented in Section 3. Findings of the analysis, limitations, and potential future research are discussed in Section 4. Conclusions are exhibited in Section 5.

2. Energy transitions governability for techno-socio-economic systems

2.1. Interactive governance and energy transitions governability

The concept of governance has been defined and applied in different ways by different social science (sub)disciplines (e.g. political science, economics, public administration) [11]. The main difference is on the perceived role of the state as a governance agency, following a normative or an analytical approach. Traditionally the idea of governance has been related to governments and their functions within society (e.g. acting as governor). However, it has been recognised within the governance theory that governance is beyond government and that societies are formed by a large number of governing actors (i.e. social units), who are constrained or enabled by social frameworks (including culture, law, politics, economics, material and technical possibilities) [6,12]. Thus (interactive) governance refers to the collective governing activities carried out by societal actors (including non-state institutions) in response to public needs and visions [6]. Kooiman [12] defines interactive governance (also called social-political governance [11]) as "the whole of interactions taken to solve societal problems and to create societal opportunities, including the formulation and application of principles guiding those interactions and care for institutions that enable them.".

The interactive perspective of governance suggests that societal needs and public goals are not given but negotiated, and are not stable but dynamically crafted relatively to the agency of participants engaged in socio-political processes [12]. These (complex) processes occur within societal (sub)systems. A societal system (or subsystem) is broadly understood as the interrelations between a number of entities belonging to the social and natural world [6]. The interactive governance perspective suggests that societal systems are made up of three interrelated components: a system-to-be-governed (SG), a governance system (GS), and the governing interactions (GI) between these two [6]. The system-to-be-governed can be conceptualised in different ways and at different scale levels [12]. This is, the questions on what the relevant elements of a system are, how to define its boundaries, and how it may be broken down analytically depend on the observers' paradigms and on the nature of the research enquiry [13]. A governing system encompasses the total set of processes and mechanisms that are available for guidance, control, and steerage of the SG to be analysed. Governing interactions refers to mutually influencing relationships among two or more actors or entities in a governance setting [12,13]. Under systems theory, societal systems are partially open systems that must take action in response to environmental changes [14]. Thus, external factors may influence governing interactions, since these three interrelated systems interact with the external environment as well [15].

Based on the interactive governance perspective, governability has been defined as: "the overall quality for governance of any societal entity or system consisting of SG, GS and GI." [6]. Governability depends on the ability of a governance system to perform on the challenges (and opportunities) than the SG raises in the presence of governing interactions [12]. Thus governability is conceptualised as a property of the system of interest built upon a holistic approach (i.e. the system is a whole formed of interrelated and interdependent parts, interacting to maintain that whole) [14]. The interactive governance theory states the recognition of diversity, complexity, dynamics, and scale of the system

to define the boundaries of analysis [13]. Diversity refers to qualities of actors and entities within the system. Complexity denotes the examination of societal structures, the relationships among the system as a whole and their parts, as well as the interactions between the system and its environment. Dynamics points out at the non-linear feature of societal change, creating the possibility of change over time. Scale refers to the spatial, temporal, quantitative or analytical dimension of the analysis [11,13].

Energy systems become more complex and dynamic as more actors and institutions are involved in governance processes for (energy) transitions to low-carbon economies. Energy transitions have been conceptualised as co-evolutionary, multi-actor, long-term dynamic processes of structural change in the way energy is produced and used [1]. It has been recognised that energy transitions may be better analysed and explained by using several complementary theories, as opposite of using a single theory of transitions [2]. How to conceptualise the system-to-be-governed has been identified as one caveat in interactive governance and governability literature [16]. Thus, we proposed the integration of a *meta*-theoretical framework [1,2] to conceptualise and describe national energy transitions as a set of three co-evolving systems: energy flows and markets, energy technologies, and energy-related policies (i.e. techno-socio-economic systems). In this article we use the interactive governance perspective which focuses on the interactions between the state, private actors, and civil society aimed at solving societal needs (or creating societal opportunities) in the electricity sector over time (see Fig. 1) [11,13]. Thus, we introduce the term 'energy transitions governability' to analyse governance processes of historical national energy transitions. Although interactive governance and governability have been used to analyse and assess energy systems (see for instance [15,17–19]), the term was not yet found in the literature.

2.2. Multi-perspective energy transitions analysis

Energy transitions have been analysed using diverse transitions theories with different roots (e.g. social studies, political science, economics) (see for instance [2,20]). Cherp et al. [2] suggested that long-term changes in energy systems occur within three main co-evolving subsystems: (1) techno-economic subsystem, explained by energy flows related to energy supply and demand coordinated through energy markets; (2) socio-technical subsystem, defined by energy technologies; and (3) socio-political subsystem, influencing energy systems by developing and implementing energy-related policy instruments [1,2]. Within this framework, different sustainability transitions concepts are used to describe energy transitions (see for instance [21]). Complementarily, Castrejon-Campos et al. [1] proposed the integration of concepts from the policy mixes for sustainability transitions literature to explain the impact of policy instruments on historical energy transitions. The main reason for using diverse energy and sustainability transitions concepts is due to changes in the system may take place as a result of different contextual and structural driving forces (or barriers) from one episode to another [1].

Concepts from the three perspectives (i.e. socio-political, socio-technical, and techno-economic) are considered in this work to gain understanding on historical electricity transitions, and what possible factors may shape the future changes towards clean energy transitions. Fig. 2 depicts the main energy transitions concepts to be included within the analytical framework for analysing the governability of national energy transitions. A detailed description of each concept may be found in [2,22–25]. Different (complementary) concepts based on the same disciplinary roots may be found in [1,2,21].

The main analytical method used to describe the governability of historical electricity transitions in Mexico was the systematic literature review and analysis of quantitative data with a theoretical heuristic approach. The flow of information through the different steps of the systematic review followed is depicted in Fig. 3 (based on the four-step flow diagram within the PRISMA statement [26]). A detailed description of the research method is presented in Appendix A and the limitations are discussed in Section 4. The documents reviewed include books, reports, datasets, scholarly articles, analyses, laws, and regulation frameworks published in academia, international organisations (e.g. International Energy Agency), and national government bodies (e.g. Mexican Secretariat of Energy, Federal Electricity Commission). The systematic review generates qualitative storylines (i.e. stylised facts) for a better interpretation of data to readers [27].

3. Historical electricity transitions in Mexico

3.1. The beginning of the electricity industry and control of private monopolies (1879–1936)

The first use of electricity in Mexico dated from 1879 when electricity was first used in a textile factory in the city of León, Guanajuato. From 1880 electricity was mainly used for public lighting in Mexico City and a few years later in other main capital cities (e.g. Guadalajara in 1884, Monterrey in 1888, and Veracruz and Mérida in 1889). The use of

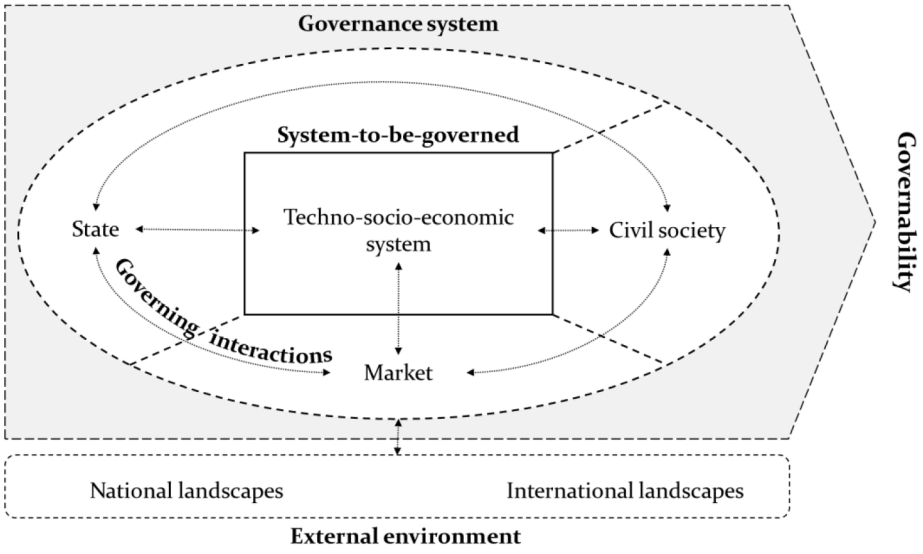


Fig. 1. Interactive governance perspective for governability of societal systems. Adapted from [6,18].

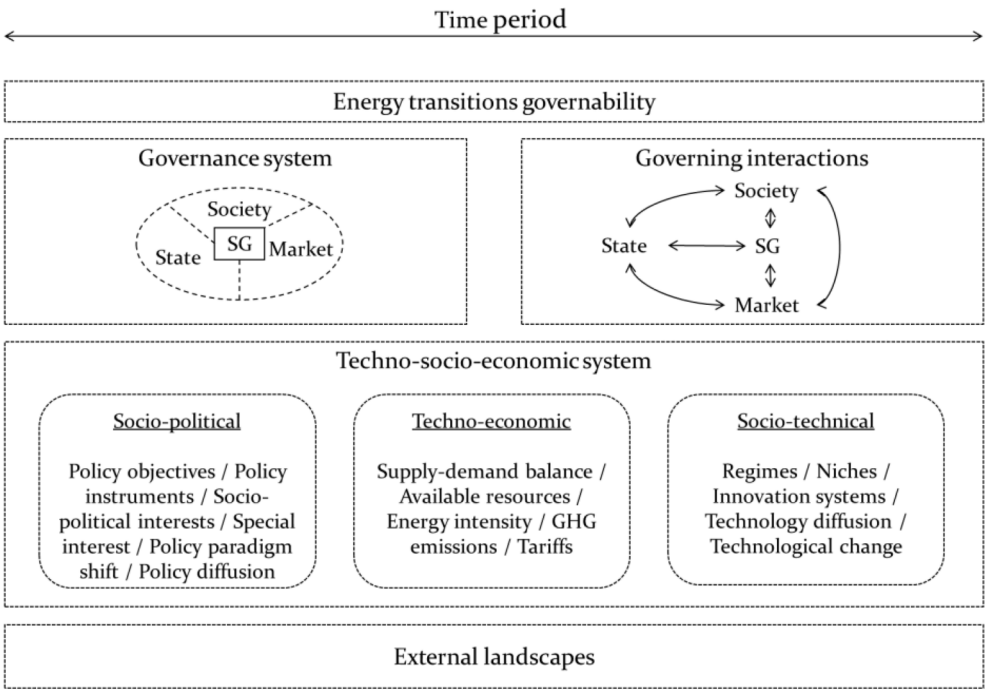


Fig. 2. Analytical framework for energy transitions governability.

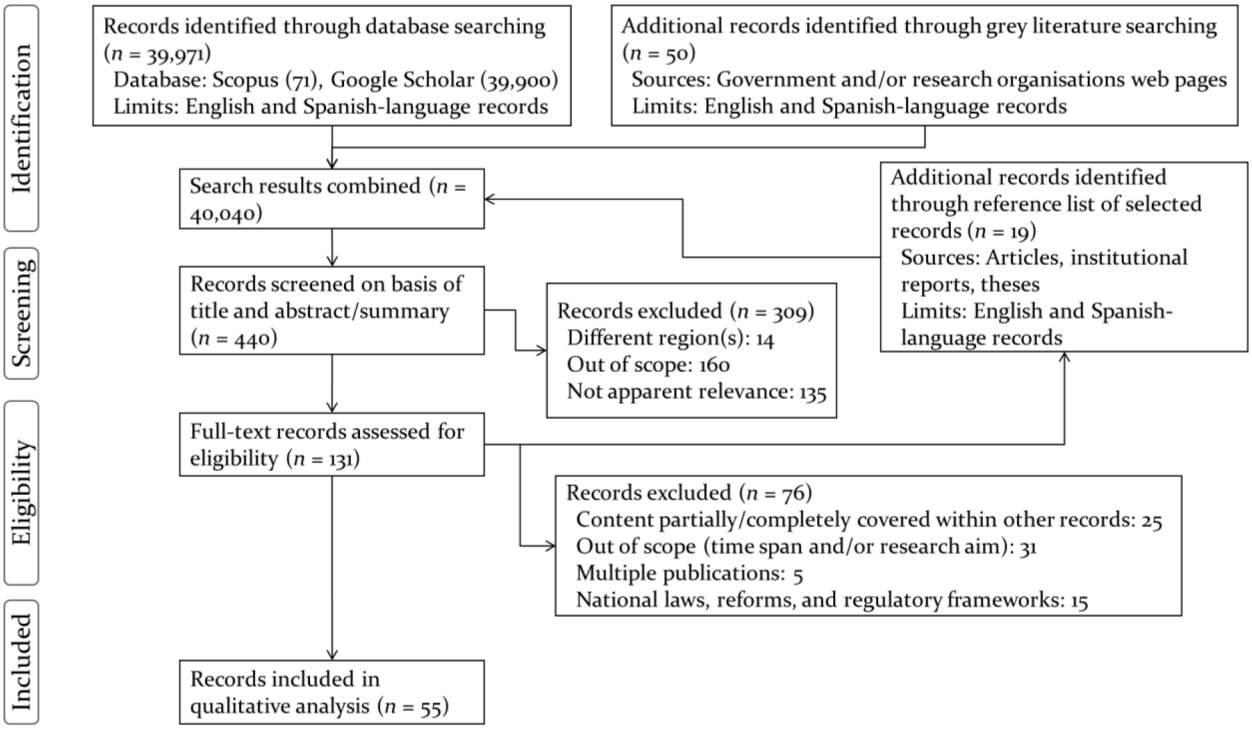


Fig. 3. Flow of information through the different phases of the systematic review. Adapted from [26].

electricity was further extended to strategic sectors such as mining, manufacturing (e.g. textile and paper factories), and transport (e.g. trams) [17,28,29].

[Actors] From 1879 to 1937 electricity was generated, transmitted, and distributed by private companies only. The period from 1890 to 1910 was characterised by the increasing electricity demand from manufacturing plants and workshops that were not able to generate their own, as well as for public services (e.g. lighting, water pumping, trams). During this period more than one hundred light and power companies were established within the country to satisfy local or regional needs. With an increasing demand and lack of state regulation a process of monopolisation took place where three private companies dominated the electricity industry until a state-owned company was created in 1937.

[Socio-political] During the beginnings of the electricity industry in Mexico, the government of Porfirio Díaz (1884–1911) adopted economic policies to attract investment and technological developments mainly from United States (US) and Europe with the aim of modernising

the country [29]. Díaz's (export-oriented) ***policy objectives*** on progress and economic growth were based on exploitation of the country's ***natural resources*** (mainly water in the case of electricity generation). However, the modernisation of the country led to wealth disparity and growing social injustice triggering the Mexican Revolution of 1910.

[External landscapes] The Mexican Revolution was a domestic ***landscape*** aimed mainly at increasing the influence of working classes [29]. The armed movement ended with the promulgation of the political constitution of Mexico in 1917 (another domestic ***landscape***). The articles relevant to the electricity sector were those related to property of land and water (article 27) and the rights of workers (article 123). Article 27 stated that all land and water within the national territory were owned by the Nation, which had the right to transfer the ownership to particulars; and that the state would regulate the exploitation of natural resources based on ***societal needs***. Article 23 established the rights of workers including the eight-hour workday, the right to strike, and the right to a rest day per week [28].

[Socio-political] - [Actors] The ***regime*** from 1879 to 1917 was characterised by neither public investment nor state regulation for the electricity industry and informal rules (***interplays*** within the interactive governance theory) in the ***governance system*** [28]. The constitution of 1917 (article 27 in particular) represented the starting point of a formal ***state intervention and regulation*** in the development of the energy sector. However, from 1917 to 1934 intervention and regulations on the electricity industry were limited [28]. State regulation formally started in 1926 with the creation of the National Power Commission (Comisión Nacional de Fuerza Motriz, CNFM) and publication of the National Electricity Code (Código Nacional Eléctrico). The code contained the technical specifications for generation and use of electricity and was later expanded to give more control to the state by allowing routine inspections to power plants, tariff regulation, and conflict resolution between producers and consumers [29]. Due to legal inconsistencies and lack of a robust regulatory framework, the code did not have the impact expected until 1934 when a constitutional reform (article 73) gave the Congress the power to (constitutionally) regulate the electricity industry and thus power generation and distribution were declared as 'public interest' activities [28].

[Techno-economic] After the revolution, the period from 1920 to 1936 was characterised by the consolidation of private monopolies, an increase in electricity tariffs, and a ***technological regime*** restructuring process [28]. Although electricity tariffs had to be approved by the state, private companies were able to establish them according to their financial structure and own (economic) interests [30]. Thus, electricity companies increased their investments without concrete government interventions. The lack of coordination within the ***governance system*** brought several tensions to the system, including complains regarding high and dissimilar tariffs throughout the territory, lack of service in areas under development, poor security of supply, and poor labour conditions (e.g. heavy workloads, low salaries, poor health conditions).

[External landscapes] The Great Depression was an international ***landscape*** that affected the national economy in general and the electricity sector in particular. Between 1930 and 1935 many small electricity companies went bankrupt due to financial constraints. Also, large consumers of electricity were economically affected, reducing revenues for power generation companies [29].

[Socio-technical] The first power equipment installed for electricity generation in Mexico was a 1.8 kW thermal plant (coal-fired) for lighting purposes. Hydroelectric power was first generated in 1889 (ten years after the first recorded use of electricity in Mexico). However, due to vast water ***resources available*** throughout the country, a technology transition from thermal to hydropower occurred during this period (see Fig. 4). During the early stages of the electricity industry in Mexico all electric equipment was imported (mainly from Europe and US) and technical specifications were set by producers, making challenging to adapt specific equipment to national needs [28]. The period from 1917 to 1936 was characterised by the construction of medium-size power plants (both hydro and thermoelectric). Necaxa, in Puebla, was the first medium-size hydro power plant (5 MW) built from 1938 to 1944. Also, piston engines were replaced by turbines in the 1920s [28], increasing efficiency and productivity.

[Socio-technical] – [Actors] Interest in innovation processes within the electricity sector dated from 1911 when a gremial organisation established support for innovation as one of their main objectives [28]. This organisation was the predecessor of the first formal electricity labour union (Sindicato Mexicano de Electricistas, SME) which was formally created in 1914. Due to poor working conditions offered by private companies, labour unions started playing an important role in electricity transitions as ***organised social movements*** creating ***socio-political interests***. Fig. 5 depicts the main governance actors in the electricity system by 1936.

3.1.1. *Multi-perspective summary (1879–1936)*

Porfirio Díaz's (national) policy objectives were oriented towards modernisation and progress in all economic sectors. Increasing demand for electricity posed pressure to the state to increase its participation in the governance system by promoting the development of the sector. Thus, the National Electricity Code was created to regulate the use of electricity generation equipment and intervene in conflict resolutions. Based on policy mix literature [34], Fig. 6 presents the main policy objectives and instruments during this period of analysis.

Electricity services started by meeting specific local or regional needs, characterised by poor supply services. Also, the lack of regulation created great variability in electricity tariffs and coverage for specific areas only. Fig. 7 presents the main outcomes of interest for analysing the electricity system performance during this period.

From the technological change point of view, the period was characterised by a transition from thermoelectric power plants to hydropower plants, construction of medium-size power plants (a few MW),

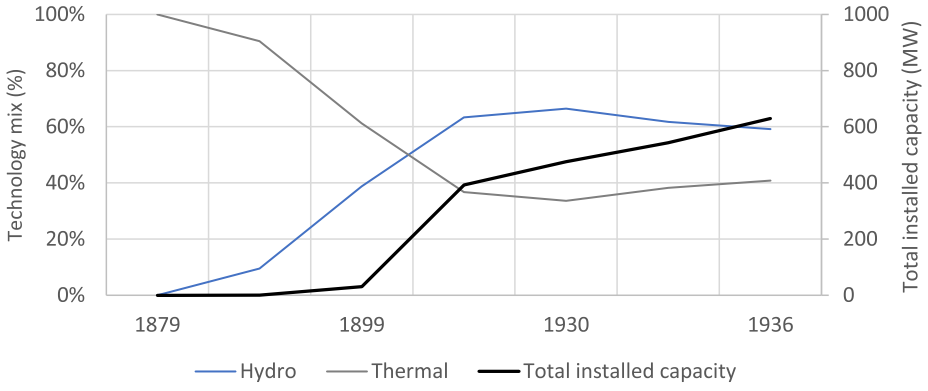


Fig. 4. Technology mix (left) and total installed capacity (right) from 1879 to 1936. Constructed with data from [28,31,32].

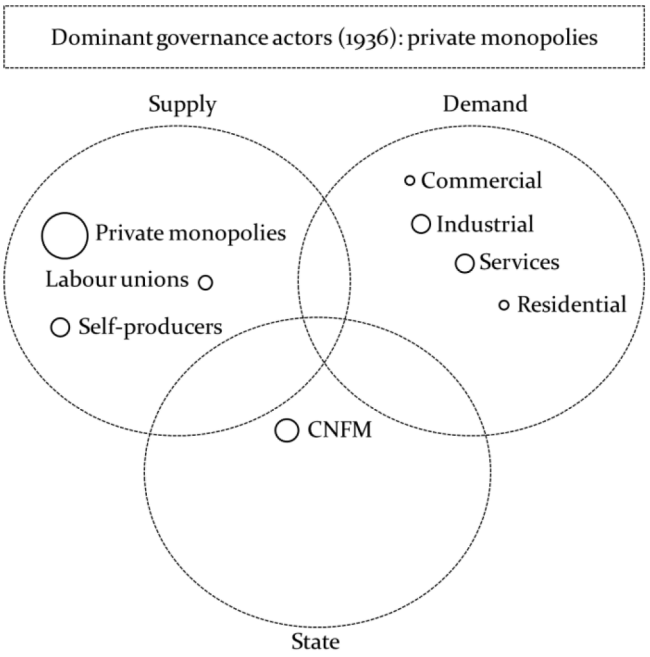


Fig. 5. Dominant governance actors by 1936. The size of the circles represents the relevance of their role within the governance system. Adapted from [29] with information from [28,33].

and a transition from piston engines to turbines (horizontal turbines in the case of hydropower). However, Mexico was completely dependent on imported equipment mainly from US, Canada, and Europe. Fig. 8 depicts the main socio-technical changes the electricity system experienced during this period.

3.1.2. *Energy transitions governability (1879–1936)*

The period from 1879 to 1936 was characterised by weak state regulation (starting with a governance system without government [35]); a process of monopolisation; a governance system controlled by the market (mainly private monopolies); a restructuring process of the regime caused by internal tensions and external landscapes; no innovation; and a local/regional development of the electricity sector. Fig. 9 and Table 1 represent the energy transitions governability snapshot for this period.

3.2. *Co-governance: private companies and the state (1937–1959)*

[Actors] Due to increasing tensions within the ***regime***, the state increased its participation within the ***governance system*** by creating in 1937 a state-owned electricity company, the Federal Electricity Commission (Comisión Federal de Electricidad, CFE), with the aim of consolidating and guiding a national electricity system including generation, transmission, and distribution at fair prices [28]. CFE started investing in small power plants mainly in the central and southern areas of Mexico. From 1940 to 1950 the ***governance system*** was dominated by the three main monopolies and CFE. Due to transmission and distribution were owned by these monopolies, the initial agreement was that CFE would provide electricity to them at reasonable prices [29]. By 1959 CFE had 38% of the total installed capacity and 49% for public service [36].

[Socio-political] The effects of the Great Depression were evident throughout the 1930's with a general decrease of exports and foreign currency shortages. To ameliorate the effects of this ***external landscape***, a process of industrialisation and an imports substitution model took place during the presidency of Lázaro Cárdenas (1934–1940). The economic development of the country required an expansion of infrastructure for electricity services towards rural areas and improving services already provided in cities under development [29]. Thus, ***policy objectives*** during this period were focused on increasing access to electricity and fostering the expansion of the sector [30]. A ***policy***

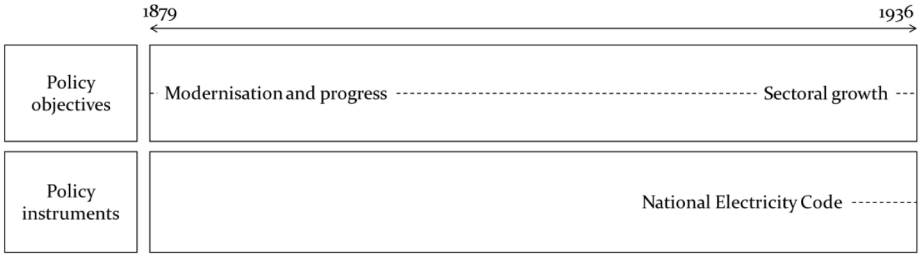


Fig. 6. Socio-political perspective snapshot (1879–1936).

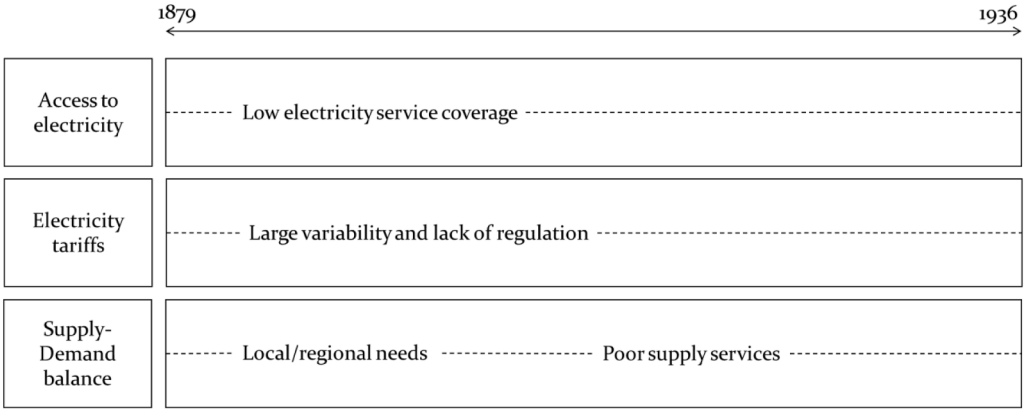


Fig. 7. Techno-economic perspective snapshot (1879–1936).

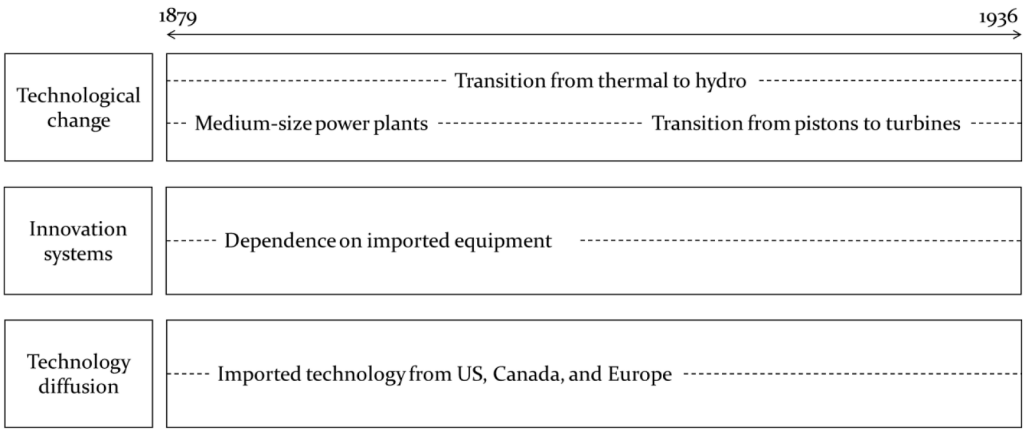


Fig. 8. Socio-technical perspective snapshot (1879–1936).

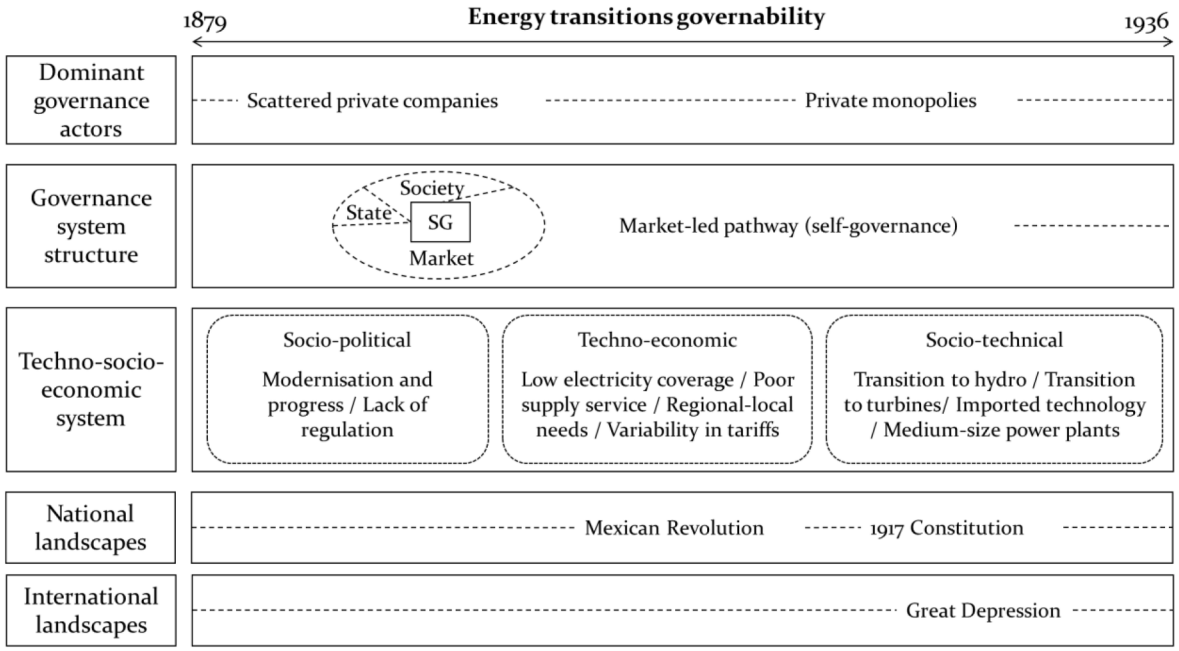


Fig. 9. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1879–1936).

Table 1
Energy transitions governability snapshot – governing interactions (1879–1936).

State -> Market
Pressure for service expansion to developing areas.
Participation on tariff regulation and conflict resolution.
Pressure for standardisation of generation equipment.
Pressure for access to financial records.
Pressure for better services (e.g. public lighting).
State -> Society
Promotion of economic growth and progress.
Society -> State
Pressure for tariff regulation.
Pressure for regulation on work conditions.
Pressure for access to electricity in developing areas.
Society -> Market
Pressure for better services and prices.
Pressure for improving working conditions.
Market -> State
Pressure for better conditions for private investments.
Pressure for more concessions.
Market -> Society
Give access to spaces where infrastructure would take place.

instrument to reach these objectives was the first Six Year Plan (1934–1940) where electricity supply was considered as a priority for the development of the country [28]. Also, an increase of electricity imports from US occurred during this period to secure electricity supply in line with increasing demand (see Fig. 10).

[External landscapes] An important domestic ***landscape*** during this period was the conflict between the state and private oil companies which ended up with their expropriation in 1938 and the creation of a state-owned oil and gas company, Mexican Petroleum (Petróleos Mexicanos, PEMEX). As a result of this ***landscape*** strong nationalistic feelings were diffused among other economic sectors (including the electricity sector); and a need for regulation and ***state intervention*** in the electricity industry was emphasised [29].

[Socio-political] After the creation of CFE, the Electricity Industry Law proposed by the Cárdenas's mandate was approved in 1939, considered as the most complex normative framework for the electricity industry at the time [28]. The law encompassed regulations on electricity generation, transformation, transmission, distribution, importation, exportation, trade, use, and consumption aiming at speeding the development of the electricity industry with a social focus. Due to the complexity of this ***policy instrument***, from 1941 to 1944 legislation and

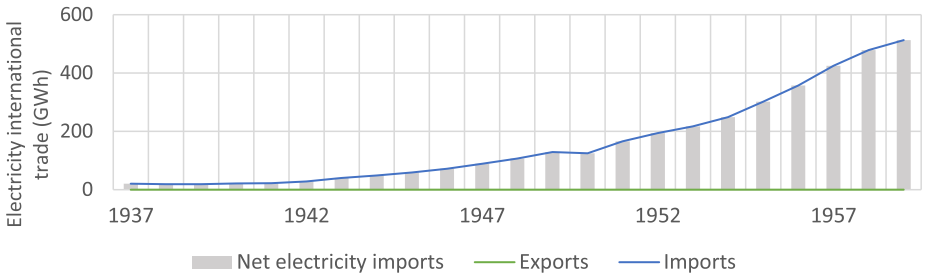


Fig. 10. Electricity imports, exports, and net imports from 1937 to 1959. Constructed with data from [37].

regulation adjustments were done to the law and its regulations. This highlights the dynamic aspect of ***policy instruments*** which adapt according to internal and external changes.

[Techno-economic] Regulations on concessions, tariffs, and profits included in the law were of paramount interest for private companies. According to the law, electricity tariffs were determined by the Secretariat of Economy (Secretaría de Economía, SE) and concessions were given to projects with the most efficient uses of natural resources and the major social impacts. These changes carried profit reductions for private companies and thus low investment in new capacity [29]. As a result, installed capacity did not increase at the same pace as the national economy. From 1940 to 1945 total installed capacity increased less than 6% (from 680 to 720 MW) [28]. This may be also attributable to the fear of private companies to be in the same situation as with the oil companies. Also, there was an increasing pressure from civil society actors (mainly large electricity users) for better services and lower prices.

[Socio-political] The period from 1940 to 1959 was characterised by the coexistence of public and private electricity companies with financial support from the state to both parts. The main role of CFE during this period was to close the gap arisen from what the private companies were not able to cover: electrifying rural communities and to foster national development. The Rural Electrification Program was established in 1952 and by joint efforts among the state, municipal governments and local communities, around 915 zones were provided with electricity by the end of the decade [38]. However, by 1959 less than 44% of the population had access to electricity [39].

[External landscapes] The World War II (1939–1945) was an international ***landscape*** that shaped economic and technological opportunities to the electricity industry. This is, exemptions from paying taxes when importing electrical equipment were granted to private companies if they were to provide electricity for public services (unless the equipment was produced within the country) [28]. Thus, new equipment was imported mainly from United Kingdom (UK), US, and Canada at the beginning of the period and later from Japan and Switzerland [28,33].

[Socio-technical] Since its beginnings CFE recorded a tendency to invest in hydropower plants while private companies in thermoelectrical [28]. This may be explained as private (mainly foreign) investors were interested in short-term financial benefits by satisfying immediate needs with thermal power plants, while the state was interested more in long-term social benefits by investing in hydropower plants (higher upfront capital cost and longer construction times but relatively lower operational costs). Thus, total installed capacity from thermoelectric took over hydropower during this period. Fig. 11 shows installed capacity for public service from 1937 to 1959.

Some other relevant technological changes took place during this period. The first can be attributed to the size of power plants. For instance, the Miguel Aleman hydropower system (built from 1938 to 1944), in Ixtapantongo, was the first large-size power plant (28 MW) shifting from horizontal to vertical axis turbines. The second important technological change was on electrical equipment: technical characteristics and efficiencies were improved over time (e.g. larger capacities and higher pressure of steam boilers). Third, a ***technological learning*** process based on ***learning-by-doing*** [40] and ***learning-by-using*** [41] was performed during this period. Fourth, in 1959 the CFE installed the first geothermal (pilot) power plant in Mexico with 3 MW of capacity, aiming at exploring new ***technological niches*** by taking advantage of the geothermal potential of the country.

[Actors] Other relevant actors who increased their participation in the ***governance system*** were labour unions. At the beginning they were independent social organisations; however, from the 1940's their involvement with the state increased, creating ***socio-political interests***. Fig. 12 depicts the dominant governance actors by 1959.

3.2.1. *Multi-perspective summary (1937–1959)*

State's policy objectives, in line with industrialisation and development, were directed towards meeting increasing electricity demand and expanding services to rural areas. The state increased its authority by creating a public electricity company and implementing different policy instruments to fulfil societal needs. Fig. 13 presents the policy mix changes during this period.

State regulations brought profit reductions and low investment in new capacity, limiting the expansion of the system, and creating

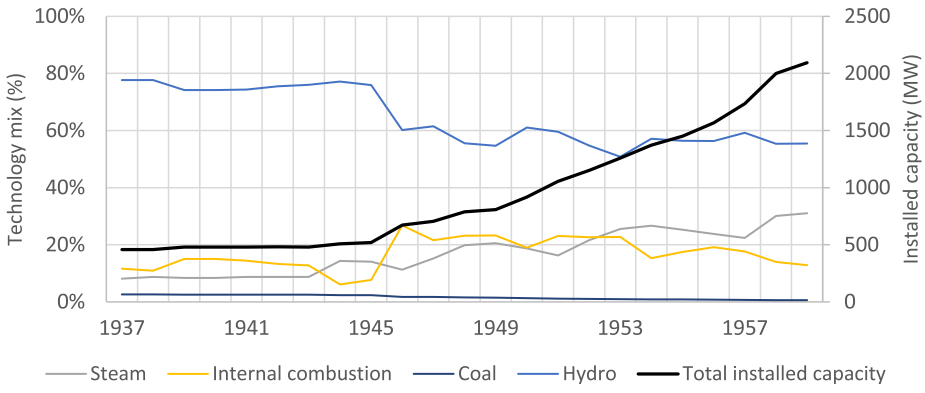


Fig. 11. Technology mix (left) and installed capacity for public service (right) from 1937 to 1959. Constructed with data from [37].

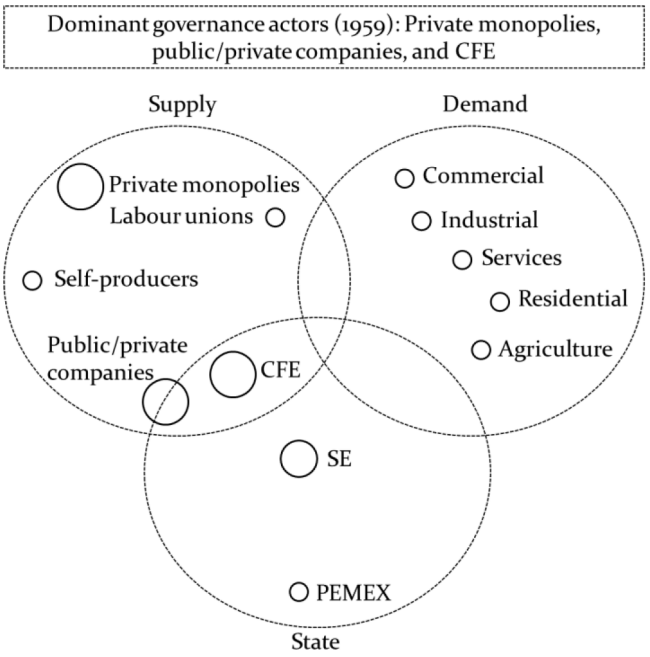


Fig. 12. Dominant governance actors by 1959. The size of the circles represents the relevance of their role within the governance system. Adapted from [29] with information from [28].

tensions in the governance system (e.g. increasing electricity tariffs). In order to meet the increasing demand, the state opted for increasing electricity imports. Fig. 14 presents the main outcomes of interest for this period.

In terms of technological change, the period was characterised by a transition from hydropower to fossil-fuel based technologies (e.g. steam, internal combustion, coal); construction of large-size power plants (tens of MW); a transition from horizontal to vertical turbines for hydropower plants; new technological niches (i.e. geothermal); a process of technological learning; and diversification of electrical equipment suppliers. Fig. 15 depicts the main socio-technical changes for this period.

3.2.2. *Energy transitions governability (1937–1959)*

This period was characterised by the end of exclusivity from private companies to generate electricity and provide services; contested interest between the state (increase social benefits) and private companies (increase profits); increase in state regulation and intervention; a transition from a market-led (self-governance) to a co-governance system pathway; transition to fossil fuel technologies; a restructuring process of the regime caused by internal pressures and external landscapes; and expansion of the sector. Fig. 16 and Table 2 represent the energy transitions governability snapshot for the period from 1937 to 1959.

3.3. *State control of the sector (1960–1991)*

[Actors] A need for expanding electricity services, great variability among tariffs, nationalistic feelings, and a need for transmission and distribution integration were the main factors for the nationalisation of the electricity industry in 1960. This was a complex process where the

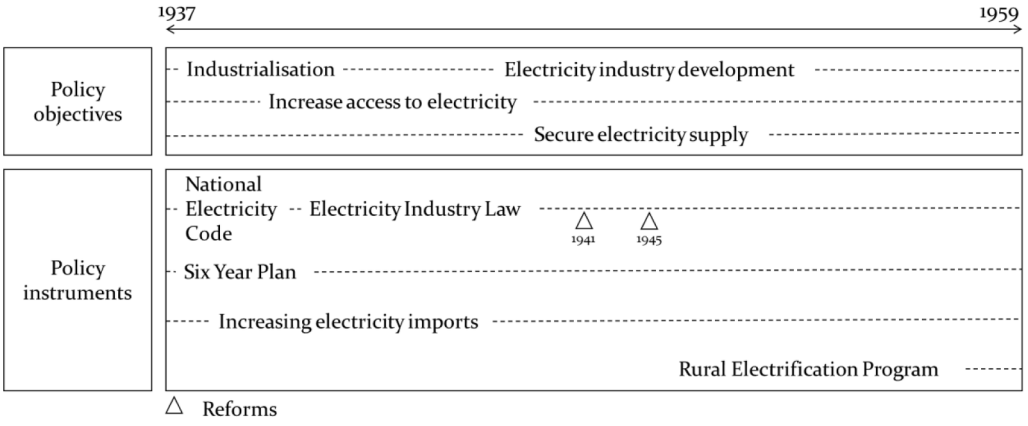


Fig. 13. Socio-political perspective snapshot (1937–1959).

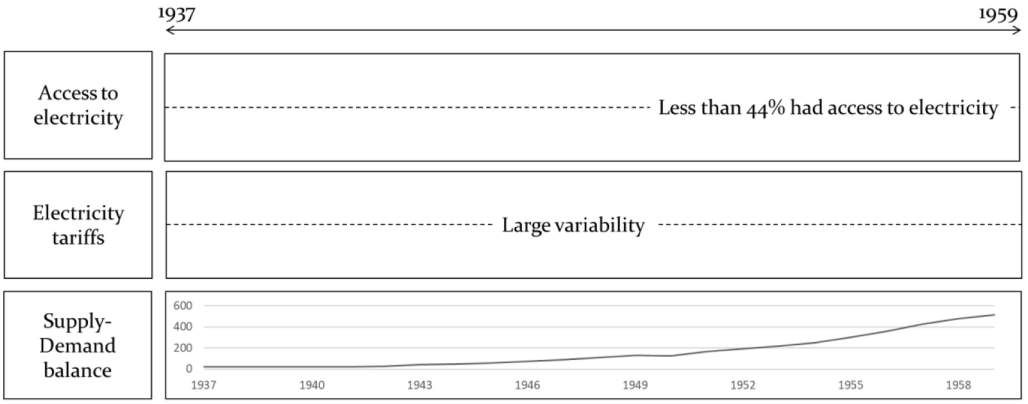


Fig. 14. Techno-economic perspective snapshot (1937–1959). Supply-Demand balance refers to the net electricity imports in GWh. Constructed with information from [28,37].

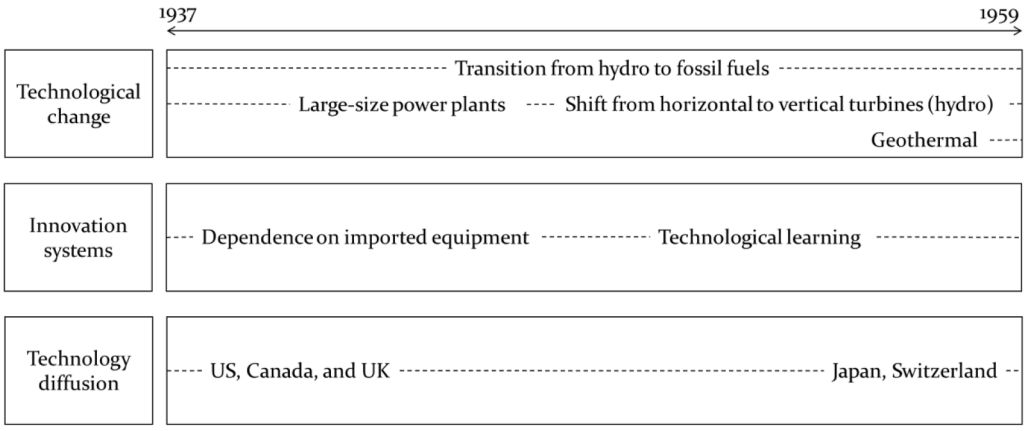


Fig. 15. Socio-technical perspective snapshot (1937–1959).

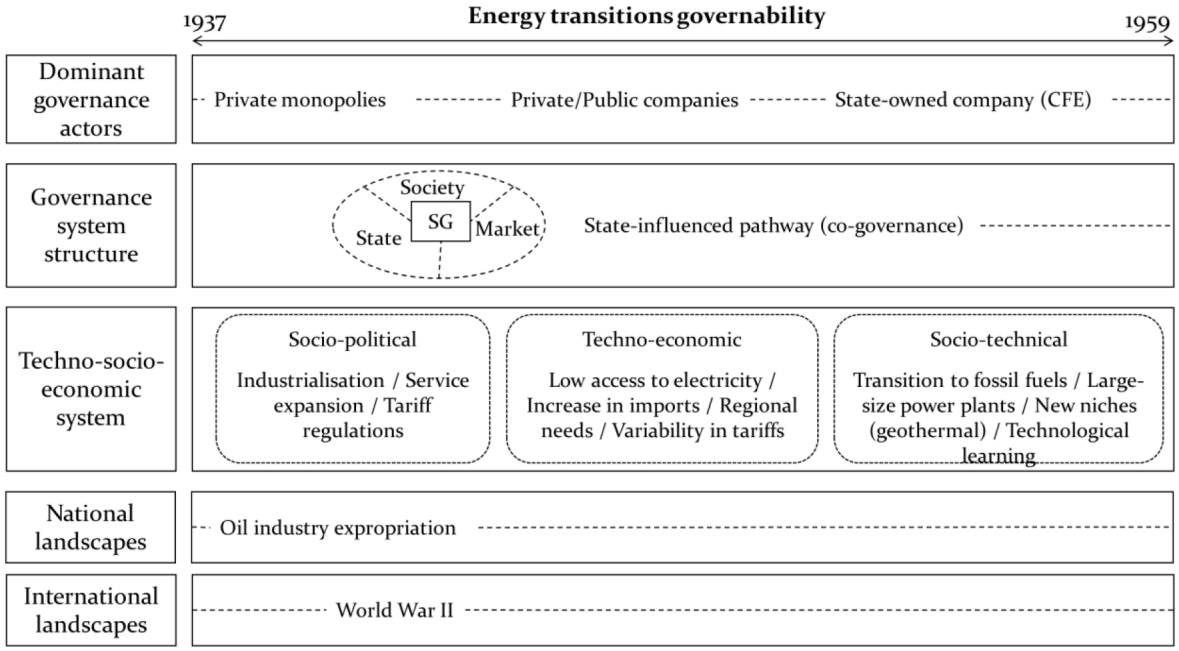


Fig. 16. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1937–1959).

Table 2
Energy transitions governability snapshot – governing interactions (1937–1959).

State -> Marke
Pressure for service expansion to rural areas.
Intervention on tariff regulation and concessions.
Intervention on conflict resolution.
Pressure for access to private financial records.
State -> Society
Promotion of industrialisation.
Promotion of social benefits.
Participation on urbanisation planning.
Society -> State
Pressure for more state control (nationalisation).
Pressure for lower prices.
Pressure for access to electricity in rural areas.
Society -> Market
Pressure for better services and prices.
Pressure for improving working conditions.
Market -> State
Pressure for better investment and profit regulations.
Market -> Society
Facilitate access to infrastructure development.

state acquired private companies by different financial means. The acquisition process lasted until 1972 when the last private company was purchased by the government [29,42]. By 1960 CFE had a 54% share from the total installed capacity in the country (2,308 MW), while the Mexican Light and Power held 25%, the American and Foreign Company 12%, and the rest of the companies 9% [33].

[Socio-political] During this period a ***policy paradigm shift*** towards nationalism and sovereignty occurred [42]. The nationalisation process formally concluded with the publication of the Public Service Electricity Law (Ley del Servicio Público de Energía Eléctrica) in 1975 which declared CFE and Compañía de Luz y Fuerza (CLyF) (before the Mexican Light and Power Company) as the only providers for public service (including generation, transmission, and distribution) [29]. In terms of private generation, the law stated that self-producers could produce their own electricity as long as CFE were not able to cover their specific needs.

The ***governance system*** had several challenges when the nationalisation took place. First, due to electricity services were offered based on local or regional demands, around 170 tariffs coexisted before 1962 and only 44% of the population had access to electricity. Second, during the 1960's the electricity systems throughout the country (not

interconnected yet) included 8 transmission voltages (from 66 to 220 kV), 29 distribution electric tensions (from 440 to 2,300 V), and 2 frequencies (50 and 60 Hz) [28]. Third, the government acquired several electricity companies with high operation costs and old equipment (some of them already above their operational lifespan). Fourth, tensions between labour unions and the government took place around the integration of these social actors within the new structure of the regime. Thus, the state addressed these technological, operational, administrative, and contractual issues by implementing different ***policy instruments*** as described below.

[Techno-economic] Following international best practices on electricity tariffs, the state led a tariff unification process from 1962 to 1964. A system of 12 tariffs were established and subsidies to agriculture, public services, and other relevant subsectors were granted by the government [36,43]. Tariffs were kept relatively constant until 1973 when they were adjusted, and subsidies for residential consumers were promoted by the state. The social focus of the ***policy paradigm*** carried with it financial constraints with increasing public debt and operational issues with low productivity levels [36]. The financial crisis of CFE and CLyF forced the state to seek new mechanisms to increase income for these energy companies. Thus, based on international prices (mainly U. S.), electricity tariffs were redefined and increased in 1990 and subsidies began to gradually be eliminated during the early 1990's. Fig. 17 depicts the electricity tariff changes from 1962 to 1991.

[Actors] Following the restructuring process of the electricity industry, labour unions were consolidated into two main unions and the state legally recognised the relevance of their role in the development of the industry. These social organisations played a key role when ***political interests*** emerged from the dynamics of the system. For instance, aiming at creating a single state-owned electricity company, the president Luis Echeverría Álvarez (1970–1976) authorised the dissolution of CLyF in 1974. However, disagreements between the state and the SME delayed this process until 2009 bringing several socio-political tensions and operational issues within the system [44].

[Socio-technical] The interconnexion of the different electricity systems was a complex process that took place in around 16 years. Although the National Electrification Program (Programa Nacional de Electrificación) was issued in 1962, the Committee for the Unification of Frequencies (Comité de Unificación de Frecuencia, CUF) was created in 1972 and was until 1976 when existing electricity systems changed to a frequency of 60 cycles per second consolidating the National Electricity System (Sistema Eléctrico Nacional, SEN). The interconnexion process brought operational, administrative, and social benefits to the system. Access to electricity increased from 44% in 1960 to 88% in 1991 (see Fig. 18).

[Socio-technical] Following energy policies from the oil and gas

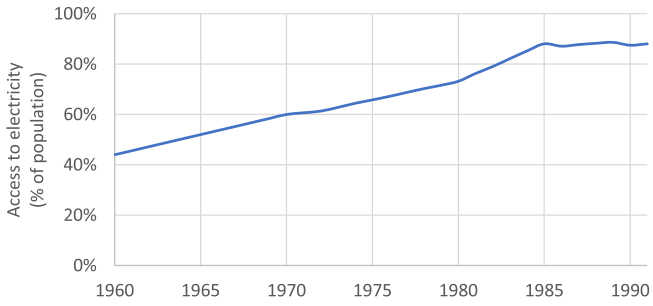


Fig. 18. Access to electricity from 1960 to 1991. Constructed with data from [36,39,48].

sectors, investments in electricity were mainly oriented towards fuel oil and natural gas. With the nationalisation of the industry, CFE started its participation in the definition and design of equipment with particular technical characteristics and started the (semi)automation process of power plants and substations. Also, the construction of larger capacity power plants (hundreds of MW) was a technological change during this period of analysis.

[External landscapes] A particular (nationwide) focus on science and technology took place during Luis Echeverría's administration (1970–1976). A national ***landscape*** was the creation of the National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología, CONACYT) in 1970 aimed at developing ***policy mixes*** on research and development (R&D), and innovation on priority topics for the Nation [47].

[Socio-technical] Although electricity production was dominated using oil as the preferred fuel, other niches received attention during this period. Fig. 19 depicts the technology mix and installed capacity for public service from 1960 to 1991. In 1966 CFE built its first 37.5 MW coal power plant. Also, the adoption of natural gas turbines (NGT) in 1965 and natural gas combined cycles (NGCC) in 1974 was possible due to international technological improvements on gas turbines [29]. On the other hand, the first 3-MW geothermal pilot plant was dismantled in 1973. However, a new geothermal field started operations in the northern part of Mexico where the first power units (75 MW) were commissioned in 1973. Finally, a nuclear power plant (Laguna Verde) started operations in 1990. Table 3 presents the international technological leaders (countries with the highest total installed capacity) on these technological niches in 1974 and 1991. Technology (including knowledge and equipment) might be diffused from these ***core*** countries to the ***periphery*** (including Mexico) [49].

[External landscapes] - [Actors] The international oil crisis in 1973 was an international ***landscape*** that triggered concerns around energy

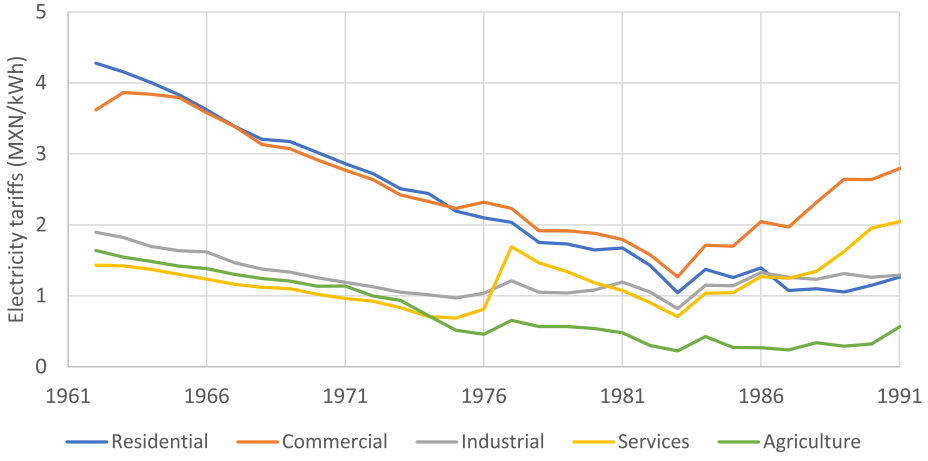


Fig. 17. Average electricity tariffs (1962–1991). (Values in real Mexican 2015 pesos). Constructed with data from [45,46].

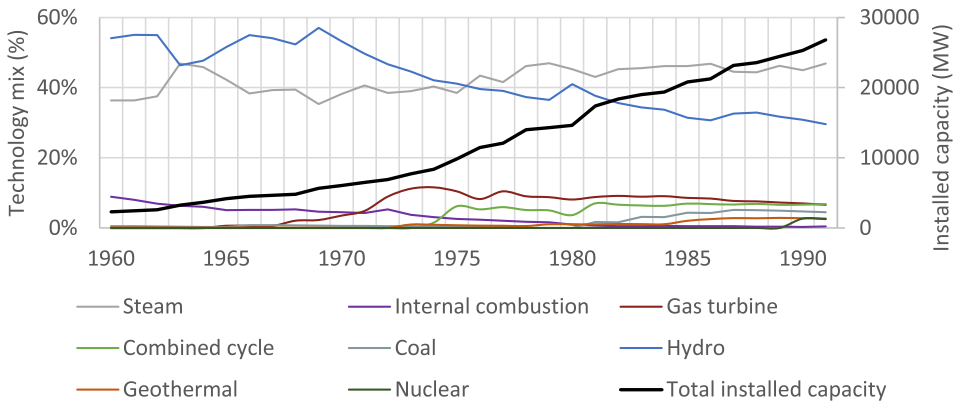


Fig. 19. Technology mix (left) and installed capacity for public service (right) from 1960 to 1991. Constructed with data from [32,37,50].

Table 3
International (core) leaders on selected electricity generation technologies in 1974 and 1991. Source: [50].

Technology	Core countries in 1974 (installed capacity in MW)	Core countries in 1991 (installed capacity in MW)
Coal	US (174,319)	US (262,661)
	UK (45,118)	Germany (42,065)
	Germany (30,843)	UK (33,704)
Gas turbine	Mexico (971)	US (48,815)
	Finland (781)	Germany (5,948)
	Australia (313)	UK (3,585)
Geothermal	Italy (382)	US (2,632)
	New Zealand (160)	Mexico (720)
	Mexico (75)	Italy (567)
Natural gas combined cycle	Mexico (130)	US (23,762)
	Hungary (116)	Japan (4,715)
		Mexico (1,933)
Nuclear	US (31,662)	US (99,609)
	Japan (3,906)	France (56,780)
	Germany (3,294)	Japan (33,404)

diversification and energy planning. The government promoted technological innovation and development for both the incumbent regime (i.e. oil-based electricity production) and emerging technological niches (i.e. coal, NGT, geothermal, NGCC, and nuclear). The National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias, INEEL[1]) was created in 1975 aiming at carrying out innovation, technological research and development in electrical generation, transmission, and distribution processes. Similarly, the National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares, ININ[2]) and the National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias, CNSNS) were created in 1979 to conduct research activities and regulate nuclear matters, respectively. Also, in 1982 the Secretariat of Energy (Secretaría de Energía, SENER[3]) was created aiming at coordinating, planning, developing, and implementing energy ***policy mixes*** nationwide. Fig. 20 shows the dominant actors of the governance system by 1991.

[External landscapes] - [Actors] Since the early 1970's the government had been borrowing large amount of foreign currencies (mostly U.S. dollars). Thus, the external debt of the public sector had drastically grown by the end of the decade. The Mexican electricity sector faced financial difficulties due to unstainable foreign debt, lack of

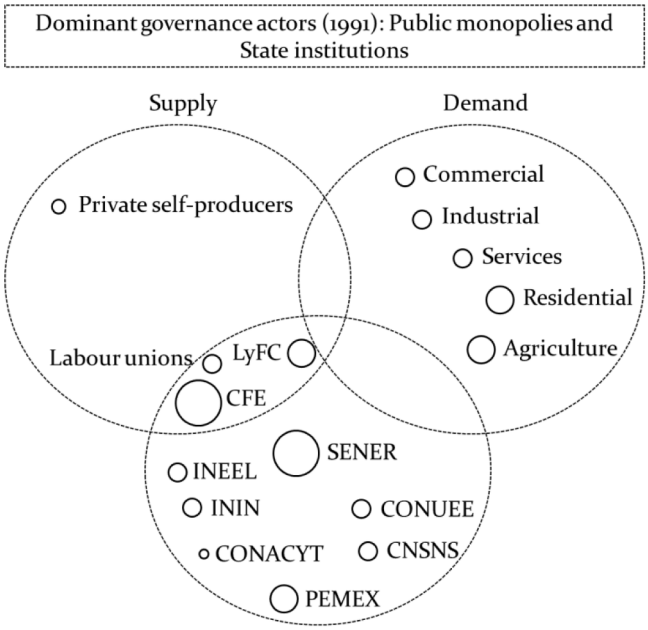


Fig. 20. Dominant governance actors by 1991. The size of the circles represents the relevance of their role within the governance system. Adapted from [29] with information from [28,47,49,51].

management autonomy of CFE, subsidised tariffs, and lower export revenues caused by the fall of international oil prices [29,51]. The 1982 economic crisis in Mexico forced the government to focus on energy savings and energy mix diversification. Thus, the National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía, CONUEE[4]) was created in 1989 aimed at developing energy efficiency strategies. Also, CFE created diverse ***policy instruments*** focused on electricity savings such as Energy Saving Program for the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico, PAESE) in 1989 and the Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica, FIDE[5]) in 1990 [52]. Fig. 21 shows the electricity intensity (total electricity consumption per unit of GDP) for this period. Also, environmental concerns arisen during this period and the General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente, LGEEPA) was published in 1988 (affecting the

[1] Before (Mexican) Electricity Research Institute (Instituto de Investigaciones Eléctricas, IIE).
[2] Before the National Nuclear Energy Commission (Comisión Nacional de Energía Nuclear, CNEN).
[3] Before Secretaría de Energía, Minas e Industria Paraestatal (SEMIP).
[4] Before National Energy Saving Commission (Comisión Nacional para el Ahorro de Energía, CONAE).
[5] Originally named Fund in Support of PAESE.

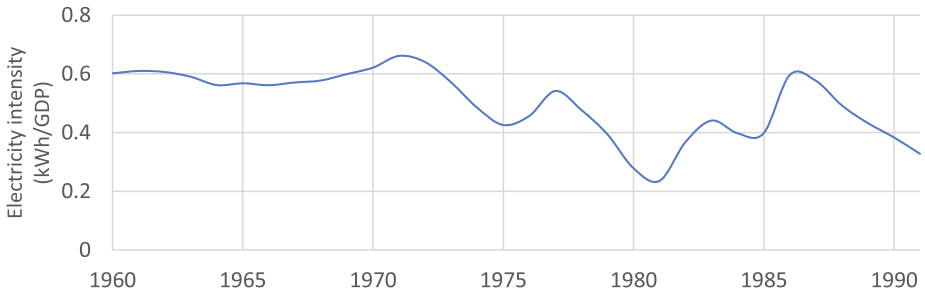


Fig. 21. Electricity intensity from 1992 to 2012. Constructed with data from [37,54,55].

electricity sector in later years).

[External landscapes] The Mexican oil boom was a national ***landscape*** that affected electricity generation and consumption [53]. With vast fossil fuel resources available within the country, during the second half of the 1980s an increase in electricity exports to US took place and imports were kept relatively constant to meet regional needs (see Fig. 22). Another important ***landscape*** during this period was the North American Free Trade Agreement (NAFTA) signed between Mexico, United States, and Canada, started negotiations in 1991, with a major focus on liberalising trade in key sectors between the three countries.

3.3.1. Multi-perspective summary (1960–1991)

The nationalisation of the electricity sector brought several challenges to the governance system including the unification of tariffs, interconnexion of the national system, expanding access to electricity, diversification of energy sources, integration of relevant actors to the new structure, reduction of energy consumption, and environmental concerns. Policy mixes during this period were oriented towards addressing these challenges as shown in Fig. 23.

In line with policy objectives, electricity access increased from 44% to 88%; electricity tariffs changed according to the state's (social) policy paradigm (including subsidies for agriculture and residential in tariff structures); electricity demand was met with almost national generation and surplus was exported to US; and electricity intensity fluctuated based on diverse internal and external events with a decreasing trend over time. Fig. 24 presents the main outcomes of interest for this period of analysis.

From a socio-technical perspective, the period was characterised by the inclusion of automation processes; construction of larger-size power plants (hundreds of MW); new technological niches (i.e. NGT, coal, geothermal, NGCC, and nuclear); a focus on fostering the creation of innovation systems; and technology diffusion from different core countries. Fig. 25 depicts the main socio-technical changes for this period.

3.3.2. Energy transitions governability (1960–1991)

This period was characterised by the control of the state in generation, transmission, and distribution following a hierarchical governance model with a social approach; a remarkable increase in access to electricity with rural and national electrification programs; a transition from a co-governance to a state-led (hierarchical governance) system pathway; expansion of the sector; a focus on innovation and support to technological niches. Fig. 26 and Table 4 represent the energy transitions governability snapshot for this period.

3.4. Partial liberalisation of the sector (1992–2012)

[Actors] A ***policy paradigm shift*** towards free markets occurred during the 1980's. Following the neoliberal ideology of 'less state intervention' the administration of Carlos Salinas de Gortari (1988–1994) started a process of liberalisation in the electricity sector. CFE and CLyF remained the owners of transmission and distribution lines, but private actors were allowed to participate in electricity generation under six new modalities. The independent power producer (IPP) scheme allowed private companies to produce and sell electricity to CFE under power purchase agreements (PPAs). Small power producer (SPP) mode included isolated rural communities generating less than 1 MW for self-supply, generation coming from small power plants with no more than 30 MW and sold to CFE, and electricity exported up to 30 MW. Power self-supply (PSS) and cogeneration power producer (CPP) schemes encompassed electricity and heat generation for fulfilling their needs and electricity surplus were sold to CFE. Power imports (PI) and exports (PE) were only allowed for covering specific needs (e.g. self-supply). Additionally, permits for self-supply granted before 1992 remained active for private producers under the continuous self-supply (CSS) scheme [29,56]. With new potential participants within the system, new regulations were needed. Thus, the Energy Regulatory Commission (Comisión Reguladora de Energía, CRE) was created in 1993 to foster an appropriate and efficient development of the electricity and natural gas industries and to protect users' interests.

[Socio-political] The rapid growing demand and the inability of state-owned electricity companies to continue expanding the system (mainly due to financial constraints) posed potential challenges to keep the ***supply–demand balance***. Some of the energy ***policy objectives*** during this regime were to secure electricity supply by different mechanisms (e.g. allowing private investment in generation and importing electricity from US) and to increase access to electricity in rural areas. Fig. 27 depicts electricity international trade from 1992 to 2012. An increasing trend in imports can be observed during the first years of this period and until 1997 when they decreased. Also, by 1992 around 93%

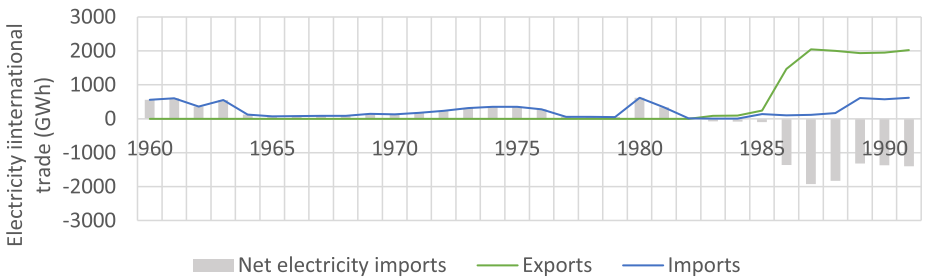


Fig. 22. Electricity imports, exports, and net imports from 1960 to 1990. Constructed with data from [32,37].

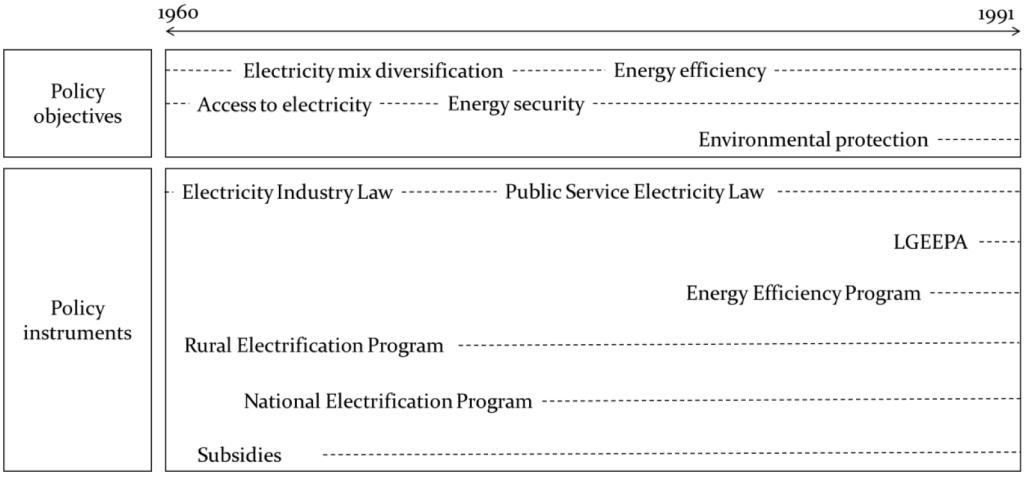


Fig. 23. Socio-political perspective snapshot (1960–1991).

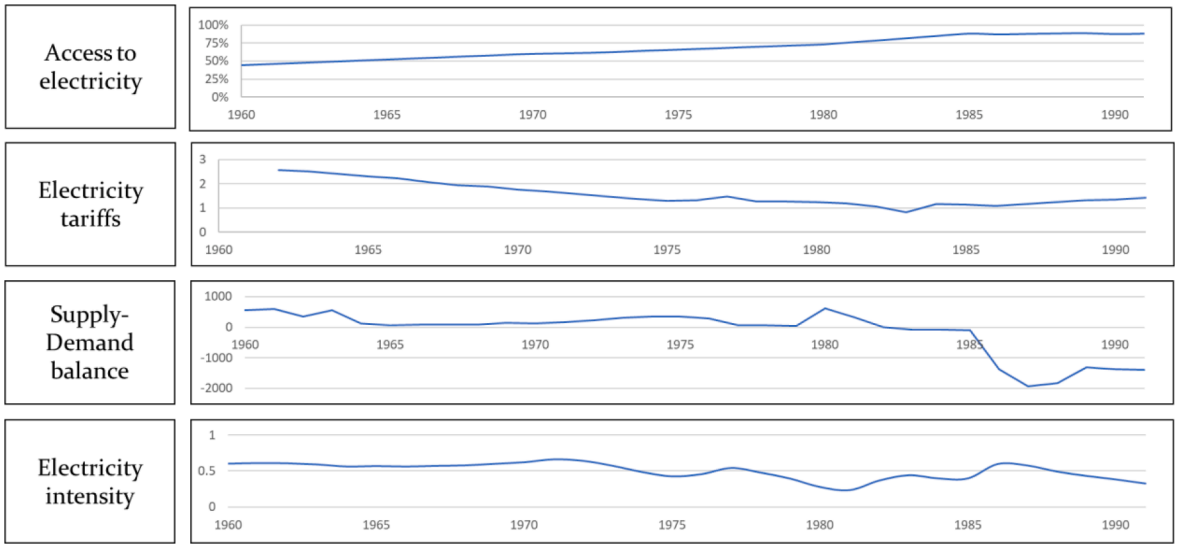


Fig. 24. Techno-economic perspective snapshot (1960–1991). Access to electricity refers to the percentage of population with access to electricity. Electricity tariff represents the changes in total average tariff considering the main consumer sectors (i.e. residential, commercial, industrial, services, and agriculture) in 2015 Mexican pesos. Supply-Demand balance refers to the net electricity imports in GWh. Constructed with data from [32,36,37,39,45,46,48,54,55].

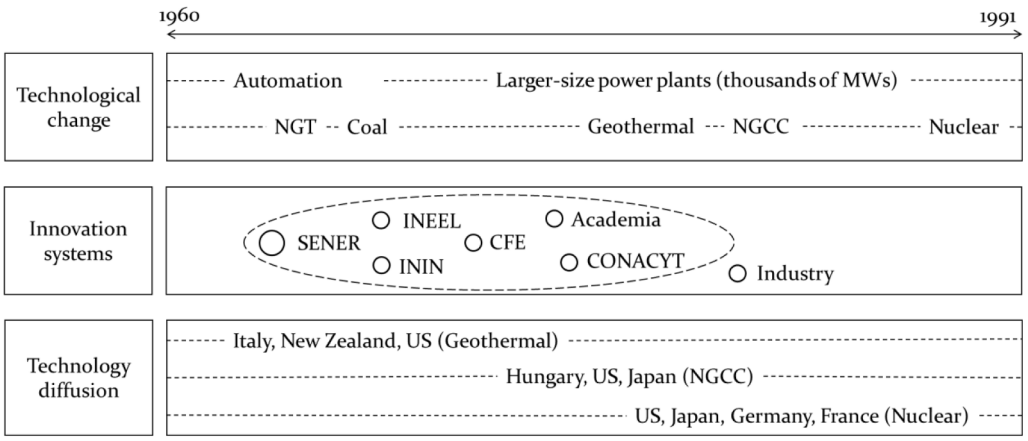


Fig. 25. Socio-technical perspective snapshot (1960–1991).

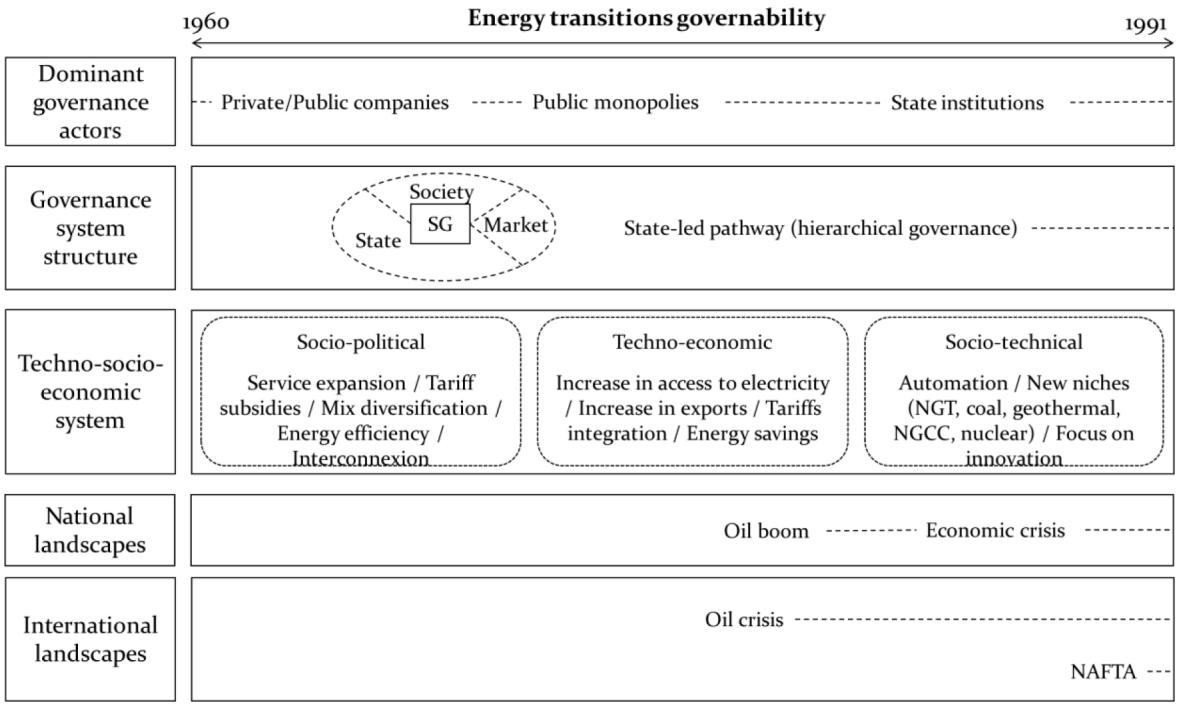


Fig. 26. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1960–1991).

Table 4
Energy transitions governability snapshot – governing interactions (1960–1991).

State -> Market
Pressure for service expansion to rural areas.
Intervention on tariff regulation and subsidies.
Intervention on expansion planning.
State -> Society
Promotion of lower electricity tariffs (subsidies).
Society -> State
Pressure for lower prices.
Pressure for access to electricity in rural areas.
Society -> Market
Pressure for better services and prices.
Market -> State
Pressure for better expansion planning.
Pressure for financial support.
Pressure for fostering innovation systems.
Market -> Society
Pressure for reducing electricity intensity.

of the population had access to electricity services. However, the state continued efforts to expand the system and reached 99% of coverage by 2012 (see Fig. 28). To allow participation of private actors, a major

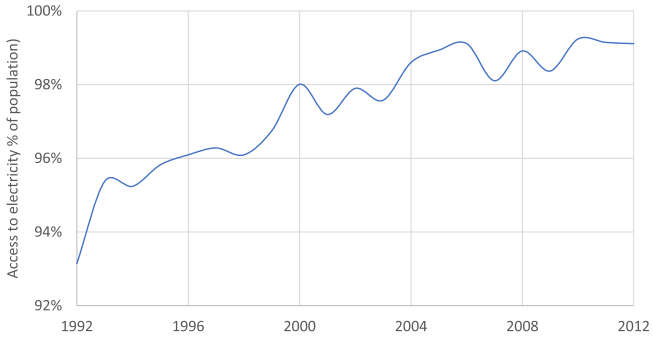


Fig. 28. Access to electricity from 1992 to 2012. Constructed with data from [59].

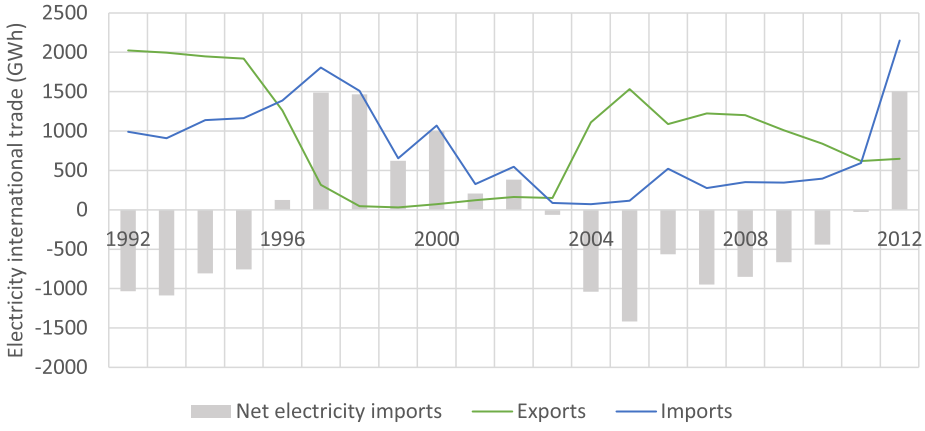


Fig. 27. Electricity imports, exports, and net imports from 1992 to 2012. Constructed with data from [32,57,58].

reform to the Public Service Electricity Law took place in 1992.

[External landscapes] Mexico became a member of the Organisation for Economic Co-operation and Development (OECD) in 1994, bringing opportunities for international cooperation. However, Mexico's economy experienced a severe recession after the Mexican peso crisis in 1994, affecting several economic sectors. This ***external landscape*** accelerated the privatisation process in the electricity sector. Although the Public Service Electricity Law was reformed during Carlos Salinas' administration, the first permit to an IPP was granted in 1997 and generation from private producers began in 2000.

[Socio-political] The next three administrations (Ernesto Zedillo, 1994–2000; Vicente Fox, 2000–2006; and Felipe Calderón, 2006–2012) proposed energy reforms oriented towards increasing private participation in the energy system. Even though the initial proposals were rejected by the Mexican Congress some changes to the electricity system took place during this period. First, the electricity tariff structure was revised and modified during 2002, increasing tariffs and reducing subsidies for some consumer sectors (and eliminated for higher-tier residential consumers) [29]. Fig. 29 shows the average electricity tariffs for the main consumption sectors during this period. Second, to promote a transition to a low-carbon economy by means of renewable energy and energy efficiency, the Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía, LASE) and Use of Renewable Energy and the Financing of the Energy Transition Law (Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética, LAERFTE) were published in 2008. In terms of energy efficiency, although the use of electricity per unit of GDP increased just after the Mexican peso crisis, a decreasing trend in electricity intensity from 1995 to 2012 can be observed in Fig. 30. Third, by a presidential decree the LyFC state-owned electricity company was dissolved in 2009 due to its administrative and operational inefficiency, transferring their responsibilities to CFE.

[External landscapes] - [Socio-political] International concerns regarding climate change and environmental protection influenced ***policy energy objectives*** towards a more sustainable economy. Thus, based on the LGEEPA law, new regulations on environmental standards for SO_x and NO_x emissions in environmentally critical areas were established in 1994. These environmental regulations limited CFE on the use of high-sulphur fuel oil for power generation in important metropolitan and industrial areas [62], thus promoting the use of natural gas [29].

After the United Nations Framework Convention on Climate Change (UNFCCC) entered into force in 1994, Mexico stated its commitment on climate change by signing the Kyoto Protocol in 1998. However, Mexico's climate change policy started in 2007 with the publication of the National Climate Change Strategy aiming at guiding policies on climate change. Regarding electricity production and use, the strategy focused on promoting energy efficiency and technology mix diversification in order to reduce GHG emissions. In 2012 the Congress approved the General Climate Change Law (Ley General sobre Cambio Climático, LGCC) establishing the institutional and programmatic framework for national policy on climate change [63]. Fig. 31 shows total GHG emissions (excluding land use change and forestry (LUCF)) and emissions by source within the energy sector. Total emission increased from 455.13 Mt CO_2-e in 1992 to 673.72 Mt CO_2-e in 2012 (an increase of 48%). Similarly, emission from electricity generation increased from 66 Mt CO_2-e to 124.9 Mt CO_2-e in the same period (representing 19% of the total GHG emissions and 27% of the energy-sector GHG emissions) [64].

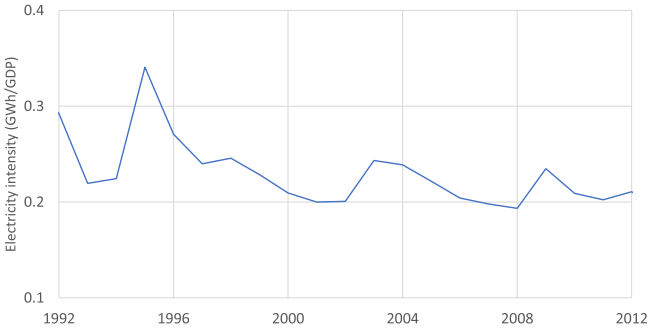


Fig. 30. Electricity intensity from 1992 to 2012. Constructed with data from [54,55].

A relevant national ***landscape*** within the energy sector was the decline of oil and gas production since the mid-2000's. Oil production declined around 34% from the peak of 3.8 million barrels per day (mb/d) in 2004 to 2.5 mb/d in 2016. Similarly, domestic production of natural gas started falling since 2009, resulting in an increase in imports (mainly from US) to meet national demand [9]. Another important international ***landscape*** was the global financial crisis in 2008. In order to ameliorate the effects of the crisis, the state adopted different measures including freezing household energy prices, decreasing industrial and commercial electricity tariffs (see Fig. 29), and increasing public expenditures on infrastructure and innovation-oriented activities [65].

[Actors] - [Socio-technical] In line with ***policy objectives*** towards a more sustainable economy, multiple academic institutions carried out research activities on clean energy and energy efficiency. Apart from INEEL, relevant institutions include the Institute of Engineering (Instituto de Ingeniería, IINGEN) at the National Autonomous University of Mexico (Universidad Nacional Autónoma de México, UNAM), the Centre for Economic Research and Teaching (Centro de Investigación y

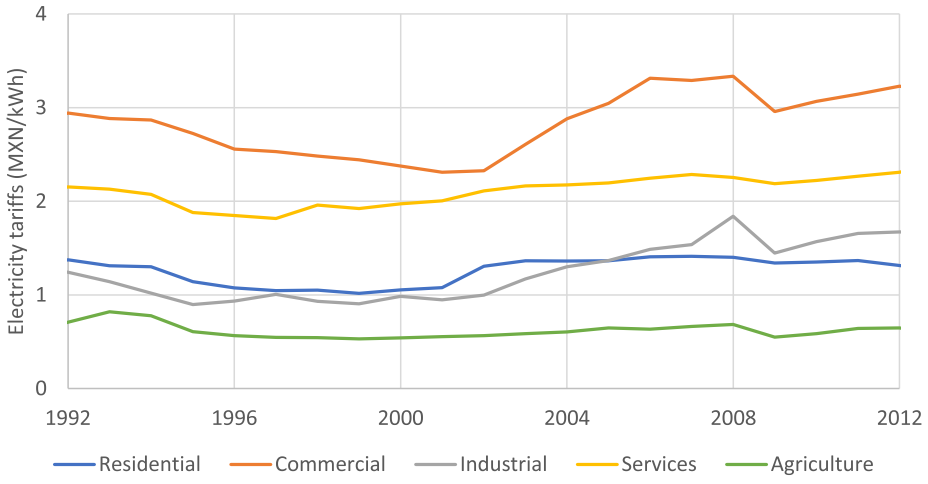


Fig. 29. Average electricity tariffs (1992–2012). (Values in real Mexican pesos of 2015). Constructed with data from [46,60,61].

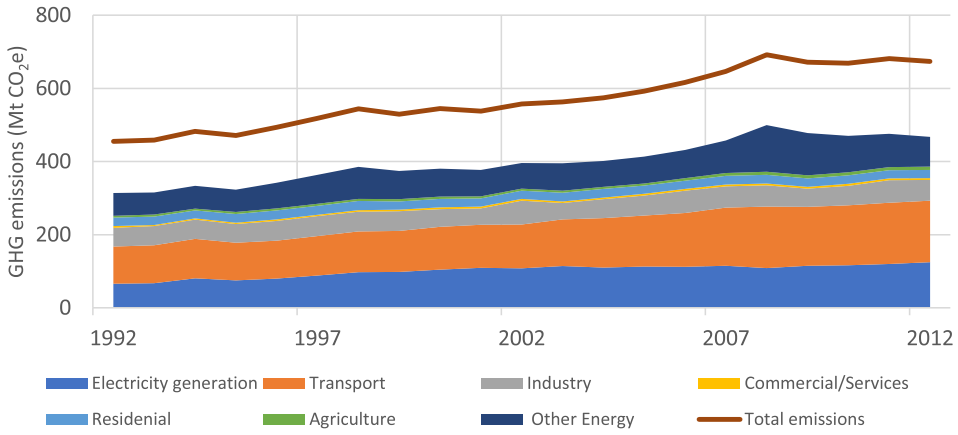


Fig. 31. Total GHG emissions, total emissions from main energy activities, and emissions by source within the energy sector. Constructed with data from [64].

Docencia Económicas, CIDE), the Metropolitan Autonomous University (Universidad Autónoma Metropolitana, UAM), the Institute of Renewable Energy (Instituto de Energías Renovables, IER) at UNAM, among many others. Also, the government created the Energy R&D Funds in 2008. The main objective of the Hydrocarbons Fund (FH) and the Energy Sustainability Fund (FSE) was to support innovation, scientific research, technology development and deployment, human capital development, and sustainable energy development nationwide. These funds were jointly led by SENER and CONACYT, aiming at coordinating innovation efforts made by academia, industry, and public institutions [66–70]. Thus, ***innovation systems*** were strengthened with (public and private) research centres, universities, and other organisations working collaboratively across the country. Fig. 32 depicts the dominant governance actors by 2012.

[Socio-technical] During this period, a technology transition from fuel oil to natural gas occurred, becoming natural gas combine cycle (NGCC) the dominant technology in the ***technological regime*** (see Fig. 33). The IPPs' NGCC installed capacity increased from 484 MW in 2000 to 11,907 MW in 2012 (an increase of 2360%) while CFE increased its NGCC capacity by 110% in the same period (from 2,914 to 6,122 MW). On the other hand, the first 1.57 MW wind project was set up in 1994 in La Venta, Oaxaca by CFE. Wind installed capacity grew from 1.57 to 598 MW from 1994 to 2012, with 511 MW owned by IPPs. Similarly, the first 5 MW solar photovoltaic (PV) project started operations in 2012 (owned by CFE). In terms of technology diffusion, Table 5 depicts the main technological leaders for different technologies selected.

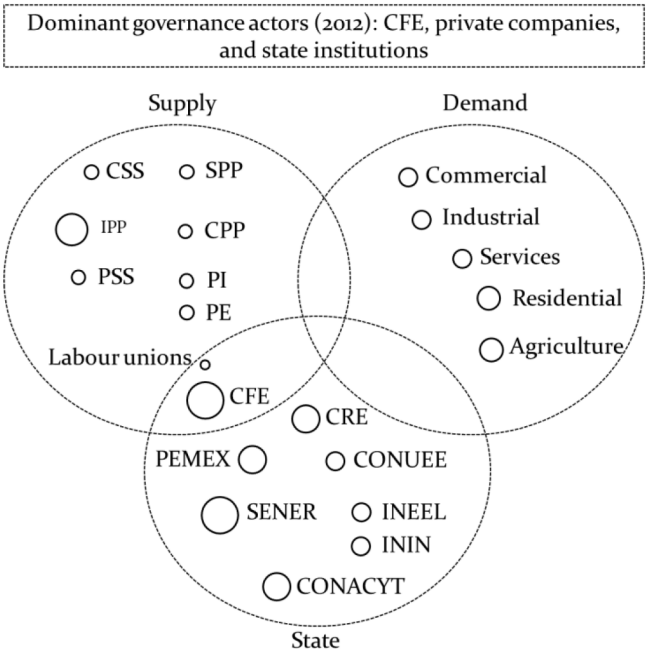


Fig. 32. Dominant governance actors by 2012. The size of the circles represents the relevance of their role within the governance system. Source: adapted from [29] with information from [47,49,56].

3.4.1. *Multi-perspective summary (1992–2012)*

Due to diverse internal and external pressures, a policy paradigm shift towards (partial) liberalisation of the market took place during this period. The main policy objectives were promoting energy efficiency and technology mix diversification; expand electricity services to rural areas; energy security; environmental protection; and climate change mitigation. Fig. 34 presents the main policy mixes adopted during this period.

During this period the system reached a 99% coverage nationwide; electricity tariffs varied based on different internal and external events; supply–demand balance also fluctuated based on diverse landscapes (e.g. a decline in hydrocarbons production); GHG emissions increased in 48%; and electricity intensity showed a decreasing trend over time. Fig. 35 depicts the main outcomes of interest to show the overall performance of the system.

The system experienced a transition to natural gas combined cycle; the first onshore wind and solar PV projects started operations; innovation systems were strengthened with new policy instruments (i.e. creation of the RD&D energy funds); technology diffusion came mainly from US, Japan, and Europe where the largest technology deployment of NGCC, wind, and solar PV took place. Fig. 36 depicts the main socio-technical changes during this period.

3.4.2. *Energy transitions governability (1992–2012)*

During this period, the governance system expanded to include less homogenous actors and institutions, creating diverging standpoints and more complex interactions. Governability during this period was characterised by a shift from 'command-and-control' state interventions to a more participative (and coordinated) interactions with non-state organisations (i.e. market actors and civil society) [11]. Fig. 37 and Table 6 depict the energy transitions governability snapshot for the period from 1992 to 2012.

4. Discussion and future research

The energy transitions governability framework was developed and applied in this article as a multi-perspective analytical framework to describe the evolution of electricity transitions in Mexico from 1879 to

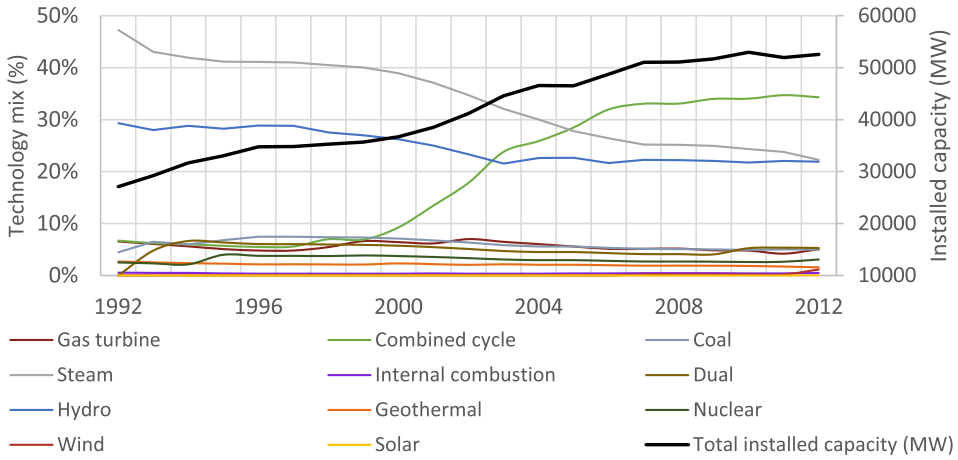


Fig. 33. Shares of technology mix (left) and total installed capacity (right) for public service (1992–2012). Constructed with data from [71–83].

Table 5
International (core) leaders on selected electricity generation technologies in 1992 and 2012. Source: [50].

Technology	Core countries in 1992 (MW)	Core countries in 2012 (MW)
Natural gas combined cycle	US (27,458)	US (221,952)
	Japan (5,040)	Italy (42,486)
	Mexico (1,933)	UK (35,150)
	Netherlands (1,819)	Mexico (22,504)
Gas turbine	US (51,161)	US (139,738)
	Germany (6,051)	Canada (11,759)
	Japan (4,103)	Japan (11,297)
Wind	US (1,823)	US (59,075)
	Denmark (436)	Germany (30,979)
	Germany (183)	Spain (22,789)
Solar PV	US (44)	Germany (34,075)
	Japan (19)	Italy (16,785)
	Italy (8)	US (8,137)
Nuclear	US (99,005)	US (101,885)
	France (57,675)	France (63,130)
	Japan (34,584)	Japan (46,148)
Hydro	US (96,059)	US (101,106)
	Canada (61,668)	Canada (75,537)
	Japan (39,523)	Japan (48,934)
Geothermal	US (2,910)	US (2,592)
	Mexico (730)	Mexico (824)
	Italy (471)	Italy (728)

2012. Based on the structural configuration of governance systems (at an actor level), four periods were explored in this article. First, a market-led pathway took place from 1879 (when the electricity industry in Mexico originated) to 1936, dominated by informal interactions between the state, private monopolies, and key actors within the society (mainly industrial consumers) with little state regulation (i.e. self-governance). After multiple tensions within the regime, a transformation process towards a state-influenced pathway occurred between 1937 and 1959 with an increasing state participation in the expansion of the electricity industry to meet societal needs (i.e. co-governance). Mainly derived from nationalistic spirits, a state-led pathway took place from 1960 to 1991 resulting in the creation of diverse public institutions to guide the development of the industry (i.e. hierarchical governance). Finally, the electricity system transitioned to a state-influenced pathway from 1992 to 2012 with a partial liberalisation of the sector coordinated by public regulatory bodies. Based on the historical evolution of the electricity sector, different drivers have been identified in shaping electricity transitions in Mexico.

First, governance decisions have depended on specific paradigms that relevant actors have adopted. For instance, informal social relations between the state and (mainly) transnational electricity companies benefited private interests (i.e. clientelism) during the early stages of the electricity industry in Mexico, allowing monopolistic practices [84]. On the other hand, a nationalistic paradigm shaped the evolution of the industry from the 1960's to the 1990's, when the state recognised the need for reliance on private capital and liberal markets to meet societal needs (e.g. increase in electricity demand). Even if it is likely that future transitions follow a market-led with state regulation pathway (directed co-governance) a policy paradigm shift may change the direction (or pace) of these structural changes. Also, the electricity tariff policy has followed different pathways throughout the periods analysed. At the beginning of the electricity sector, tariffs were set by private companies based on economic interests (increase profit) and were mainly based on (variable) operational costs. Then, a policy paradigm shift towards nationalisation and sovereignty set tariffs below real generation costs promoting social benefits to the Nation (following oil development and cross-sectoral subsidies). The social aspect of nationalisation brought financial constraints to state-owned companies, resulting in an increase in electricity prices since the late 1980's but subsidising some key subsectors. One plausible explanation for setting subsidies for agriculture and residential subsectors under the socio-political perspective is the relevance of acquiring low/middle income class voters by decreasing the price paid by these sectors [42]. Although subsidies have been falling throughout the years, this state intervention represents (socio-political) challenges in the future (e.g. regressive effects, tensions between governance actors with high political costs).

Second, available (indigenous) resources have played a key role in directing the path and pace of electricity production technologies. When multiple changes in the system reinforce each other, inertia and path dependency emerge. In the case of Mexico, electricity generation has followed a path-dependent pathway ruled by available energy resources in the country (e.g. fuel oil or natural gas production). Fossil fuels are geologically finite, geographically fixed, and unevenly distributed around the world. Thus, when countries, such as Mexico, have had access to (indigenous) fossil fuels tend to privilege long-standing incumbent regimes (e.g. by supporting aging fossil-fuel incumbent power plants) creating a technological lock-in effect for new technological niches (e.g. wind, solar, geothermal) [85]. However, the ever-growing electricity demand in the country has called for the utilisation of different (complementary) technologies for power generation (sometimes referred as energy additions [5]). The decline in hydrocarbons production in the country since the mid-2000's has accelerated the promotion of clean energy development and diffusion. Thus, a transition away from fossil fuels (i.e. technology-based energy transition) is likely to take place in the future due to the geologically finite nature of these fossil fuel resources. However, constraints on clean energy technologies (e.g. limited steam extraction for geothermal power generation or

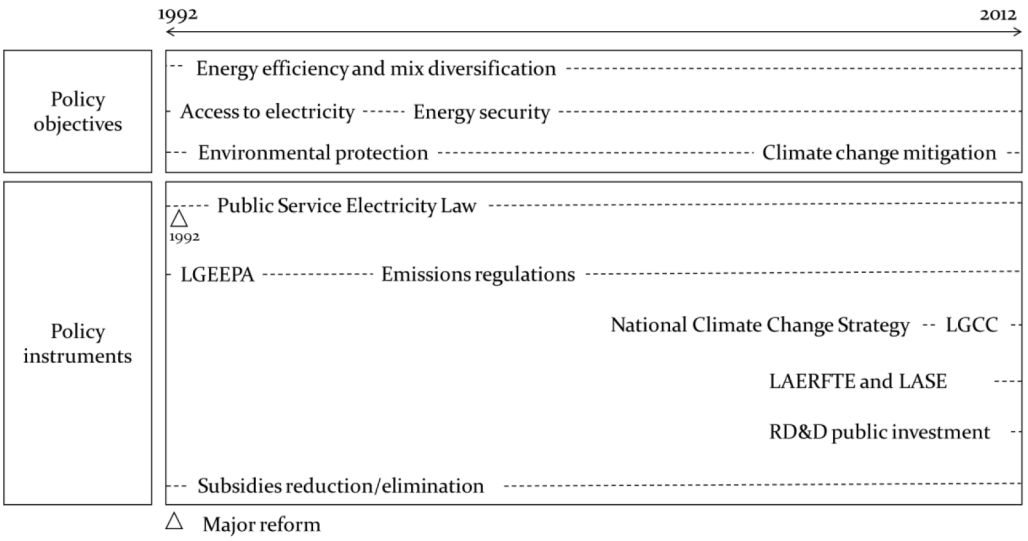


Fig. 34. Socio-political perspective snapshot.

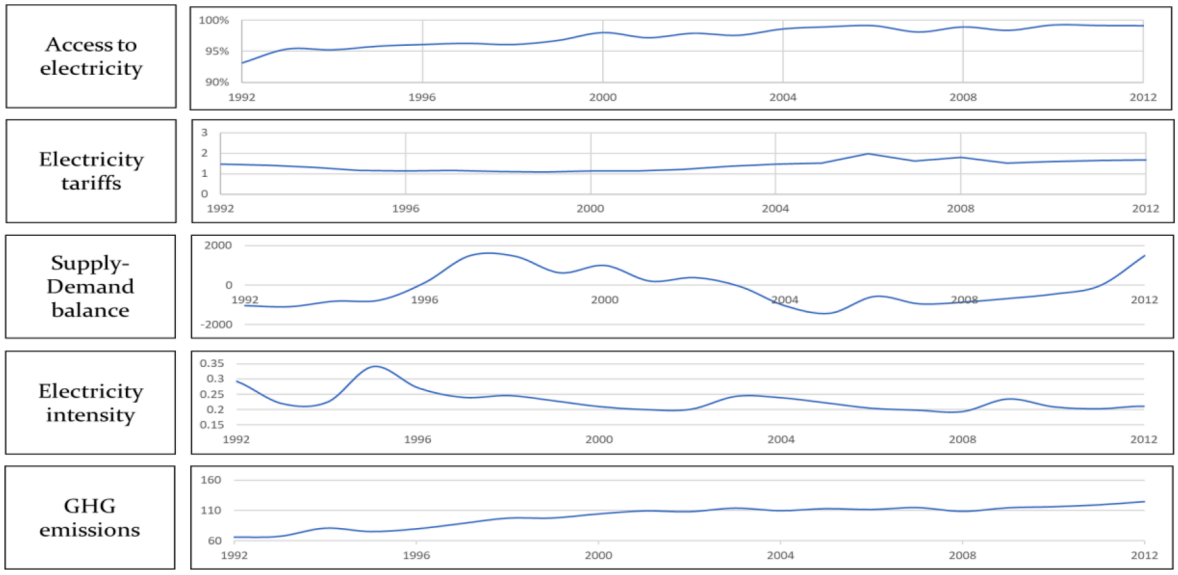


Fig. 35. Techno-economic perspective snapshot. Access to electricity refers to the percentage of population with access to electricity. Electricity tariff represents changes in the total tariff considering the main consumer sectors (i.e. residential, commercial, industrial, services, and agriculture) in 2015 Mexican pesos. Supply-Demand balance refers to the net electricity imports in GWh. GHG emissions depicts emissions from electricity generation in Mt CO_2-e. Electricity intensity refers to electricity needed to generate one unit of GDP (in current US$). Constructed with data from [46,54,55,57–59,61,64].

extended use of land for solar farms) may pose challenges to the diffusion of these technologies. Although efforts on supporting the development of clean energy technologies have been made (e.g. public energy R&D, promoting innovation systems), technological lock-in has been (a will remain) a key challenge for new niches if fossil-fuel incumbent regimes are promoted by the state due to operational and socio-political interest (e.g. clientelism). Thus, the integration of coordinated energy innovation policy mixes towards clean energy transitions are needed (technology-push and market-pull mechanisms) to overcome technical and market barriers.

Third, increasing environmental and climate change concerns have modified the way electricity is produced and used (nationally and internationally). International agreements on climate change mitigation may gain further weight in deploying clean technologies and adopting energy efficiency measures (e.g. demand response management) even if socio-political interests exist within the governance system. However, a transition to a low-carbon economy in Mexico may pose significant challenges such as increasing inequality or exacerbating vulnerability of particular communities if key (ecological, economic, political, and social) aspects such as inclusivity, mineral extraction, land utilisation, and population management are not included in the political agenda [86,87]. A first step to better understand transitions at different scales could be to adopt a more holistic approach by including the potential negative effects of a clean energy transition (e.g. political conflict, degradation of the environment, economic inequality) as opposed to simply focus on emissions reduction (i.e. mitigation strategies).

To comply with international agreements on climate change mitigation and to meet electricity demand, Mexico has facilitated the adoption of neoliberal models towards private investments in low carbon energy technologies since the 1990's. However, the economic approach of private companies has led to adverse social effects on vulnerable communities whose traditional lifestyles and economic livelihoods are threaten by such investments (e.g. land acquisitions through unfair land-lease contracts) [88]. The socio-economic effects of

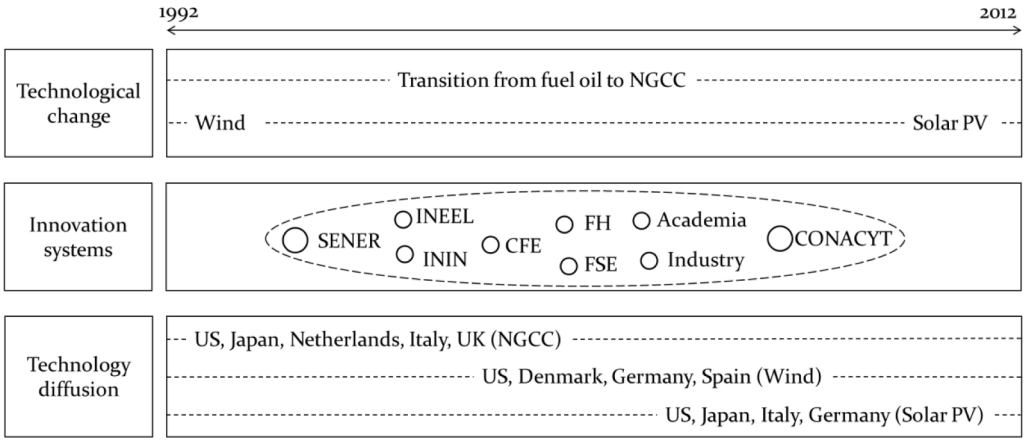


Fig. 36. Socio-technical perspective snapshot.

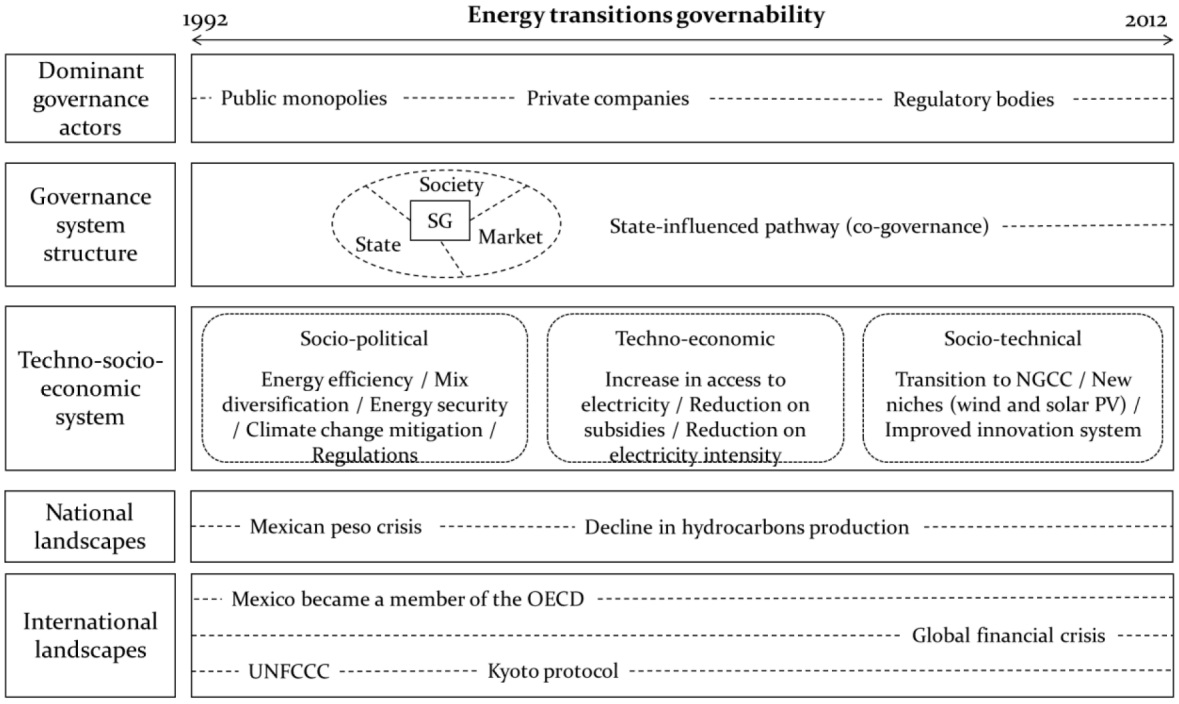


Fig. 37. Energy transitions governability snapshot – governance system, system-to-be-governed, and (national and international) landscapes (1992–2012).

renewable energy developments on vulnerable communities in Mexico have been extensively discussed in recent years [86,88–94]. It has been argued that a 'just' energy transition that prioritise safe, affordable, and sustainable energy for all individuals and across all areas (including local communities) is needed [88–90]. A transition towards a more sustainable energy system may be problematic if specific variables of the local context (e.g. land tenure, human rights) are not considered within energy planning [92]. To facilitate a fair energy transition in Mexico the definition of more democratic and participatory mechanisms for energy planning should be considered by policymakers (e.g. by combining top-down and bottom-up approaches for energy planning) [92–94]. Thus, energy transitions governability may be improved by fostering (local and international) communication and cooperation among actors and institutions to define policy mixes in line with national societal needs while complying with international agreements.

The structural transformations occurred during the last period (1992–2012) derived in a broad energy reform approved by the Mexican Congress in 2013 (affecting both the power and the oil and gas sectors). The reform and its ongoing effects are beyond the scope of this article due to three main reasons. First, the impacts of new (or reformed) energy policy mixes are usually not observed immediately after their implementation due to the long-term, evolving nature of processes of structural change within electricity transitions. Instead, adaptations to these policy mixes frequently take place derived from internal and external tensions within the system (e.g. policy paradigm shifts, opposition to change, international agreements). Second, data availability for some of the key variables used in this work (i.e. sustainability concepts) presents a significant limitation for describing the ongoing electricity transition. For instance, the latest data on GHG emissions from the energy sector published by the National Institute of Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático, INECC) corresponds to 2015. Third, the energy reform encompasses several complex structural changes at different scales (e.g. modifications to the Mexican constitution, enactment of new laws, new legislation, new actors, a different governance structure, and the development and implementation of several strategies and programs) aimed at accelerating the

Table 6
Energy transitions governability snapshot – governing interactions (1992–2012).

State -> Market
Intervention on energy efficiency and mix diversification.
Regulation of tariffs.
Regulation on power generation.
Intervention on environmental protection and climate change mitigation.
State -> Society
Intervention on subsidies.
Promotion on expansion of services.
Intervention on energy efficiency.
Society -> State
Pressure for access to electricity in rural areas.
Pressure for lower prices.
Society -> Market
Pressure for better services and prices.
Pressure for use of clean energy technologies.
Market -> State
Pressure for tariff increase.
Pressure for financial support.
Pressure for improving innovation systems.
Market -> Society
Pressure for reducing electricity intensity (e.g. demand side management).

transition to a low-carbon economy. The analysis of a fifth period (e.g. 2013–2020) using the proposed analytical framework may significantly increase the length of the article. Thus, the application of energy transitions governability as an analytical framework to explore the complex structural transformations derived from the 2013 energy reform merits special attention and it is proposed as future research.

The empirical application of the proposed analytical framework to the Mexican case has identified drivers (and challenges) in electricity transitions at different structural levels that may be applicable to other developing countries. For instance, developing countries share some common characteristics affecting their electricity systems such as the increasing electricity demand and thus the need for infrastructure expansion [1]. However, the framework may be also applied to other countries (or regions) by explicitly establishing the key energy/sustainability concepts and periods of analysis to be used for the investigation. Also, its application may be extended to different societal systems (e.g. oil and gas sector, clean energy technologies, transport sector with a focus on deploying electric mobility) by identifying the relevant concepts for each perspective (socio-political, techno-economic, and socio-technical) to describe structural system transformations over time. Similarly, the framework proposed may be used as an analytical tool to conduct comparative research between countries or regions to extend its applicability and improve the generalisability of the findings.

Although the analytical framework has demonstrated its applicability to (qualitatively) describe historical electricity transitions in Mexico, it presents some limitations. First, we have used concepts from literature on policy mixes for sustainability transitions, energy/sustainability transitions, and interactive governance theory to describe changes in socio-techno-economic systems. However, complementary concepts may be used to explain transformation processes not covered here. These may include concepts found within the same disciplinary roots (e.g. technology costs, voters' preference, international competition, public opinion, corporatism) or relevant concepts/processes derived from complementary literature (e.g. geography, political ecology, energy justice). Second, according to systems thinking, any societal system (e.g. oil and gas) is interrelated with other systems (e.g. electricity), influencing them and providing context for future changes. An analysis of the oil and gas sector using the analytical framework presented here, may aid to better understand the interactions between these two sectors and get a broader picture of energy transitions in developing countries. Similarly, the analytical framework may be applied to electricity subsystems (e.g. renewable energy technologies) to propose energy strategies to meet specific policy objectives (e.g. 50% of total electricity production from clean energy sources by 2050). Third, data availability and reliability have been identified as important limitations for the applicability of the proposed analytical framework for developing countries (e.g. outdated information available from public organisations or data inconsistency from different sources). Although a more robust research method was sought by following the systematic review process described in Appendix A, it should not be interpreted as the coverage of the full collection of sources on the history of the electricity industry in Mexico. The procedures involved in conducting research or collecting data (i.e. methods) usually exclude and privileges diverse social actors [95,96]. In the case of Mexico, for instance, illegal activities (fuel theft, violent confrontation, organized crime, and cartels) may play a role in socio-political processes [97]. However, the lack of reliable information makes hard to research their specific role in societal transitions. Being conscious of these caveats, the research method applied in this work may be improved by diversifying sources, comparing findings with other studies, and triangulating research methods (e.g. on-site interviews or expert elicitation) [10]. Also, complementary sources (not covered here) may provide additional information regarding structural transformations in the electricity system in Mexico (e.g. including sources in other languages or using different keywords).

5. Conclusions

The electricity sector is a complex system that has been under continuous change since its creation. The aim of this article was to explore the evolution of historical electricity transitions in Mexico (1879–2012) from the perspective of the interactive governance approach. Four periods of analysis were proposed based on the structural configuration of governance systems. Interactive governance theory and governability enable an analytical framework for exploring the role of social actors, technological change, policy mixes, and the interactions among them in national energy transitions. We conceptualised the system-to-be-governed as a co-evolving socio-techno-economic system by using a *meta*-perspective framework for national energy transitions. Structural changes in energy systems at their diversity, complexity, dynamics, and scale pose challenges to governance systems and have highlighted the role of these in guiding energy transitions. In the case of Mexico, it started as self-governance system led by the market (mainly private monopolies) without government regulation. Then, a co-governance mode was adopted with coordination among the government, private companies, and civil society to guide the development of the industry. After a policy paradigm shift towards nationalism and sovereignty took place, a hierarchical governance mode was adopted to meet societal needs (e.g. access to electricity, expansion of the system, tariff reduction). Finally, a liberal market paradigm adopted by the state transitioned to a co-governance system where private participation in electricity generation was allowed to meet increasing demand and overcome financial, technological, and operational challenges in the regime.

This article is a complementary analytical exercise to previous work focused on explaining historical electricity transitions in Mexico. The multi-perspective approach used in this work overcomes some of the limitations of analytical frameworks applied before (e.g. socio-technical change) by making a distinction between the economic, political, and technological aspects of the system and their interactions (as opposite as a 'seamless-web' approach). The use of concepts from energy transitions and policy mixes for sustainability transitions were useful to understand the role of policy mixes, social actors, technological change, and the system's performance in different episodes of electricity transitions. The interactive governance perspective assumes that different modes of governing may be more appropriate depending on contextual characteristics of the societal system to be analysed. By using interactive governance theory, we have attempted to synthetise these 'micro-logics' into a broader theoretical construct as suggested by [2]. This may help at

understanding why different countries have adopted different policy mixes to tackle similar issues like climate change mitigation or energy security (e.g. different policy paradigms tend to influence governance decisions and thus the pathway of energy transitions).

As the case study presented here revealed, governability of national energy transitions has varied considerably from one episode to another depending on how governance systems have handled societal needs. Different factors have influenced how the electricity system in Mexico has transitioned from one configuration to another. First, governance decisions have been influenced by (policy) paradigms adopted by relevant actors. Second, available (indigenous) resources have played a key role in guiding the pace and pathway of electricity production technologies. Third, increasing environmental and climate change concerns have modified the electricity sector development. We have suggested that energy transitions governability may be improved by fostering (local and international) communication and cooperation among actors and institutions to define policy mixes which meet the societal needs.

CRediT authorship contribution statement

Omar Castrejon-Campos: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Lu Aye:** Validation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Felix Kin Peng Hui:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Description on the research method adopted to describe the governability of historical electricity transitions in Mexico

This article focuses on answering the following research questions: how governing structures in the electricity sector have evolved over time? What role have these governing structures played in shaping electricity transitions? What have been the main drivers for structural change within the Mexican electricity system?

The aim of this article is to explore the evolution of historical electricity transitions in Mexico from 1879 to 2012 by applying the analytical framework described in Section 2. Thus, a systematic review process was conducted in this work with the objective of describing structural changes within the Mexican electricity system following a theoretical heuristic approach. A comprehensive literature search was initially developed in November 2019 and updated in August 2021. To facilitate replicability, the process followed a series of steps (i.e. research design) to identify, screen, and select relevant documents for analysis as described as follows.

Step 1. Identification of sources

Two main tools were used to conduct a preliminary search on historical electricity transitions in Mexico: broad disciplinary databases and grey literature searching (e.g. reports, working papers, government documents). Scopus (https://www.scopus.com) and Google Scholar (https://scholar.google.com) were the two databases chosen to locate relevant studies for the purpose of the analysis. In the case of grey literature, different web pages were selected for a preliminary search of relevant documents. These include the Mexican Secretariat of Energy (Secretaría de Energía, SENER) website (https://www.gob.mx/sener), the Federal Electricity Commission (Comisión Federal de Electricidad, CFE) website (https://www.cfe.mx), the Mexican government website (https://www.gob.mx/), and the International Energy Agency website (https://www.iea.org/).

At first, a search was conducted on Scopus using a combination of English-language keywords such as “Mexico”, “electricity”, “transition”, “history”. The preliminary search resulted in 71 documents (including articles, conference papers, books chapters, reviews, and books) using the following string: TITLE-ABS-KEY (“Mexico” AND “electricity” AND (“transition” OR “history”)). We also searched relevant literature using a combination of keywords in Spanish-language on Google Scholar. Keywords used include “México”, “electricidad”, “historia”, “industria eléctrica”, “sector eléctrico”, and “sistema eléctrico”. The preliminary search resulted in 39,900 results (including citations). From these, only the first 300 results sorted by relevance were selected for screening due to time limitation. No publication date or publication status restrictions were imposed.

The grey literature search included targeted, iterative hand searching of government and/or research organisation websites. A total of 50 additional records were added to the review from the grey literature search, including annual reports, working papers, laws, regulatory frameworks, datasets, manuals, theses, critical analyses, among others.

Step 2. Title/abstract screening

A preliminary screening process of 421 documents was conducted on the criteria of title and abstract/summary (if available) to verify their relevance to the review. From these, 309 records were excluded due to three main reasons: (1) the studies focused on different regions (e.g. United States) and/or broader regions (e.g. Latin America) with no (or not enough) relevant information on Mexico; (2) the studies were out of scope (i.e. covering broader topics such as population, democracy processes, general history of Mexico, etc.); and (3) no apparent relevance was found (e.g. analysis of historical temperatures in specific regions of Mexico) and/or did not match the research aim (i.e. describe historical electricity transitions in Mexico).

Step 3. Full-text screening and eligibility

During this step we reviewed 112 documents. They were filtered based on their relevance on contributing to a critical analysis according to the analytical framework proposed. A total of 76 records were excluded due to four main reasons: (1) content of the studies were partially or completely covered by other records (e.g. books or reports describing in detail the history of the electricity sector in Mexico for different periods); (2) the documents covered periods of time not contemplated within this analysis (e.g. after 2012) or were out of scope in terms of the research aim (e.g. historical analysis of specific government institutions); (3) the same data were included in multiple publications (e.g. description of the structure and objectives of the Mexican Energy Funds were included in several annual reports); and (4) national laws, their corresponding reforms, and regulatory frameworks were not cited due to word limitation and to avoid misperceptions (i.e. reforms modify both previous laws and published related documents such as regulatory frameworks).

On the other hand, reference lists of included records (e.g. articles, reports, thesis) were manually screened to identify additional relevant studies. A total of 19 additional studies were included to the review going through the (iterative) literature review process. After this step, the number of relevant documents was reduced to 55.

Step 4. Records included

A total of 55 records were accordingly cited within this article to describe historical electricity transitions in Mexico under the interactive governance approach. The review process followed by this article was updated in August 2021.

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Review

Evolution of clean energy technologies in Mexico: A multi-perspective analysis

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ABSTRACT

Electricity is fundamental for supporting economic development in emerging economies. Power generation from clean energy sources may help to meet societal needs such as increasing electricity demand while complying with contemporary global challenges (e.g. climate change). This paper aims at qualitatively describing the development of clean energy technologies in Mexico by using a multi-perspective analytical framework. By integrating a meta-theoretical framework for national energy transitions and core concepts from policy mixes for sustainability transitions literature, a series of stylised facts are developed to qualitatively describe the evolution of clean energy technologies in Mexico from 1879 to 2021. Interactive governance theory is used as an analytical framework to synthesise these storylines by highlighting the role and interactions among technologies, actors, and policy instruments in governance processes. The case study revealed that the ever-growing electricity demand in Mexico have called for exploring different available energy sources and technologies over time. Diminishing oil and gas domestic reserves, increasing concerns around environmental issues, and worldwide agreements on greenhouse gas emission reductions have been the main drivers for clean energy and energy efficiency development in Mexico. However, different barriers to a clean energy transition in Mexico have been identified and discussed in this study: (1) access to a vast oil and gas resources in the past reinforced the position

Abbreviations: BAU, business as usual; CCS, carbon capture and storage; CEC, clean energy certificate; CEMIE, Mexican Energy Innovation Centre (Centro Mexicano de Innovación en Energía); CENACE, National Centre of Energy Control (Centro Nacional de Control de Energía); CFE, Federal Electricity Commission (Comisión Federal de Electricidad); CNEG, Geothermal Energy National Commission (Comisión Nacional de Energía Geotérmica); CNSNS, National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias); CO_2, carbon dioxide; CO_2e, carbon dioxide equivalent; CONACYT, National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología); CONAE, National Commission for Energy Saving (Comisión Nacional para el Ahorro del Energía); CONUEE, National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía); CPP, cogeneration power producer; CRE, Energy Regulatory Commission (Comisión Reguladora de Energía); CSS, continuous self-supply; ENCC, National Climate Change Strategy (Estrategia Nacional de Cambio Climático); ENE, National Energy Strategy (Estrategia Nacional de Energía); FCC, Climate Change Fund (Fondo para el Cambio Climático); FIDE, Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica); FIRCO, Shared Risk Fiduciary Fund (Fideicomiso de Riesgo Compartido); FOTEASE, Energy Transition Fund (Fondo para la Transición Energética y el Aprovechamiento Sustentable de la Energía); FSE, Energy Sustainability Fund (Fondo de Sustentabilidad Energética); GDP, gross domestic product; GHG, greenhouse gas; GI, governing interactions; GS, governance system; GW, gigawatt; GWh, gigawatt-hour; IEA, International Energy Agency; IIE, Electricity Research Institute (Instituto de Investigaciones Eléctricas); INDC, Intended Nationally Determined Contribution; INEEL, National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias); ININ, National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares); IPP, independent power producer; IRENA, International Renewable Energy Agency; kW, kilowatts; kWh, kilowatt-hour; LAERFTE, Law for the Use of Renewable Energy and the Financing of the Energy Transition (Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética); LASE, Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía); LCFE, Federal Electricity Commission Law (Ley de la Comisión Federal de Electricidad); LGCC, General Climate Change Law (Ley General sobre Cambio Climático); LGEEPA, General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente); LIE, Electricity Industry Law (Ley de la Industria Eléctrica); LPDB, Bioenergy Law (Ley de Promoción y Desarrollo de los Bioenergéticos); LTPA, long-term power auction; LUCF, land use change and forestry; LyFC, Compañía de Luz y Fuerza; MLP, Multi-level perspective; $MtCO_2e$, million tonnes of carbon dioxide equivalent; MTPA, medium-term power auction; MW, megawatts; MWh, megawatt-hour; NAFINSA, Nacional Financiera; NAFTA, North American Free Trade Agreement; NAMA, Nationally Appropriate Mitigation Actions; NEI, National Emissions Inventory; NGCC, natural gas combined cycle; NO_x, nitrogen oxides; OECD, Organisation for Economic Co-operation and Development; PAER, Special Program for the Use of Renewable Energy (Programa Especial para el Aprovechamiento de Energías Renovables); PAESE, Program of Energy Savings in the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico); PE, power exports; PECC, Special Program for Climate Change (Programa Especial de Cambio Climático); PEMEX, Mexican Petroleum (Petróleos Mexicanos); PETE, Special Program for the Energy Transition (Programa Especial de la Transición Energética); PI, power imports; PJ, Petajoules; PPA, power purchase agreement; PPP, purchase power parity; PROCER, Mexico-US Renewable Energy Cooperation Program (Programa de Cooperación en Energía Renovable); PRODESEN, National Electricity System Development Program (Programa de Desarrollo del Sistema Eléctrico Nacional); PRONASE, National Program for Sustainable Use of Energy (Programa Nacional para el Aprovechamiento Sustentable de la Energía); PRONASOL, National Solidarity Program (Programa Nacional de Solidaridad); PROSENER, Energy Sectoral Program (Programa Sectorial de Energía); PSS, power self-supply; PV, photovoltaic; R&D, research and development; RD&D, research, development, and demonstration; REC, Renewable Energy Cooperatives; SE, Secretariat of Economy (Secretaría de Economía); SEMARNAP, Secretariat of the Environment, Natural Resources and Fisheries (Secretaría de Medio Ambiente, Recursos Naturales y Pesca); SEMARNAT, Secretariat of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales); SEMIP, Secretariat of Energy, Mining and Semi-Public Industries (Secretaría de Energía, Minas e Industria Paraestatal); SENER, Secretariat of Energy (Secretaría de Energía); SG, system-to-be-governed; SIE, Energy Information System (Sistema de Información Energética); SLCPs, short-lived climate pollutants; SO_x, sulphur oxides; SPP, small power producer; T&D, transmission and distribution; TCP, Technology Collaboration Program; toe, tonnes of oil equivalent; TWh, terawatt-hour; US, United States.

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of fossil-fuel incumbent regimes, displacing clean energy technological niches; (2) lack of investment in clean energy research, development, and innovation; (3) policy paradigms have shifted based on (dynamic) societal needs and socio-political interests in favour of fossil fuel power generation. To overcome these barriers and allow a transition towards a clean energy electricity system in Mexico, multiple policy instruments have been identified and discussed.
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Introduction

There is a broad consensus that to put the world on a path to a reasonable climate future, significant reductions in greenhouse gas (GHG) emissions are necessary (Harvey et al., 2018). The vast majority of GHG emissions come from a small set of countries where the energy sector represents the main source of these emissions. Although Mexico has one of the lowest levels of carbon dioxide (CO_2) emissions per capita among the Organisation for Economic Co-operation and Development (OECD) countries (IEA, 2016), it is the world's 11th largest GHG emitter due to its fossil fuel-intensive energy mix (Harvey et al., 2018; Banacloche et al., 2020). In 2018, CO_2 emission from power and heat generation in Mexico accounted for 34.5% of total emissions from fuel combustion, being the highest pollutant activity nationwide (Banacloche et al., 2020).

Mexico is the eleventh-largest global economy by purchase power parity (PPP), and the second-largest in Latin America (IEA, 2017). It is expected to become the seventh-largest economy worldwide by 2050 (PwC, 2017). However, Mexico's growth has been achieved at the expense of its environment and society, exposing the country to severe climate change risks (IEA, 2016, 2017; Banacloche et al., 2020). Mexico is endowed with abundant (fossil and renewable) energy resources. Given the right mix of policy instruments, Mexico has the potential to develop clean energy and thus diversify its energy mix and significantly reduce its GHG emissions (IRENA, 2015a). To meet international climate pledges, Mexico has set ambitious national GHG emissions reduction targets (22% by 2030 from business as usual and 50% versus 2000 levels) (Jano-Ito & Crawford-Brown, 2016; Veysey et al., 2016). The largest contribution to GHG emissions reduction is expected from the electricity sector (IEA, 2017). Thus, targets for power generation from clean energy sources were established aimed at reaching a share of 35.1% in total electricity generation by 2024, 38.2% by 2030, and 50% by 2050 (DOF, 2020a). According to the (new) Electricity Industry Law (2014), clean energy technologies include renewable energy sources (geothermal, wind, solar, hydropower, biomass), as well as electricity generation through nuclear power, hydrogen, fossil-fired generation with carbon capture and storage (CCS), and efficient cogeneration (DOF, 2014a).

Mexico has a fast-growing electricity sector, with annual demand increasing 2.8% since 2000 (on average) and it is projected to increase by more than half by the end of the decade (IEA, 2017). Expediting the speed of Mexico's clean energy diffusion may result in annual net savings of up to USD 11.6 billion in the national energy system costs by 2030 (accounting for externalities such as health effects and carbon emission reductions) (IRENA, 2015a). However, limited progress has been made to date. As of 2019, electricity generation from clean energy technologies (not including cogeneration) was 65.1 TWh (20% of the total generation). The mix was composed mainly of hydropower (7%), followed by onshore wind (5%), nuclear (3%), geothermal (2%), and solar photovoltaic (PV) (2%) (IEA, 2021). Also, Mexico reached 448.5 million tonnes of CO_2 emissions from fuel combustion in 2018 (24% more than in 2000) (IEA, 2020a). Structural transformations in the Mexican electricity system have changed the way electricity is produced and used over time. A deeper understanding of the barriers (and drivers) of clean energy development in Mexico is needed to explore different pathways to achieve national energy and climate objectives.

The aim of this paper is to qualitatively describe the development of clean energy technologies in Mexico by using a multi-perspective analytical framework. By integrating a meta-theoretical framework for national energy transitions and relevant concepts from policy mixes for sustainability transitions literature, a series of stylised facts are developed to describe the evolution of clean energy technologies in Mexico from 1879 to 2021. Then these storylines are synthesised using an interactive governance approach to highlight the relative role of energy technologies, actors, and policy instruments (and the interactions among them) in governance processes. Although different analytical frameworks have been used to describe economic, technological, and socio-political changes in the Mexican electricity system at different periods in time (see, for instance, (García Lázaro, 2016; Jano-Ito & Crawford-Brown, 2016; Ramírez-Camperos et al., 2013)), the detailed evolution of clean energy technologies has received little attention and their development has been marginally described within a broader scope (i.e. electricity systems). Thus, the contributions of this paper are three-fold. First, this paper builds on previous studies on energy transitions by thoroughly describing the evolution of clean energy technologies in national electricity transitions, highlighting advances and setbacks in their diffusion. Second,

the period of analysis covers the national clean energy development since the first use of electricity in Mexico (1879) to date (2021), providing an updated comprehensive historical analysis. Third, the application of an integrative multi-perspective analytical framework contributes to the discussion on the design and development of national policy mixes towards a clean energy transition in Mexico by making a distinction between the economic, social, political, and technological aspects of the system and their interactions (opposite to a 'seamless-web' approach). The findings of the study contribute to the existing literature in the following ways. Drivers and barriers for deploying clean energy technologies in Mexico are identified and discussed. Also, potential policy instruments towards a clean energy transition in Mexico (based on current policy objectives, specific targets, and performance indicators) are discussed. The work is intended for energy policymakers, researchers, energy analysts, and energy practitioners.

The rest of paper is organised as follows. Section 2 presents the integrated analytical framework for describing the evolution of clean energy technologies in the electricity sector. Section 3 illustrates an empirical application of the framework to the Mexican case (1879–2021). The current (2021) policy objectives, specific targets, and performance indicators towards a clean energy transition in Mexico are presented in Section 4. In addition, potential policy instruments towards a clean energy transition in Mexico are discussed in this section. Drivers and barriers for a clean energy transition in Mexico are discussed in Section 5. Also, potential future research and conclusions are exhibited within this section.

Integrative analytical framework for techno-socio-economic systems in energy transitions

Multi-perspective analysis for national energy transitions

Energy (or electricity) transitions have been conceived as complex, long-term, multi-actor, dynamic, co-evolutionary processes of structural transformations regarding energy (or electricity) production and consumption (Castrejon-Campos et al., 2020). A single transition theory can be used to gain insights on these complex structural changes. However, by using multiple complementary theoretical approaches (e.g. political science, social studies, economics) energy transitions may be better explained and analysed (see, for instance, (Cherp et al., 2018; Turnheim et al., 2015)). Cherp et al. (2018) proposed a multi-perspective analytical framework to explain the long-term structural changes that occur in national energy systems through the analysis of three main co-evolving subsystems: (1) socio-technical subsystem, characterised by the interaction of different energy technologies; (2) techno-economic subsystem, defined by the energy that is supplied and used through the coordination of energy markets; and (3) socio-political subsystem, explained by the development and implementation of energy policy instruments that influence energy systems (Castrejon-Campos et al., 2020; Cherp et al., 2018). Within this meta-theoretical framework, multiple (complementary) concepts in the sustainability transitions literature are adopted to explain national energy transitions as co-evolving techno-socio-economic systems (see, for instance, (Cherp et al., 2017)). Similarly, Castrejon-Campos et al. (2020) suggested the integration of core concepts from the policy mixes literature to investigate the role of policy mixes in historical energy transitions. Concepts from the three perspectives (i.e. socio-technical, socio-political, and techno-economic) and policy mixes for sustainability transitions literature are used in this paper to gain insights on the role of clean energy technologies in historical electricity transitions, and to identify potential drivers (and barries) towards a clean energy transition in Mexico (see Fig. 1). Transitions in energy systems may occur derived from the interactions of diverse contextual drivers and barriers, with different relative influence from one phase to another. Thus, a more comprehensive explanation of these structural changes is sought by using multiple (yet complementary) sustainability and energy transitions concepts (Castrejon-Campos et al., 2020; Cherp et al., 2018).

In the socio-political perspective, the state is the focus of the analysis (Cherp et al., 2018). The adoption and implementation of policy instruments by the government include different (social, political, or special) interests based on the conceptualisation of 'state'. Policy objectives (e.g. economic growth, energy security, climate change mitigation, technological leadership, reliable access to electricity) are the main focus on state-centric approaches. Competing socio-political interests (e.g. voters' preference, political parties, social movements) and special interests (e.g. industrial lobbies) are the main factors that influence policy mixes within state-structural approaches (Cherp et al., 2018; Hall, 1993). Policy mixes for energy transitions comprise a strategic element (encompassing policy strategies, objectives, and specific plans/programs), the analysis of dynamic policy processes, and the examination of the role that institutions and relevant actors play in the design and implementation of policy instruments and the interactions among them (Rogge et al., 2017; Rogge & Reichardt, 2016). Institutions are defined as "structures and rules that enable and constrain state and other political actors" (Cherp et al., 2018). The role of institutions has been explored following different neoinstitutionalism (e.g. sociological, historical, and rational choice) and discursive institutionalism approaches (Hall, 1993). Within the latter a key concept is policy paradigm shift. A policy paradigm is "a pattern of framing policy problems and searching

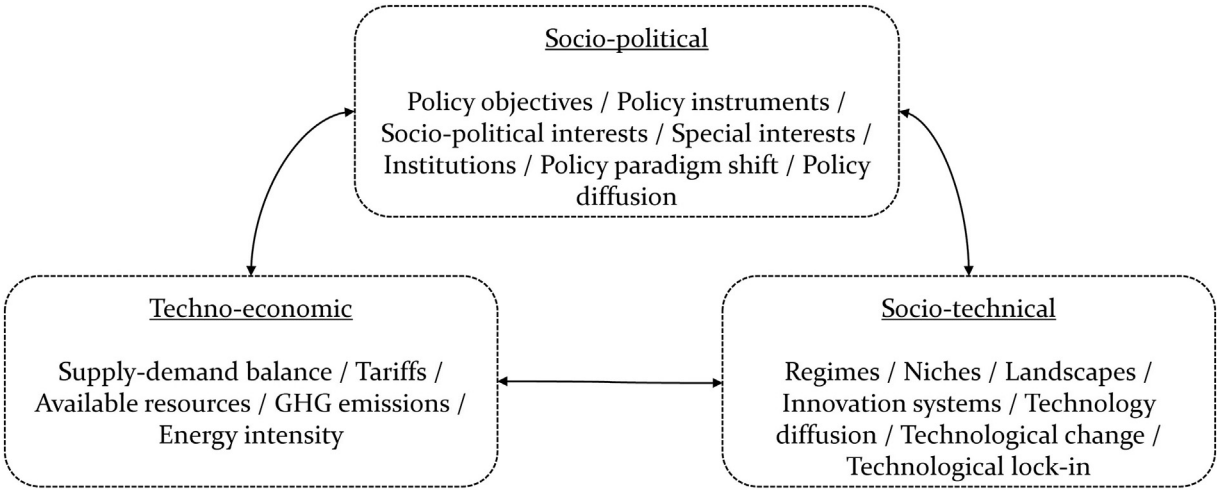


Fig. 1. Energy and sustainability transitions concepts used to explain national energy transitions.
Source: adapted from (Castrejon-Campos et al., 2020) with information from (Cherp et al., 2018; Rogge & Reichardt, 2016).

for solutions" (Cherp et al., 2018). A policy paradigm shift takes place when relevant social actors and the state agree on an alternative solution to or a different definition of a problem, highlighting the role of learning within this dynamic process (Hall, 1993). International relations theories aid to explain the phenomenon when countries with different characteristics adopt similar policies to deal with energy issues (e.g. energy crises). Pressures from international institutions, international harmonisation, best practices from other countries or international policy promotion may encourage the adoption of new or alternative energy policy instruments (i.e. policy diffusion). However, policies adopted from other countries may be not suitable/compatible with domestic structures (i.e. institutions and capacities).

According to the techno-economic perspective, the notion of supply-demand balance in electricity systems refers to the idea that any change in electricity supply or demand should be counterbalanced by analogous adjustments in other aspects of the electricity systems (Cherp et al., 2018). For instance, if domestic electricity demand is increasing, it must be met by expanding electricity generation or imports. On the other hand, if electricity generation is expanded using clean energy technologies, it must be accompanied by phasing out fossil-fuel sources of generation. Also, the idea of market equilibrium used within this perspective states that energy supply and demand are in a stable equilibrium if producers and consumers agree on prices/tariffs for electricity services. This is production, consumption, and trade in markets are in equilibrium under competitive markets (Cherp et al., 2018). Resources available for electricity production is another relevant aspect to be included within the analysis (e.g. fossil fuel deposits, uranium deposits, flows of water, solar radiation, average wind speed, heat flows from Earth). For instance, it may not be worth investing in building several geothermal power plants in countries like Australia, Brazil, or Russia, while in other places like New Zealand, Italy, or Mexico is worth doing it due to their geothermal potential (considering several environmental factors) (Coro & Trumpy, 2020). Increasing concerns on climate change mitigation and thus designing policy mixes aimed at reducing GHG emissions have posed special interest in understanding the evolution of energy systems. Mitigation strategies should be directed towards both energy generation and consumption. Thus, energy efficiency (e.g. through energy intensity analysis) has also become a relevant variable to be included within (quantitative) models to explore energy system pathways. Energy efficiency technologies may play a greater role in energy transitions due to their potential benefits: pollution reduction, public health improvement, and financial savings. Also, it has been argued that energy savings may be the fastest, cheapest, and most environmentally friendly mitigation strategy to meet energy needs in developing countries (Bauer, 2007; Nibedita & Irfan, 2021).

Within the socio-technical perspective, two main streams of research for transition studies have been used to explain energy transitions: technological innovation systems (Markard et al., 2012) (combination of innovation systems and technological systems) and socio-technical transition analysis (which includes frameworks such as transition management (Meadowcroft, 2009), strategic niche management (Kemp et al., 1998), and multi-level perspective (Geels, 2002)). These strands share the concepts of a socio-technical system, a (incumbent) socio-technical regime, and (technological) niches (Cherp et al., 2018). A socio-technical system is defined as a configuration of technologies, regulations and actors, services and infrastructure that fulfils a societal function (e.g. energy provision) (Schot et al., 2016). A socio-technical regime is defined as a shared set of routines and rules enclosed in a socio-technical system to assure they are able to meet relevant societal needs. Niches are socio-technical subsystems with less stable and more fluid boundaries, rules, practices, and actors (Cherp et al., 2018; Geels & Schot, 2007; Jano-Ito & Crawford-Brown, 2016). Within the multi-level perspective (MLP) framework (Geels, 2002), the regime must be destabilised by external pressures (i.e. landscapes) in order to give place to niches to fulfil the relevant function (Jano-Ito & Crawford-Brown, 2016). Innovations can be fostered by regimes to survive or expand, but they may hinder them if they represent a threat for their stability (Cherp et al., 2018). When the latter takes place, it is known as technological lock-in. Thus, industrial economies may "become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale" (also known as carbon lock-in) (Unruh, 2000). Contrarily, a regime shift may take place when incumbent regimes make room to newcomers emerging from previously protected niches (e.g. renewable energy technologies) (Cherp et al., 2017; Kemp et al., 1998). Regime shifts may enable technology transitions where a change in the proportion of energy produced by emerging energy sources (or technologies) occur (sometimes called energy additions (York & Bell, 2019)). Also, multiple explanations for technological change can be used within the socio-technical perspective by using concepts from technological innovation systems literature. For instance, learning processes focused on gaining knowledge and experience of a particular technology may occur through various channels. When the focus is on experience gained through production processes (i.e. technology deployment) learning may increase through learning-by-doing (Arrow, 1962), learning-by-using (Rosenberg, 1982), and/or learning-by-interacting (Lundvall & Andersen, 1988). On the other hand, when the focus is on increasing learning through innovation activities within the early stages of the innovation chain, learning may increase through learning-by-researching (Kouvaritakis et al., 2000). Huenteler et al. (2016) found quantitative support to the argument that improving national learning conditions (e.g. suitable organisational processes, skilled workforce) may have a significant impact on technology costs reductions and thus increase technology diffusion in developing countries. This highlights the important role of technological learning and innovation systems in energy transitions.

By using concepts from the three perspectives and policy mixes for sustainability transitions, an inventory of 'micro-logics' is formulated to explain specific elements or episodes of energy transitions (e.g. the role of clean energy technologies in electricity transitions). Interactive governance theory is proposed in this study to synthesise these micro-logics into a broader theoretical construct, as suggested in previous studies (see, for instance, (Cherp et al., 2018)).

Energy transitions and the interactive governance approach

Within the interactive governance approach, societal systems (e.g. energy systems) are the result of synergies between three main interrelated components: a governance system (GS), a system-to-be-governed (SG), and the governing interactions (GI) among these systems (Kooiman, 2016). A governance system includes the different mechanisms and processes for control, guidance, and steerage of the system-to-be-governed. The conceptualisation of the system-to-be-governed can take place under distinct analytical paradigms and at diverse scale levels depending on the nature and scope of the research inquiry (Kooiman, 2008; Kooiman & Bavinck, 2013). How to conceptualise the SG has been identified as a relevant analytical limitation in the interactive governance perspective (Jentoft, 2007). To overcome this caveat, this study uses the meta-theoretical framework described in the previous section to explore the role of clean energy technologies in national energy transitions as a co-evolving techno-socio-economic system (see Fig. 2) under the interactive governance approach. Governing interactions involves relevant relationships and influences between the main actors or social units in a specific governance setting (Kooiman, 2008; Kooiman & Bavinck, 2013). External forces (outside the control of the system of interest) may affect or influence the behaviour of societal systems and their interactions due to mutually influencing interactions with their external environment (Di Lucia, 2013; Jackson, 2002).

Although interactive governance has been applied mainly to one particular societal field (i.e. fisheries and aquaculture issues) (see, for instance, (Kooiman, 2016; Kooiman & Bavinck, 2013)), due to its broad

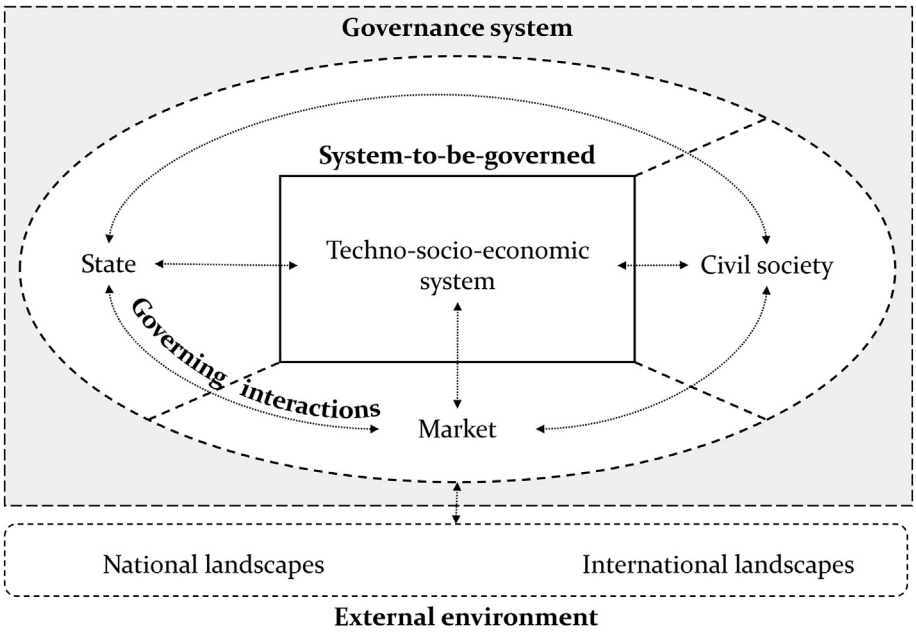


Fig. 2. Conceptualisation of societal systems under the interactive governance approach.
Source: adapted from (Hernández Ibarzábal, 2017; Kooiman, 2016).

scope and systematic analysis, it is gaining interest in other disciplines such as energy. For instance, interactive governance frameworks have been used to investigate the role of organisational governance and decision-making in Renewable Energy Cooperatives (REC) in Germany (Brummer, 2018). Di Lucia (2013) employed the concept of system governability to analyse the problems facing the governance of biofuels in the European Union. García Lázaro (2016) applied interactive governance theory to analyse the role of the state, private companies, and civil society in the public service of electric lighting in Mexico City (from 1881 to 1938). Similarly, Hernández Ibarzábal (2017) examined the governability of Mexico's natural gas sector under the Mexican constitutional energy reform approved in 2013 by applying an interactive governance approach. Also, governance of societal transitions has been gaining interest in social-ecological and environmental modelling (Halbe et al., 2020), sustainable innovations (Loorbach et al., 2020; Nilsson et al., 2012), and energy systems (Jano-Ito & Crawford-Brown, 2016; Kuzemko et al., 2016).

The interactive governance approach is used in this article to analyse governance processes focusing on the relative role of the market, the state, and the civil society in promoting clean energy development over time. The review of several documents and relevant datasets under a theoretical heuristic approach has been applied in this study as the principal analytical method used to describe the development of clean energy technologies in the electricity sector in Mexico. The review process derives in micro-logics that are presented as stylised facts and described in a qualitative manner (Moallemi et al., 2017). Then these qualitative storylines are synthesised under the interactive governance approach using the analytical framework described in this section (see Fig. 3).

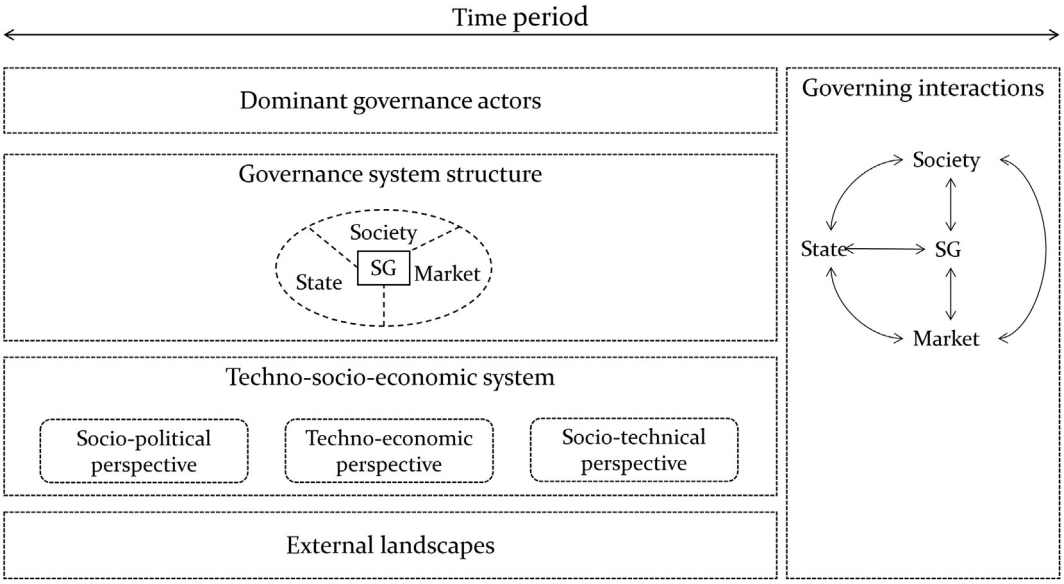


Fig. 3. Analytical framework for describing the development of clean energy technologies in electricity transitions.

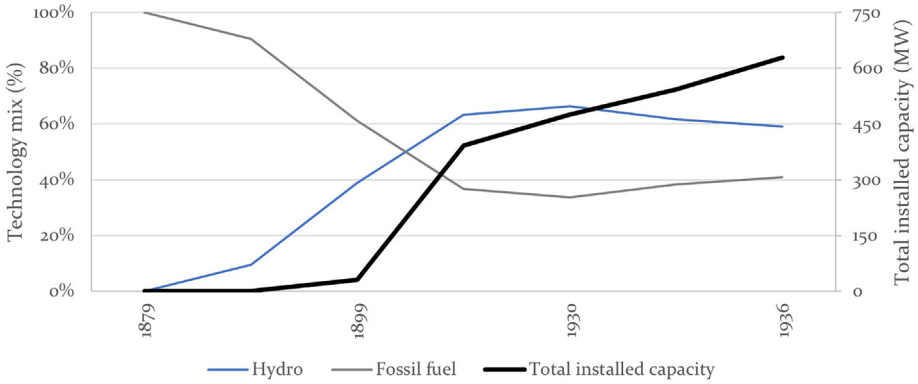


Fig. 4. Shares of technology mix (left) and total installed capacity (right) from 1879 to 1936.
Source: elaborated with data from (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a; Solis Rojas, 2012; INEGI, 2015).

Clean energy development in Mexico

The early stages of the electricity sector in Mexico (1879–1949)

The first equipment used for electricity generation in Mexico was a 1.8 kW (coal-fired) thermal plant installed in a textile factory for lighting purposes in the city of León, Guanajuato in 1879 (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a; García Lázaro, 2016; Jano-Ito & Crawford-Brown, 2016). During the following ten years from the origin of the power sector in Mexico, electricity was completely generated from conventional thermal technologies (e.g. coal/oil-fired). The first recorded use of hydroelectric power in Mexico dated from 1889 in the state of Chihuahua (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a). Clean energy technologies have had different development time frames due to diverse drivers and barriers over time as described in the following sections.

During the early stages of the electricity sector in Mexico, national ***policy objectives*** set by the government of Porfirio Díaz (1884–1911) were focused mainly on economic growth and progress. Thus, different economic ***policy instruments*** were implemented aimed at modernising the country through foreign investment and the adoption of technological developments in other parts of the world (i.e. cross-border ***technology diffusion***). For instance, technology diffusion from Europe and the United States (US) was promoted by the administration of Díaz by offering exemptions from paying taxes when electrical equipment was imported and installed in Mexico. Also, national progress was sought through the exploitation of domestic natural resources. Although electricity generation was dominated by conventional thermal technologies, the extensive ***water resources available*** in Mexico allowed the rapid development of hydropower (see Fig. 4), resulting in a ***technology transition*** from thermal to hydro.

From 1879 to 1936 the ***governance system*** was controlled mostly by the market (mainly private monopolies) with little ***state intervention*** in relevant decision-making processes such as expansion planning. Thus, private companies focused on increasing profits by supplying services to certain regions and/or customers. This mode of ***self-governance*** was not in line with ***policy objectives*** of national economic development, bringing multiple socio-political tensions to the regime (e.g. different electricity tariffs for different regions and customers, poor labour conditions, lack of service in rural areas). Acknowledging the ***societal needs*** of increasing access to electricity nationwide and improving services supplied by private companies (Wionczek, 1965), the government of Lázaro Cárdenas (1934–1940) created the Federal Electricity Commission (Comisión Federal de Electricidad, CFE) aimed at increasing state's participation in governing processes through a state-owned electricity company and consolidating a national electricity system (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a). In line with the creation CFE, the Electricity Industry Law was approved by the Mexican Congress in 1939. This ***policy instrument*** established a set of regulations for the whole electricity supply chain with a particular focus on meeting ***societal needs*** (e.g. expanding electricity services at fair prices) (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a). For instance, concessions for new power generation projects were awarded based on higher social benefits with the most efficient use of natural resources. Also, the state extended its presence within the ***governance system*** by regulating and defining electricity tariffs through the Secretariat of Economy (Secretaría de Economía, SE).

Within the energy sector, the creation of Mexican Petroleum (Petróleos Mexicanos, PEMEX) as a state-owned oil company and the expropriation of private oil companies in 1938 were relevant domestic ***landscapes*** that affected the electricity sector in later years (Jano-Ito & Crawford-Brown, 2016). Fig. 5 depicts the principal actors and institutions in the electricity sector by 1950. The size of the circles illustrates the relative importance of their role in governance processes. Based on the sources reviewed and presented in this paper, the values for the size of the circles were subjectively determined.

The most important ***technological changes*** occurred towards the development of clean energy technologies during this period were the construction of the fist large-size (28 MW) hydropower system (Miguel Alemán) and the ***technology transition*** from horizontal to vertical axis turbines (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a). Fig. 6 and Table 1 depict the snapshot for the early stages of the electricity sector under the interactive governance approach.

The beginning of alternative energy technologies in Mexico (1950–1972)

Policy objectives within the electricity sector from 1937 to 1959 focused on the development of the sector by providing financial support to both private and public electricity companies (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a). Thus, the Rural Electrification Program was introduced in 1952 as a ***policy instrument*** aimed at expanding access to electricity to rural areas (a relevant social gap arisen from market dynamics) and fostering national development (Jano-Ito & Crawford-Brown, 2016). The primary role of CFE during its beginnings was to design and implement solutions to meet these ***societal needs***. Although electricity production was dominated by hydropower and fossil fuel technologies (mainly steam) in similar proportions from 1950 to 1972 (see Fig. 7), other ***technological niches*** received attention during this period such as geothermal energy.

In 1955 the Geothermal Energy National Commission (Comisión Nacional de Energía Geotérmica, CNEG)[1] was created to study possibilities and developments of geothermal energy in Mexico (before 1955

[1] The CNEG was sponsored by CFE, Mexico's central bank, and Nacional Financiera (NAFINSA). The CNEG was dissolved in 1971 and the CFE's Geothermal Division took charge of geothermal development in Mexico.

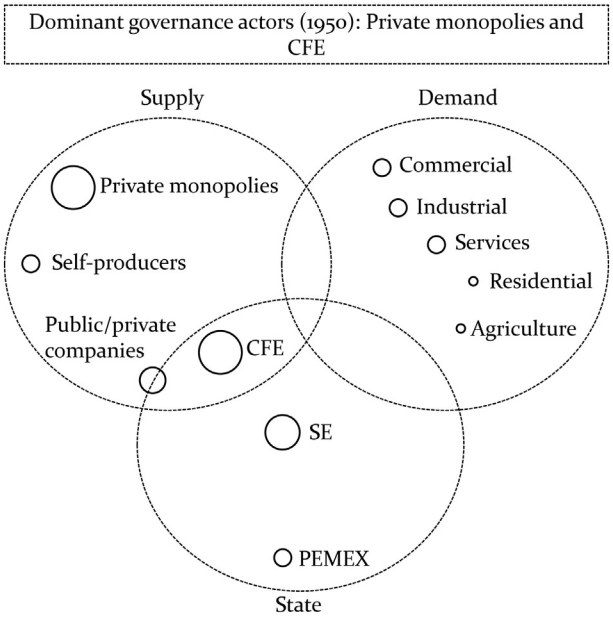


Fig. 5. Main actors within the governance system by 1950. Source: adapted from (Jano-Ito & Crawford-Brown, 2016) with information from (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a).

Table 1
Electricity system snapshot under the interactive governance approach (1879–1949) – governing interactions (actor level).
Source: elaborated with information from (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a; Jano-Ito & Crawford-Brown, 2016).

From	Interactions	To
Market	Pressure for increasing service concessions. Pressure for better investment conditions.	State
Market	Promotion of productivity improvement through electricity services.	Society
State	Promotion of technology diffusion through economic incentives. Intervention in conflict resolution. Pressure for improving supply services. Pressure for expanding services to rural areas.	Market
State	Intervention in conflict resolution. Promotion of increasing access to electricity nationwide. Promotion of development and modernisation of the sector.	Society
Society	Pressure for electricity access in rural areas. Pressure for intervention in work rights. Pressure for intervention in tariff regulation and control.	State
Society	Pressure for competitive tariffs. Pressure for improving work conditions (e.g. workload, salaries).	Market

several places with hydrothermal springs were known in the country – mainly used for recreation and bathing– underlining the national potential for electricity generation). Thus, the first 3.5-MW geothermal (demonstrative) power plant was installed in 1959 in the Pathé geothermal field, in the state of Hidalgo (Jano-Ito & Crawford-Brown, 2016). The plant was a CFE's acquisition from the Larderello geothermal field in Italy, where installed capacity had reached almost 300 MW by 1950 (Lund, 2005). The power plant never operated at full capacity in Mexico due to insufficient steam, however it remained operating until 1973 (Quijano-León & Gutiérrez-Negrín, 2003). A ***technological learning*** process based on *learning-by-using* (Rosenberg, 1982), *learning-by-doing* (Arrow, 1962), and *learning-by-researching* (Kouvaritakis et al., 2000) took place over the following years. This is, knowledge may flow across countries in two main forms: embodied in traded intermediate or final goods (e.g. pilot plants, solar panels, wind turbines) or disembodied in patents, blueprints, exchange of ideas among researchers or scientific bodies, and imitation (Bosetti et al., 2008). In order to increase (disembodied) technological knowledge, in the 1960's personnel from CFE were commissioned to study the development of geothermal energy reached in New Zealand (González Quiñones, 2015). This highlights the relevant role that international spillovers play in the process of ***technology diffusion*** for nascent technologies (e.g. geothermal in this case) from ***core countries*** (e.g. Italy or New Zealand) to ***periphery*** countries (such as Mexico). Also, CFE started geological, geochemical, and geophysical studies in the state of Baja California since 1958 (González Quiñones, 2015). Exploration, drilling, and exploitation activities progressed during the 1960's and early 1970's until the first large-scale geothermal field started commercial production in 1973 in Cerro Prieto (Baja California) with a 37.5-MW unit (Jano-Ito & Crawford-Brown, 2016).

A ***policy paradigm shift*** focused on autonomy and nationalism arose during this period due to different tensions within the ***regime*** (e.g. dissimilar electricity prices along the country, the need for national access to electricity, and the existence of several electricity systems not

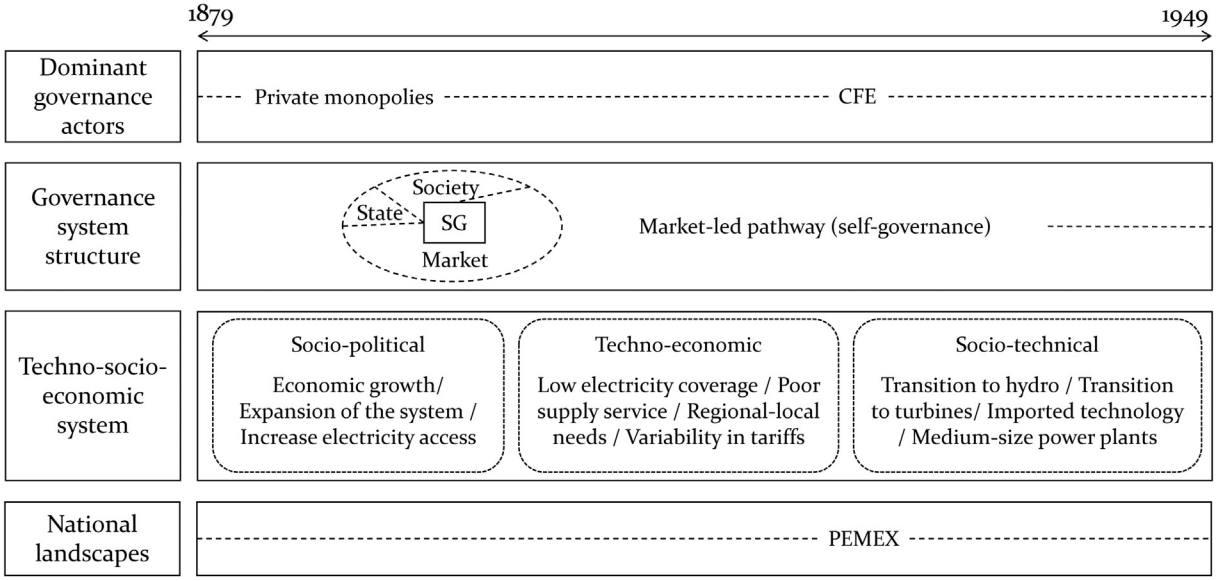


Fig. 6. Electricity system snapshot under the interactive governance approach (1879–1949) –system-to-be-governed, governance system, and external landscapes.

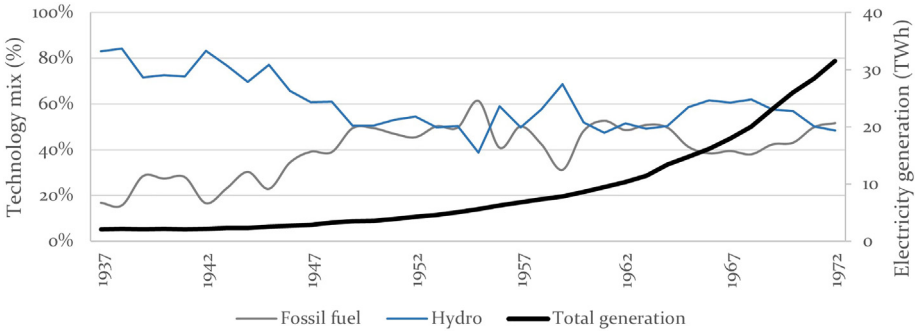


Fig. 7. Shares of technology mix (left) and total electricity generation (right) for public service (1937–1972).
Source: elaborated with data from (Sarabia Bueno & Rodríguez y Rodríguez, 1994).

interconnected) (Carreón-Rodríguez et al., 2007). For instance, despite efforts by CFE in expanding electricity services to rural areas, only 44% of the population had access to electricity by 1960. Following the nationalistic feelings derived from the oil and gas sector, the nationalisation of the electricity industry occurred in 1960 during López Mateos' administration (1958–1964). Thus, the state carried out a complex acquisition process until the last private corporation was acquired in 1973 (Carreón-Rodríguez et al., 2007; Jano-Ito & Crawford-Brown, 2016). With a state-owned energy system, investment decisions in the electricity sector were significantly influenced by PEMEX as the dominant player in the oil and gas sector, promoting the use of fuel oil for power generation (Jano-Ito & Crawford-Brown, 2016).

During Luis Echeverría's government (1970–1976) a particular interest on science and technology emerged, resulting in the creation of the National Council of Science and Technology (Consejo Nacional de Ciencia y Tecnología, CONACYT) in 1970. CONACYT's aim was to design, develop, and implement ***policy mixes*** on innovation activities (including research and development (R&D)) on strategic sectors (e.g. the energy sector) (González Quiñones, 2015). Although this was an important national ***landscape***, CONACYT's role in promoting clean energy technologies was limited until 2008. Fig. 8 depicts the key actors in the electricity sector by 1972. Fig. 9 and Table 2 represent the electricity system snapshot for the period from 1950 to 1972.

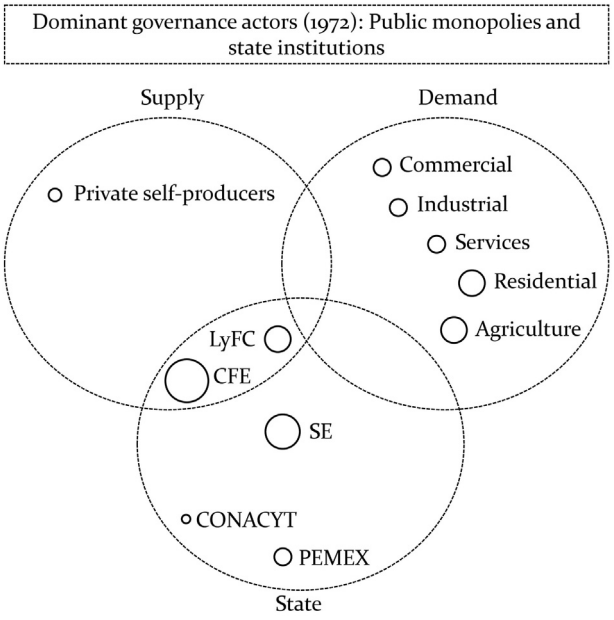


Fig. 8. Main actors within the governance system by 1972.
Source: adapted from (Jano-Ito & Crawford-Brown, 2016) with information from (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a; González Quiñones, 2015). LyFC: Compañía de Luz y Fuerza.

The early stages of clean energy technologies in Mexico (1973–2007)

The nationalisation process formally ended up in 1975 when the Public Service Electricity Law (Ley del Servicio Público de Energía Eléctrica) was published. According to this new law (which derogated the previous Electricity Industry Law), the only electricity suppliers for public service in Mexico were CFE and Compañía de Luz y Fuerza (LyFC) (including generation, transmission, distribution, and commercialisation) (Jano-Ito & Crawford-Brown, 2016). Electricity production for private companies was allowed under the self-producers scheme only if state-owned electricity companies were unable to provide the service to them (e.g. due to technical issues). Thus, private generation accounted for around 7% of the total electricity generated annually from 1975 to 1999 (see Fig. 10).

A relevant external ***landscape*** that affected several energy systems worldwide in 1973 was the international oil crisis.[2] The oil supply disruptions around the world highlighted the importance of energy planning with a particular focus on technology diversification. In Mexico, following the efforts on science and technology, the state supported innovation activities and technology development for both the ***incumbent regime*** (i.e. hydropower and fossil-fuel technologies) and new ***technological niches*** (e.g. coal, natural gas-fired technologies, geothermal, wind, solar, and nuclear). With the objective of performing R&D activities, as well as technological innovation on electricity production from alternative energy sources (including wind, solar, geothermal, and biomass), a new state-owned institution was created in 1975, the National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias, INEEL[3]) (González Quiñones, 2015; Huacuz Villamar, 2016). INEEL's R&D activities on clean energy technologies started by mapping the potential for electricity generation based on the availability of these sources (including data gathering and analysis) (Huacuz Villamar, 2016). Similarly, two public institutions were established in 1979 to regulate and conduct R&D activities on nuclear matters: the National Commission for Nuclear Safety and Safeguards (Comisión Nacional de Seguridad Nuclear y Salvaguardias, CNSNS) and the National Institute for Nuclear Research (Instituto Nacional de Investigaciones Nucleares, ININ). Even though several energy-related activities were carried out by different public organisations, the Secretariat of Energy (Secretaría de Energía, SENER[4]) was created in

[2] As a result, the International Energy Agency (IEA) was created in 1974 (initially) aimed at helping with the co-ordination of a collective response to major disruptions in oil supply.

[3] Before Electricity Research Institute (Instituto de Investigaciones Eléctricas, IIE).

[4] Before Secretariat of Energy, Mining and Semi-Public Industries (Secretaría de Energía, Minas e Industria Paraestatal, SEMIP).

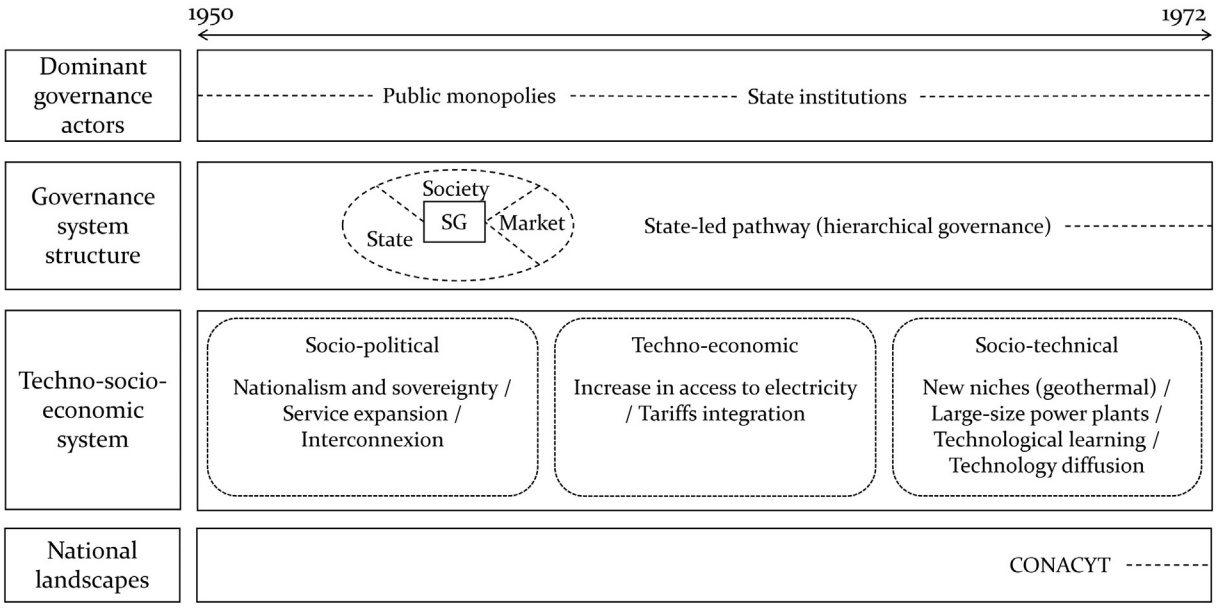


Fig. 9. Electricity system snapshot under the interactive governance approach (1950–1972) – system-to-be-governed, governance system, and external landscapes.

1982 to coordinate these efforts and to design, develop and implement ***energy policy mixes*** at a national level.

Although an (international) interest in alternative energy sources emerged after the oil crisis, electricity supply and demand in Mexico were significantly affected by a national ***landscape*** known as the Mexican oil boom (Sanchez, 1983). With substantial ***oil resources available*** for Mexico after the discovery of the Cantarell Complex in 1976 and aiming at exploiting the rising oil prices at the time, electricity production was led by fossil fuel technologies displacing alternative technologies (hydropower and geothermal). However, the 1982 economic crisis in Mexico was another national ***landscape*** that changed the direction of energy production and consumption. Thus, energy efficiency, technology mix diversification, and environmental protection gained interest in the energy policy agenda. The General Law for the Ecological Equilibrium and Protection of the Environment (Ley General del Equilibrio Ecológico y la Protección al Ambiente, LGEEPA) was enacted in 1988 as a ***policy instrument*** to cope with environmental concerns in different strategic sectors (with an impact on the electricity generation in subsequent years) (Jano-Ito & Crawford-Brown, 2016). Also, aimed at designing and implementing ***policy instruments*** on energy efficiency, the National Commission for the Efficient Use of Energy (Comisión Nacional para el Uso Eficiente de la Energía, CONUEE[5]) was created in 1989. Similarly, CFE developed in 1989 the Program of Energy Savings in the Electricity Sector (Programa de Ahorro de Energía del Sector Eléctrico, PAESE) aimed at identifying and designing ***policy instruments*** to save electricity withing the power sector. Due to PAESE's limited budget, CFE created in 1990 the Trust for the Saving of Electric Energy (Fideicomiso para el Ahorro de Energía Eléctrica, FIDE) to support and implement electric-efficiency programs (e.g. replacement programs for refrigerators, air conditioning, and fluorescent lights, minimum energy efficiency standards for appliances, energy consumption labelling/sealing, and training programs) (Bauer, 2007; de Buen-Rodríguez, 2007; Friedmann & Sheinbaum, 1998). Fig. 11 shows the total electricity consumption per unit of GDP (i.e. electricity intensity) for this period, highlighting the role of these programs in electricity efficiency improvements (complementary to technological improvements in power generation). Mexico's electricity intensity declined by 34% from 1973 to 2007.

[5] Before National Commission for Energy Saving (Comisión Nacional para el Ahorro del Energía, CONAE).

The first efforts on renewable energy development (additional to hydropower and geothermal) in Mexico focused on rural areas (i.e. off-grid applications such as small wind turbines for water pumping, solar kitchens, solar heaters, and biogas production) (Huacuz Villamar, 2016). The Mexican government included small-scale off-grid renewable energy systems for rural electrification as an important component of the National Solidarity Program (Programa Nacional de Solidaridad, PRONASOL) launched in 1989 (Foster & Pate, 1992). Hybrid systems (solar and wind) were initially thought as a solution to supply electricity to rural areas when expansion of the grid was considered costly and technically challenging (e.g. difficulties to build transmission and distribution lines) (Huacuz Villamar, 2016).

The development of (pilot) wind projects in Mexico started in the late-1970's. For instance, a 1.5-kW horizontal-axis wind turbine was installed in INEEL's experimental station named El Gavillero (State of Mexico) in 1979 with the objective of charging electric batteries and bringing lighting to the station. However, mainly due to financial constrains the development of wind turbines within the institute stopped

Table 2
Electricity system snapshot under the interactive governance approach (1950–1972) – governing interactions (actor level).
Source: elaborated with information from (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a; de la Garza, Melgoza, de la Garza, Laviada, et al., 1994b; Jano-Ito & Crawford-Brown, 2016).

From	Interactions	To
Market	Pressure for increasing financial support. Pressure for promoting technological development and innovation.	State
Market	Promotion of competitive tariffs (social benefits). Promotion of service expansion towards rural areas.	Society
State	Pressure for improving supply services. Intervention on planning processes (e.g. expansion of the system). Pressure for system interconnexion nationwide. Intervention on tariff regulation (including subsidies). Pressure for expanding services to rural areas.	Market
State	Promotion of increasing access to electricity. Promotion of tariff reduction for some sectors (subsidies). Promotion of better electricity supply services.	Society
Society	Pressure for increasing government incentives (e.g. subsidies). Pressure for expanding electricity services.	State
Society	Pressure for reducing electricity tariffs. Pressure for enhancing supply services.	Market

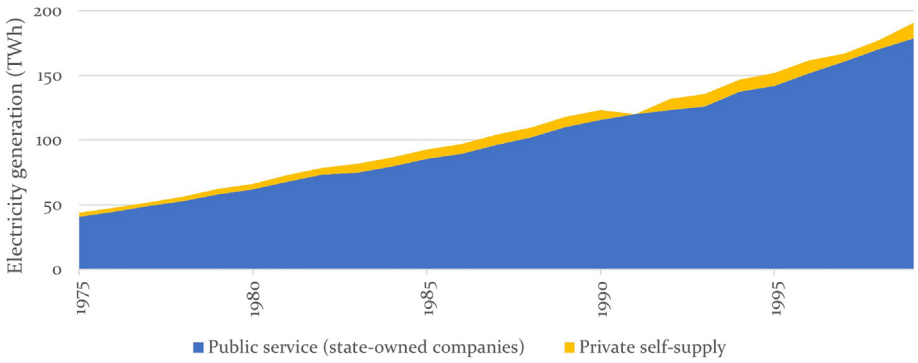


Fig. 10. National electricity generation (1975–1999).
Source: elaborated with data from (IEA, 2021).

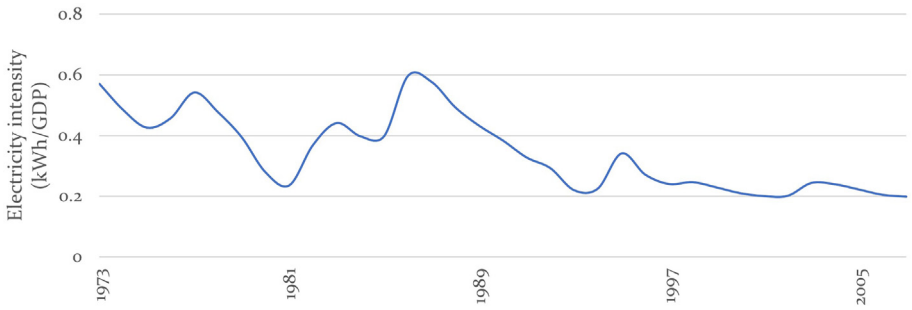


Fig. 11. Electricity intensity from 1973 to 2007.
Source: elaborated with data from (The World Bank, 2021; OECD, 2021).

for almost 15 years (Huacuz Villamar, 2016), resulting in ***knowledge obsolescence*** (i.e. knowledge created was lost over time). From the mid-1980's other small-scale wind projects (a few kW) were developed with public and private participation (mainly decentralised projects) (Jano-Ito & Crawford-Brown, 2016; Ruiz et al., 2008).

Although interest from the government on building a nuclear facility started after the nationalisation of the sector, due to internal and external issues its construction was delayed several years until the first nuclear power plant (Laguna Verde) commenced functions in 1990 (Jano-Ito & Crawford-Brown, 2016). Also, geothermal exploration and drilling activities continued in different parts of the country, which led to the opening of different large-scale geothermal fields: Los Azufres (Michoacán) with 5 MW in 1982, Los Humeros (Puebla) with 6 MW in 1990, and Las Tres Vírgenes (Baja California Sur) with 10 MW in 2002 (Gutiérrez-Negrín & Quijano-León, 2004; Jano-Ito & Crawford-Brown, 2016; Quijano-León & Gutiérrez-Negrín, 2003).

The North American Free Trade Agreement (NAFTA) signed by the US, Canada, and Mexico, which negotiations started in 1991, was another relevant ***landscape*** that increased international cooperation and trade in strategic sectors (including the energy sector) between the three countries. Thus, the Mexico-US Renewable Energy Cooperation Program (Programa de Cooperación en Energía Renovable, PROCER) was established in 1991 aimed at working on technical, financial, and institutional issues on renewable energy development in Mexico (Foster & Pate, 1992). The same year CFE created the Office for New Energy Sources, aimed at coordinating projects related to solar, wind, biomass, and hybrid systems (Ruiz et al., 2008). Similarly, the Mexico Renewable Energy Program was launched in 1994.[6] The goals of the program were to increase the use of renewable energy technologies in Mexico, increase the economic, social, and health standards in rural communities, and increase quality and reduce costs of renewable energy technologies by expanding markets for the US industry (Ruiz et al., 2008). Around 400 renewable energy systems were installed in different states within Mexico by 2000 derived from this program (Hanley et al., 2000). It has been suggested that the main beneficiary of the activities promoting solar energy in Mexico was the PV industry in US aimed at creating a captive market for its products (Ruiz et al., 2008). Also, the Shared Risk Fiduciary Fund (Fideicomiso de Riesgo Compartido, FIRCO) was created in 1994 to help with the installation of photovoltaic systems in the agriculture sector by providing financial aid (Jano-Ito & Crawford-Brown, 2016).

After the nationalisation of the electricity industry, the electricity sector was mainly financed by loans from the World Bank, loans from the Inter-American Development Bank, bilateral loans, supplier credits, and federal resources (Ramírez-Camperos et al., 2013). However, during Salinas de Gortari's administration (1988–1994) the Mexican energy sector faced several economic and financial issues: the state's lower export revenues due to the fall in oil prices in the international oil market; the increasing debt of state-owned electricity companies due to a fee-structure policy focused on granting subsidies for some sectors (not adjusted for inflation) and new credit conditions set by international organisations (unsustainable foreign debt); the lack of management autonomy of CFE; and the inability of the state to invest in new (high-capital) projects to meet the rapid growing demand (jeopardising the ***supply-demand balance***). These factors motivated Salinas de Gortari to adopt a ***policy paradigm*** towards liberalisation and free markets aimed at reducing public expenditure on new infrastructure for sectoral development (Ramírez-Camperos et al., 2013).

Relying on a neoliberal thought of 'less state intervention' seen in other parts of the world (i.e. ***policy diffusion***), Salinas' administration started a process of liberalisation in the electricity sector. In 1992 the

[6] The program was sponsored by the US Department of Energy (USDOE) and the US Agency for International Development (USAID), in partnership with Mexican state and federal organisations and international environmental groups. The program was managed by the Sandia National Laboratories.

Mexican Congress approved President Salinas' proposal to reform the Public Electricity Service Law aimed at incorporating private investment into electricity generation activities. State-owned electricity companies kept the ownership of transmission and distribution lines, however private companies could generate power under six new schemes: (1) independent power producer (IPP), (2) cogeneration power producer (CPP), (3) power self-supplier (PSS), (4) small power producer (SPP), (5) power imports (PI), and (6) power exports (PE). In addition, private electricity generation for self-supply, approved before the new law entered into force, maintained their validity under the continuous self-supply (CSS) modality (for a description of these modalities see (Jano-Ito & Crawford-Brown, 2016; Ramírez-Camperos et al., 2013)). The Energy Regulatory Commission (Comisión Reguladora de Energía, CRE) was established in 1993 to regulate the development of the electricity sector considering these new participants in the market[7] (Jano-Ito & Crawford-Brown, 2016). Fig. 12 shows the key actors in the electricity system by 1993.

A relevant international ***landscape*** in this period was the incorporation of Mexico as an OECD member in 1994, opening access to information exchange (e.g. best practices) and fostering international cooperation on energy matters. However, the Mexican economic crisis of 1994 resulted in an acute recession that affected different strategic sectors. This national ***landscape*** had a positive effect on the speed of liberalisation processes in the electricity sector. While the reform to the Public Service Electricity Law was passed in 1992, due to the complexity of several administrative processes, the first permit for electricity generation to an IPP was approved in 1997 (to Applied Energy Services) and commercial production started in 2000 (Jano-Ito & Crawford-Brown, 2016). State-owned companies generated 58% (178.8 TWh) of the total electricity produced within the country in 2012 (see Fig. 13), and the rest was generated by private companies (27% by IPPs for public service and 15% for self-supply). This highlights the role of private companies to meet societal needs such as increasing electricity demand.

Diversification of energy technologies within the electricity sector was led by natural gas-fired technologies (mainly natural gas combined cycle (NGCC)), transitioning from fuel oil to natural gas. This may be explained by multiple factors: the liberalisation process across other countries (i.e. ***policy diffusion***), the deregulation of the natural gas sector in Mexico in 1995, the technological progress in natural gas burning technologies (i.e. ***technology diffusion***), environmental regulations, and the low prices of natural gas. For instance, new regulations on highly pollutant greenhouse gases such as sulphur oxides (SO_x) and nitrogen oxides (NO_x) were set in 1994 by the Secretariat of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT[8]) in line with the LGEEPA law. These new environmental standards posed a significant limitation in electricity production from burning high-sulphur fuel oil within main industrial and metropolitan zones (Barnés-Regueiro et al., 2002), resulting in the promotion of natural gas as a substitute (Jano-Ito & Crawford-Brown, 2016). Also, the decrease in natural gas prices in the US (mainly derived from the production from unconventional sources) has reinforced the use of this fuel for electricity generation in Mexico since the 2000's, creating a ***technological lock-in*** effect as investments in new infrastructure tend to favour large-scale fossil fuel-based power plants due to economies of scale (Unruh, 2000).

Although power generation from wind and solar PV started in 1990[9] (mainly small-scale off-grid projects in rural areas), the first medium-scale (1.57 MW) wind power plant was installed in 1994 in La Venta, Oaxaca (owned by CFE) and the first large-scale (5 MW) solar PV development commenced operations in 2012 (also a project developed by CFE) (Jano-Ito & Crawford-Brown, 2016). Fig. 14 depicts the total electricity generation nationwide as well as the shares of fossil fuel and clean energy technologies from 1974 to 2007.

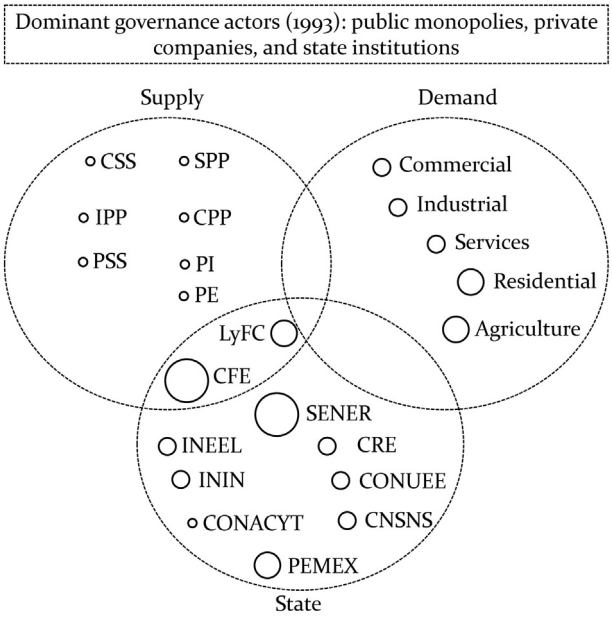


Fig. 12. Main actors within the governance system by 1993.
Source: adapted from (Jano-Ito & Crawford-Brown, 2016) with information from (de la Garza, Melgoza, de la Garza, Laviada, et al., 1994a; Huacuz Villamar, 2016; Ramírez-Camperos et al., 2013).

Starting in 2001, a series of measures were established aimed at improving grid access for renewable energy technologies (see Table 3). These measures were contemplated through the 'grid interconnection contract' (IRENA, 2015a; IRENA, 2015b).

The signature of the Kyoto Protocol from the Mexican government in 1998 (and its ratification in 2000) confirmed its international commitment on climate change mitigation. However, the first national ***policy instrument*** focused on combating climate change was the National Climate Change Strategy published in 2007. The strategy aimed at reducing GHG emissions by fostering energy production from alternative sources (i.e. mix diversification) and promoting savings in energy consumption (i.e. energy efficiency) (Jano-Ito & Crawford-Brown, 2016). Fig. 15 and Table 4 represent the electricity system snapshot for this period.

Promoting clean energy development (2008–2018)

The recent development of clean energy for power generation in Mexico started in 2008 with the Law for the Use of Renewable Energy and the Financing for the Energy Transition (Ley para el Aprovechamiento de las Energías Renovables y el Financiamiento de la Transición Energética, LAERFTE). LAERFTE's objectives were to regulate the use of clean energy technologies for non-public service (i.e. self-supply) and set an energy transition national strategy. As a result, a remarkable interest from private sector to develop renewable energy projects (mainly wind) was evident in the system (see Fig. 16) (IRENA, 2015a). Thus, additional measures for grid connection were established since 2010 (see Table 5). Also, as part of Mexico's low-carbon strategy, the Sustainable Use of Energy Law (Ley para el Aprovechamiento Sustentable de la Energía, LASE), and the Bioenergy Law (Ley de Promoción y Desarrollo de los Bioenergéticos, LPDB) were published in 2008.

[7] After the deregulation of natural gas in 1995, regulation on activities related to natural gas and transport of liquified natural gas through pipelines were included in CRE's responsibilities (Ramírez-Camperos et al., 2013).

[8] Before Secretariat of the Environment, Natural Resources and Fisheries (Secretaría de Medio Ambiente, Recursos Naturales y Pesca, SEMARNAP).

[9] The annual average power generation from wind technologies was 1 GWh/year from 1990 to 1993 (<0.001% of total generation). Similarly, the annual average electricity generated from solar PV was 10 GWh/year from 1990 to 2011 (<0.005% of total generation).

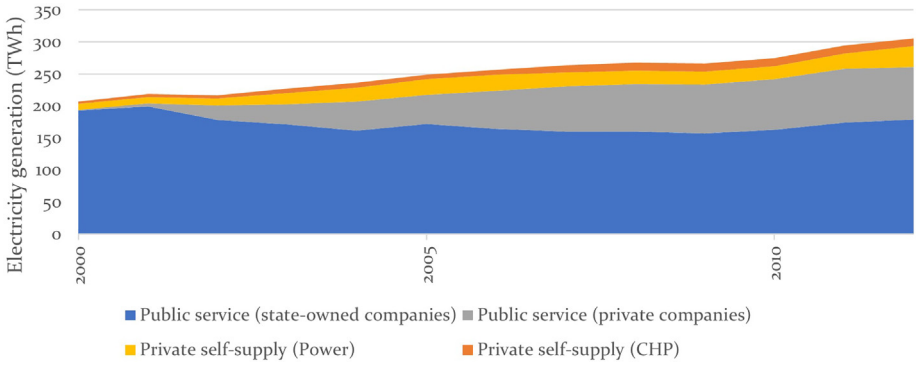


Fig. 13. National electricity generation (2000−2012).
Source: elaborated with data from (IEA, 2021).

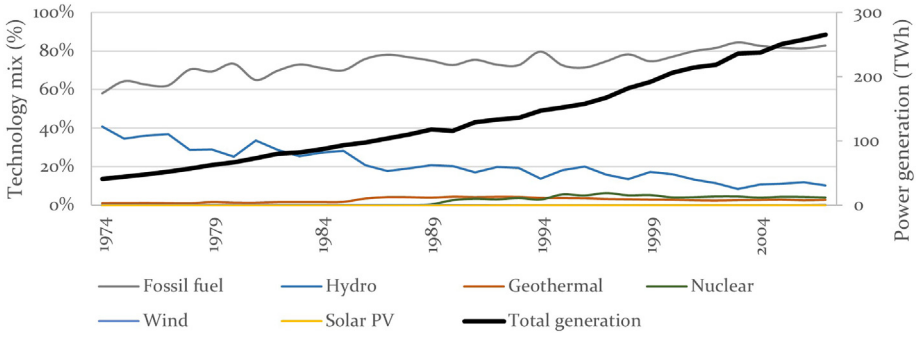


Fig. 14. Shares of technology mix (left) and total electricity generation (right) (1974–2007).
Source: elaborated with data from (IEA, 2021; Sarabia Bueno & Rodríguez y Rodríguez, 1994;SENER, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2021).

The 2008 global economic crisis was an international ***landscape*** that affected most financial and economic markets worldwide. In Mexico, multiple ***policy instruments*** were implemented by the state with the objective of reducing the impacts of the recession and fostering economic progress through strategic sectors. Within the electricity sector, electricity tariffs were reduced for some sectors (e.g. industry) and frozen for residential consumers (Sidaoui et al., 2011). Also, public expenditures were allocated to develop technological R&D activities to overcome technical issues on electricity generation, improve technology performance, and support technology niche markets (e.g. wind, solar, and geothermal). In line with the ***policy objective*** of strengthening and improving innovation systems, the state created the Energy Sustainability Fund (Fondo de Sustentabilidad Energética, FSE) in 2008, jointly led by CONACYT and SENER. The main objective of the fund is to support research, development, and demonstration (RD&D), technological innovation, sustainable energy development, and human capital training in key areas (SENER, 2013a; SENER, 2017a). An important initiative derived from public investment in RD&D for clean energy technologies was the creation of the first Mexican Energy Innovation Centres (Centros Mexicanos de Innovación en Energía, CEMIEs) in 2013 (Geothermal, Solar, and Wind). As of 2018, around USD 172 million had been allocated to clean energy technology projects (see Fig. 17). Also, direct funding for (mainly) energy efficiency programs was provided by the Energy Transition Fund (Fondo para la Transición Energética y el Aprovechamiento Sustentable de la Energía, FOTEASE) established in 2009 (SENER, 2020). Since its creation and until 2019 the FOTEASE fund has received around USD 465 million from the federal budget and has financed 53 projects (with 9.4% of the resources allocated to renewable energy projects and the rest used for projects with an energy efficiency component). Funded projects include the development of a renewable energy National Inventory, the publication of a Renewable Energy Atlas, and multiple projects on distributed generation, public lighting, and electromobility (IRENA, 2015b; SENER, 2020). Electricity intensity kept relatively constant during this period (see Fig. 18).

Another relevant national ***landscape*** in 2009 was the dissolution of the public power company LyFC (which operated in Mexico's central region). This decision was made based on the evident lack of operational and administrative efficiency from the state-owned company; thus, all activities and responsibilities were transferred to CFE (Jano-Ito & Crawford-Brown, 2016). An international ***landscape*** was the creation of the International Renewable Energy Agency (IRENA), being Mexico a member since its creation in 2011.[10] Seeking to promote low-carbon development in line with international commitments, the General Climate Change Law (Ley General sobre Cambio Climático, LGCC) was passed in 2012. This ***policy instrument*** established the national policy framework on GHG emission reductions and climate change mitigation (Veysey et al., 2016). Fig. 19 depicts domestic GHG emissions from main energy activities (e.g. electricity generation, transport, industry) and total emissions from 1990 to 2017 (excluding land use change and forestry (LUCF)). Total GHG emission climbed from 444.74 $MtCO_2e$ in 1990 to 733.82 $MtCO_2e$ in 2017 (a growth of 65%). In the same way, emission from electricity generation rose from 66.6 $MtCO_2e$ to 162.6 $MtCO_2e$ in the same period (accounting for 31% of the energy-sector emissions and 22% of the total GHG emissions) (INECC, 2018).

Mexico was lacking investment and productivity growth in both the oil and gas sector, as well as in the power sector. Mexico's oil and gas production started to decline during the mid-2000's,[11] power generation costs were going up due to inefficiency in electricity supply

[10] IRENA was officially founded in 2009, however it took around 2 years to set the institutional structure and ensure efficient internal and external communications (https://www.irena.org/history).

[11] Oil production declined from the peak of 3.8 million barrels per day (mb/d) in 2004 to 1.9 mb/d in 2019.

Table 3
Measures for grid connection for clean energy technologies from 2001 to 2007.
Source: adapted from (IRENA, 2015b) with information from (DOF, 2001; DOF, 2003; DOF, 2006; DOF, 2007).

Measure	Year	Goal
Grid interconnection contract	2001	To allow grid interconnection for renewable energy plants over 500 kW.
Stamp system (estampilla postal)	2003	To establish a system of transmission fees per kWh.
Wheeling agreement	2004	To establish the regulations for producers under the self-supply scheme to use the grid to transport electricity from off-site plants to load centres.
Self-supplied power (Potencia Autoabastecida)	2006	To offer capacity credit for renewable energy that provides firm capacity during the hour of maximum demand. It included energy banking and transmission cost discounts in the range of 50–70%.
Open season (temporada abierta)	2006	To set an open bid system in which IPPs and companies under the self-supply scheme would bid privately for transmission capacity, in addition to the generation project. 2.6 GW of wind capacity were successfully assigned in 2006.
Solar grid connection	2007	To set grid connection rules for small-scale solar producers (<30 kW).

Table 4
Electricity system snapshot under the interactive governance approach (1973–2007) – governing interactions (actor level).
Source: elaborated with information from (Carreón-Rodríguez et al., 2007; de la Garza, Melgoza, de la Garza, Laviada, et al., 1994b; González Quiñones, 2015; Huacuz Villamar, 2016; Jano-Ito & Crawford-Brown, 2016; Ramírez-Camperos et al., 2013).

From	Interactions	To
Market	Pressure for increasing investment in new capacity to meet demand. Pressure for increasing financial support. Pressure for increasing electricity tariffs. Pressure for supporting (national) technological development.	State
Market	Promotion of reduced tariffs for specific sectors (subsidies). Pressure for reducing electricity intensity.	Society
State	Intervention on partial liberalisation of the sector. Regulation on environmental standards. Regulation on electricity generation with new actors. Intervention on technology diversification. Regulation on electricity tariffs (reduction of subsidies).	Market
State	Promotion of increasing access to electricity to rural areas. Promotion of tariff reduction for some sectors (subsidies). Intervention on energy efficiency measures.	Society
Society	Pressure for increasing government incentives (e.g. subsidies). Pressure for expanding electricity services.	State
Society	Pressure for reducing electricity tariffs. Pressure for enhancing supply services.	Market

(increasing subsidies to supply electricity at low costs), and GHG emissions were advancing towards a direction not compatible with long-term ***climate policy objectives*** (IEA, 2017). Thus, the Mexican Congress approved in 2013 the energy reform proposed by the administration of Enrique Peña Nieto (2012–2018). The reform opened to competition the long-closed oil, gas, and power sectors with the aim of boosting oil and gas production, increasing the share of clean energy sources in electricity generation, increasing energy efficiency, and reducing GHG emissions (IEA, 2017). The reform required modifications to the Mexican Constitution (Articles 25, 27, and 28) and several secondary laws were enacted by the Mexican Congress (10 new laws and 12 modified ones) to achieve the reform's objectives. This reform was considered as "the most ambitious energy system transformation worldwide" since the 1990's (IEA, 2017). Within the electricity sector, the energy reform opened to competition generation (except nuclear) and retailing, while transmission and distribution prevailed as state-controlled activities (although private companies were allowed to invest, operate, and maintain the required lines by signing specific contracts with the state) (Jano-Ito & Crawford-Brown, 2016). Thus, CFE was legally separated in different subsidiaries for power generation, transmission, distribution, and retail activities to promote a more competitive structure. Correspondingly, multiple responsibilities were

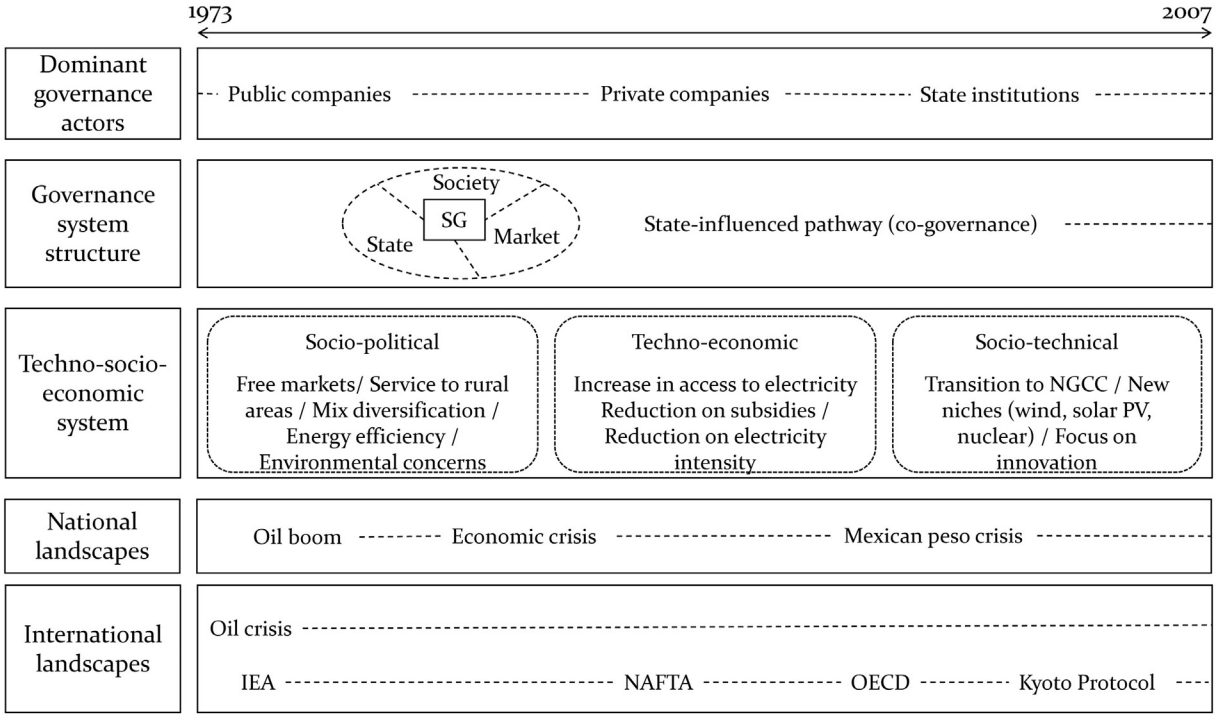


Fig. 15. Electricity system snapshot under the interactive governance approach (1973–2007) – system-to-be-governed, governance system, and external landscapes.

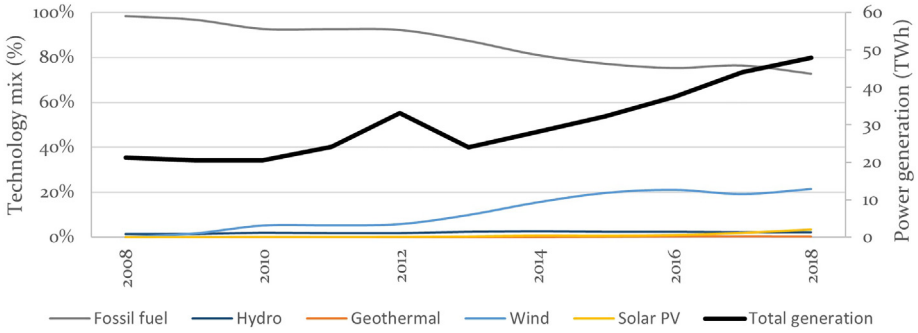


Fig. 16. Shares of technology mix (left) and total electricity generation (right) for self-supply (2008–2018).
Source: elaborated with data from (IEA, 2021).

Table 5
Measures for grid connection for clean energy technologies from 2010 to 2012.
Source: adapted from (Gutiérrez-Negrín & Quijano-León, 2004) with information from (DOF, 2010a; DOF, 2010b; DOF, 2010c; DOF, 2012a).

Measure	Year	Goal
Stamp system revised	2010	To revise and amend transmission charges for renewables under the stamp system.
Net-metering scheme	2010	To establish net metering for small-scale and medium-scale generators.
Large-hydro interconnection	2010	To set the interconnection rules for large hydropower plants (>30 MW).
Self-supply interconnection	2012	To regulate collective generation for small scale self-supply.

transferred to SENER (e.g. planning for system expansion), CRE (e.g. tariff regulation), and CENACE (e.g. system operation). Also, the Secretariat of Finance (Secretaría de Hacienda y Crédito Público, SHCP) was responsible to set certain electricity tariffs (mainly for residential and agriculture sectors). Derived from the 2013 energy reform several strategies, programs, and specific initiatives were developed. A detailed description and analysis of these policy documents may be found in (IEA, 2017). Fig. 20 depicts the key legislation and main ***policy instruments*** in force by 2018 that the state adopted to promote a clean energy and low-carbon transition (some instruments derived from the 2013 reform and others were reformed in line with policy objectives).[12]

The (new) Electricity Industry Law (Ley de la Industria Eléctrica, LIE) was promulgated in 2014, establishing a new regulatory framework for the electricity sector (DOF, 2014a). This new legislation created a wholesale market where suppliers and users were able to negotiate power supply contracts and tariffs. According to the law, the National Centre of Energy Control (Centro Nacional de Control de Energía, CENACE) became the national electricity system operator.[13] CENACE's aim is to meet electricity demand at lowest reasonable cost while guaranteeing the operation of the system in terms of reliability, efficiency, continuity, and safety. Also, the law introduced new ***policy instruments*** focused on promoting a clean energy transition. A clean energy quota obligation scheme (clean energy certificates, CECs[14]) was created to guarantee that generators sell a specific percentage of power produced with clean energy technologies or acquire tradable certificates (Jano-Ito & Crawford-Brown, 2016). A central piece of the reform was a system of auctions for electricity generation, capacity, and CECs aimed at providing more certainty upon future cash flows for generation companies (IEA, 2017). Three long-term power auctions (LTPAs) (in 2015, 2016, and 2017) and one medium-term power auction (MTPA) (called in 2017 and concluded in 2018) were organised, resulting in power purchase agreements (PPAs) between clean energy generators (mainly wind and solar energy) and retailers (being CFE the main retailer) (del Río, 2019). Fig. 21 depicts the main actors of the system by 2018.

In August 2014, the Geothermal Energy Law was created aiming at regulating activities related to mapping, exploration, and exploitation of geothermal resources and allowing private-sector participation in electricity generation (DOF, 2014b) (previously these activities were regulated by the National Water Law and CFE was the only organisation allowed to generate electricity from geothermal resources) (IRENA, 2015a; NREL, 2017). As a result, in March 2015, the first private geothermal field started generation and commercialisation of electricity with the first two 5-MW units. This was the Domo de San Pedro geothermal field (Nayarit) owned by Grupo Dragon. In 2016, Grupo Dragon added another 25.5-MW unit. It is worth noting that Mexico has the world's fifth largest geothermal power installed capacity (after US, Philippines, Indonesia, and New Zealand) and has great potential for future development (IEA, 2017).

Regarding fiscal incentives, the Income Tax Law establishes that equipment and machinery used for power generation from clean energy sources have a 100% accelerated depreciation[15] (IEA, 2017). On the other hand, a carbon tax on production and import of fuels was imposed in 2014 (on fuels with a higher CO_2 content than natural gas). Thus, the carbon tax applies to fossil fuels (coal, coke, and oil and coal products) across all sectors, including when used for electricity generation (OECD, 2019). The carbon tax was set at about 39 MXN/tonC (3 USD/tonC)[16] (IRENA, 2015b). The Energy Transition Law (LTE) sets that SENER is able to propose additional tax or financial mechanisms to promote clean energy technologies when these mechanisms have the potential to increase savings (for either the state or consumers) or to reduce GHG emissions (IEA, 2017; DOF, 2015).

Although clean energy development was promoted by the state since 2008, little progress was achieved during this period. As 2018, around 80%

[12] These documents are updated based on short, medium, and long-term policy objectives.

[13] CENACE started operations in 1977 as a specialised office within CFE. However, in 2014 this institution was declared as an independent public institution.

[14] The CECs scheme is similar to a tradable green certificates (or portfolio standard) scheme but is expanded to grant certificates for clean generation (which includes renewable energy technologies, nuclear power, hydrogen, efficient cogeneration, and fossil-fired generation with CCS).

[15] This policy instrument (i.e. accelerated depreciation) was first introduced in in 2004 by a reform to the 2002 Income Tax Law and was maintained in the new 2013 Income Tax Law.

[16] The exchange rate corresponds to the date when the law was approved (13 December 2013). One ton of C yields to 3.66 tons of CO_2 under perfect combustion conditions.

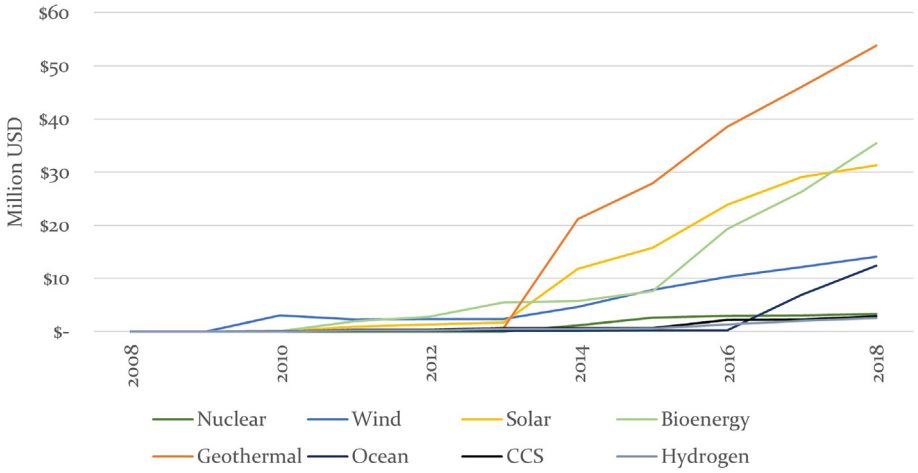


Fig. 17. Cumulative public investment in RD&D for clean energy technologies from the Sustainability Energy Fund.
Source: elaborated with data from (SENER, 2013a, 2014a, 2015a, 2016a, 2017a, 2018a).

of electricity production came from fossil-fuel technologies (see Fig. 22). An important international ***landscape*** is that Mexico officially became the 30th member country of the International Energy Agency in February 2018, and its first member in Latin America. This may bring benefits for Mexico in terms of access to energy data, adoption of best practices (i.e. ***policy diffusion***), ***technology diffusion*** (e.g. international spillovers, technological learning), and international collaboration focused on achieving (conditional) climate ***policy objectives***. For instance, co-operation on continued R&D and market deployment of new and improved energy technologies is highly encouraged by the IEA members to achieve shared goals on energy diversification, environmental protection, energy security, and economic growth. A noteworthy example of potential benefits for Mexico is the participation in the Technology Collaboration Programs (TCPs), an initiative that involves over 6000 international experts across government, academia and industry dedicated to advancing innovation and application of specific energy technologies (IEA, 2020b). Fig. 23 and Table 6 represent the electricity system snapshot for this period.

An administrative hurdle for clean energy development (2019–2021)

The original design of the 2013 energy reform granted the Federal Government with attributes to significantly influence the performance of the energy system (e.g. through different 'seats' within institutional committees) (Percino-Picazo et al., 2021). Thus, five years after the approval of the energy reform and part way in its implementation, the administration of Andrés Manuel López Obrador (who took office in December 2018) started a counter reform based on a ***policy paradigm shift*** towards nationalisation and energy sovereignty (i.e. a state-dominated governing system as opposed to the market-oriented reform). ***Policy objectives*** in the current administration are based on a state-controlled energy system led by the state-owned companies (i.e. CFE and PEMEX). Within the power sector, several modifications to previous ***policy instruments*** have been proposed and some already implemented in line with these policy objectives. For instance, the LIE has been modified in order to favour the dispatch of electricity generated by CFE and condition the access to new private participants (promoting unfair practices) (Percino-Picazo et al., 2021; DOF, 2021a; Ocampo, 2021). Other amendments to the LIE include a new criteria to grant CECs, elimination of CFE's obligation to buy energy through auctions or competitive processes, and the ability of CRE to revoke self-supply permits (DOF, 2021a; Ocampo, 2021). Similarly, the state modified the terms for the strict separation of CFE (derived from the LIE and LCFE laws) (DOF, 2019). Based on the argument that the legal separation has reduced CFE's performance and increased operational costs, the implemented modifications allow CFE to reorganise its generation assets to the discretion of SENER. Also, private participation in transmission projects has been cancelled under these modifications. In addition, the FSE has been involved in a restructuring process derived from a decree issued by the Federal Government ordering the extinction or termination of public trusts and similar mandates without organic structure (DOF, 2020b). The new policy paradigm adopted by the government has derived in significant socio-political tensions within the electricity system, resulting in legal actions against the state (mainly due to unfair market practices for private participants). Currently, the LIE reform (which was stayed by a Federal judge due to violations of the Mexican Constitution) and legal processes against modifications implemented by the state are pending the Supreme Court decision.

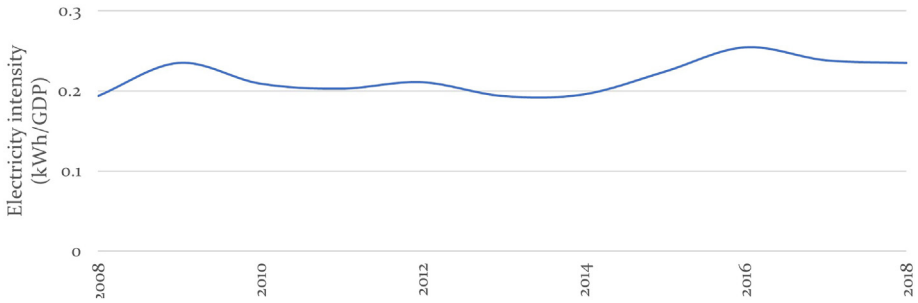


Fig. 18. Electricity intensity from 2008 to 2018.
Source: elaborated with data from (The World Bank, 2021; OECD, 2021).

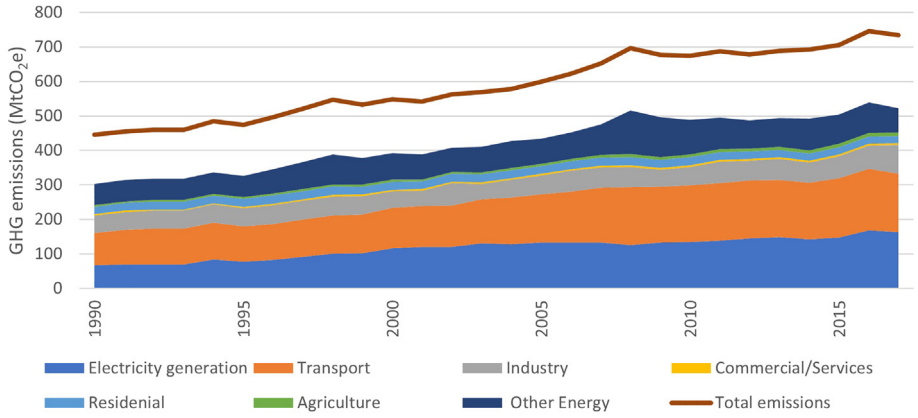


Fig. 19. GHG emissions from main energy activities and total GHG national emissions from 1990 to 2015. The gap in the figure corresponds to non-energy related emissions (e.g. domestic livestock, waste management, and processes in manufacturing industries and construction without fossil fuel combustion).
Source: elaborated with data from (INECC, 2018).

	Energy	Climate Change
Laws	Electricity Industry Law (LIE, 2014) Federal Electricity Commission Law (LCFE, 2014) Coordinated Energy Regulators Law (2014) Geothermal Energy Law (2014) Energy Transition Law (LTE, 2015)	General Climate Change Law (LGCC, 2012) Special Tax Law on Production and Services (carbon tax and credits, 2013) Law on Environmental and Industrial Safety (2014) General Law of Ecological Equilibrium and Environmental Protection (LGEEPA, 2018)
Plans	National Development Plan (PND 2013-2018)	
Strategies	National Energy Strategy (ENE 2014-2028) Transition Strategy to Promote the Use of Cleaner Technologies and Fuels (2016)	National Climate Change Strategy (ENCC, 2013) Intended Nationally Determined Contribution (INDC, 2015)
Programs	Energy Sectoral Program (PROSENER 2013-2018) National Electricity System Development Program (PRODESEN 2018-2032) National Program for Sustainable Use of Energy (PRONASE 2014-2018) Special Program for the Energy Transition (PETE 2017-2018) Special Program for the Use of Renewable Energy (PEAER 2014-2018)	Special Program for Climate Change (PECC 2014-2018) Nationally Appropriate Mitigation Actions (NAMA, 2015)
Initiatives	Energy Sustainability Fund (FSE) Energy Transition Fund (FOTEASE)	Climate Change Fund (FCC) National Emissions Inventory (NEI)

Fig. 20. Overview of Mexico's policy instruments and initiatives on energy and climate change in force by 2018.
Source: adapted from (Banacloche et al., 2020) with information from (IEA, 2017; IRENA, 2015a; IRENA, 2015b; SENER, 2018a).

An international ***landscape*** that significantly affected (and is still affecting) electricity production and consumption globally was the COVID-19 pandemic. In Mexico, the suspension of institutional activities and thus the extension of administrative processes in the electricity sector have been some effects of this landscape. This is evident, for instance, with CRE not granting permits for new private participants (action instructed by the Federal Government) and CENACE delaying interconnection studies of variable generation plants (e.g. solar PV and wind) for an indefinite period (Percino-Picazo et al., 2021). Another important international ***landscape*** was the United States-Mexico-Canada Agreement (USMCA) which entered into force in July 2020.[17] USMCA aimed at supporting mutually beneficial trade between the three countries, leading to freer markets, fairer trade, and robust economic growth in North America. Regarding energy matters, the USMCA aims at providing a predictable framework for the three countries to continue expanding trade in energy products by promoting good regulatory practices and encouraging environmental protection. However, the implementation of the USMCA (and other international agreements) may be threatened by the state's blockage of the Mexico's path towards competitive liberalisation of the electricity market (Ocampo, 2021). Fig. 24 and Table 7 depict the electricity system snapshot based on available relevant data for this period.

[17] The USMCA agreement replaces the previous NAFTA agreement between the three North American countries.

Towards a clean energy transition in Mexico

As many developing countries, Mexico's population is growing and urbanising, and thus more urban infrastructure needs to be built over the coming decades (including electricity infrastructure). Also, due to Mexico has a large export-oriented manufacturing sector, an increase in electricity consumption from the (largest electricity-consuming) industry sector is expected for coming years (IEA, 2017). In 2019, >60%

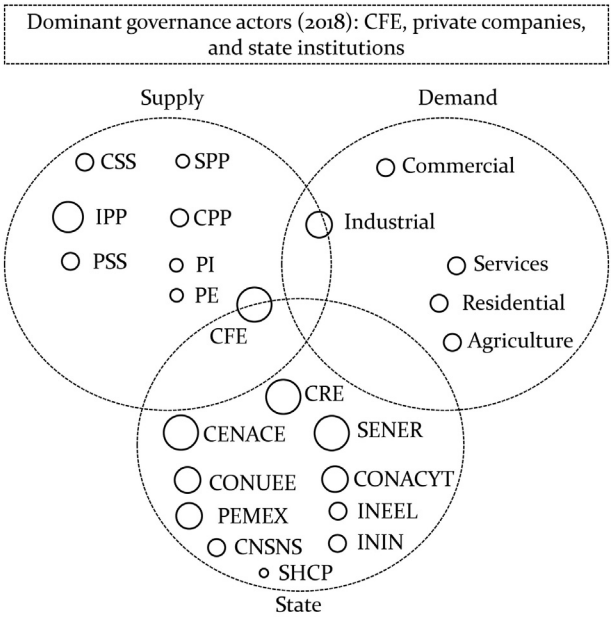


Fig. 21. Main actors within the governance system by 2018.
Source: adapted from (Jano-Ito & Crawford-Brown, 2016) with information from (IEA, 2016, 2017; IRENA, 2015a).

of electricity in Mexico was generated with natural gas, benefiting from low gas prices in US (USDOE, 2020). However, Mexico's dependence on (imported) natural gas has become a major concern. The increase of natural gas consumption for the industry and power sectors, and the decline in national oil and gas production led to around 70% imports in natural gas in 2019 (mainly from US) (USDOE, 2020; Mundo Ayala, 2021). Power generation to meet domestic demand could be affected by the volatility of natural gas prices. This highlights the relevance of clean energy technologies for keeping the supply-demand balance at reasonable costs (i.e. energy security).

Although the administration of López Obrador has changed market rules within the electricity industry, the Mexican government has reaffirmed the national ambitious targets regarding electricity generation with clean energy technologies, energy efficiency improvements based on energy intensity reduction, and GHG emission mitigation to address climate change (i.e. policy objectives). Based on a review of policy documents currently in force and complementary initiatives (including reformed versions of those presented in Fig. 20), the main policy objectives, specific targets, and performance indicators for a clean energy transition in Mexico are depicted in Tables 8-10. The focus is on the electricity sector; however, cross-sector targets are also considered for reference (e.g. expected GHG emission reductions from all sectors). Specific policy instruments are needed to direct the process towards a smooth clean energy transition and overcome technological, economic, and social barriers. Thus, the main policy instruments identified for a clean energy transition in Mexico are discussed within this section (also included within Tables 8-10). These policy instrument mixes aim at promoting the use of clean energy technologies, demand side management, distributed generation, and provide services to low-income population (Jano-Ito & Crawford-Brown, 2016).

The two most common policy instruments for promoting power generation from clean energy technologies are feed-in tariffs and renewable (or clean energy) portfolio standards (Harvey et al., 2018). Mexico has opted for a target-based clean energy standard to stimulate the market for clean generation. To meet these targets, a compliance system (CECs) and a price-finding mechanism (power auctions) were developed under the 2013 energy reform. Although a rapid clean energy market development was expected after the wholesale market started operations in 2016, new private generators have slowly increased their share in the market from 0.52% in 2016 to 11.82% in 2020 (based on verifiable installed capacity) (Percino-Picazo et al., 2021). Similarly, qualified suppliers only increased from zero to 3.4% of the total demanded capacity from 2016 to 2020 (Percino-Picazo et al., 2021). However, the number of permits granted by CFE for electricity generation was reduced by 86% in this period (from 158 in 2016 to 22 in 2020) (Percino-Picazo et al., 2021). Thus, clear market rules for non-discriminatory access and transparent regulatory independence should be sought to promote investment in clean energy infrastructure in line with the clean energy portfolio standard adopted by the state.

Soft costs (e.g. sitting and permitting) and connection to the grid may represent important challenges for clean energy technologies. Soft costs in energy infrastructure projects can be reduced by simplifying administrative processes (e.g. permit granting, pre-zoning). Mexico has already worked on this potential barrier. For instance, the process to connect a power generation plant to the grid has been reduced from 47 to just 9 (administrative) steps (IEA, 2017). In addition, a National Atlas of potential zones for clean energy deployment was published in 2017 aimed at reducing soft costs for large clean energy projects and helping planning expansion of national transmission and distribution (T&D) grids (IEA, 2017). With new large-scale clean energy projects to be built, new T&D lines will be needed. Also, improvements in the National Transmission Grid and the General Distribution Grids will be required to support the expected growth in electricity supply from variable energy sources (i.e. wind and solar). Mexico's electricity losses are significantly higher than other OECD countries. >21% of the electricity generated is not charged due to technical (e.g. poor state of the network) and non-technical (e.g. theft, non-payment) losses, resulting in higher transmission and distribution costs (IEA, 2017). Thus, reducing network losses is an important policy instrument to be included in the policy mix (e.g. through smart grid infrastructure). Also, bringing down technical and non-technical electricity losses may help to reduce the investment required for building new capacity and improve operational efficiency (IEA, 2017). Similarly, development of

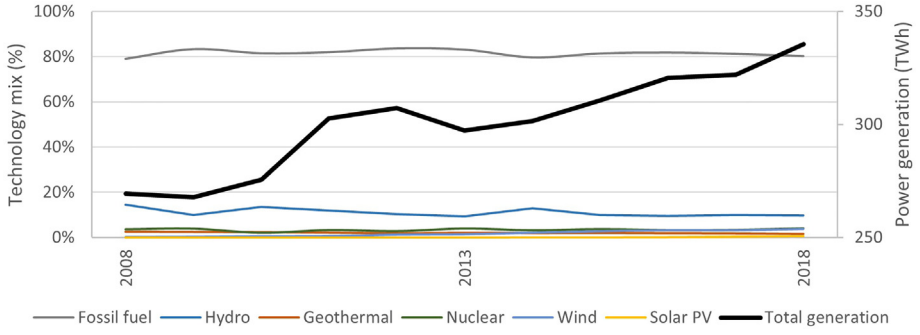


Fig. 22. Shares of technology mix (left) and total electricity generation (right) (2008–2018).
Source: elaborated with data from (IEA, 2021; SENER, 2008, 2009, 2010, 2011, 2012, 2013b, 2014b, 2015b, 2016b, 2017b, 2018b, 2021).

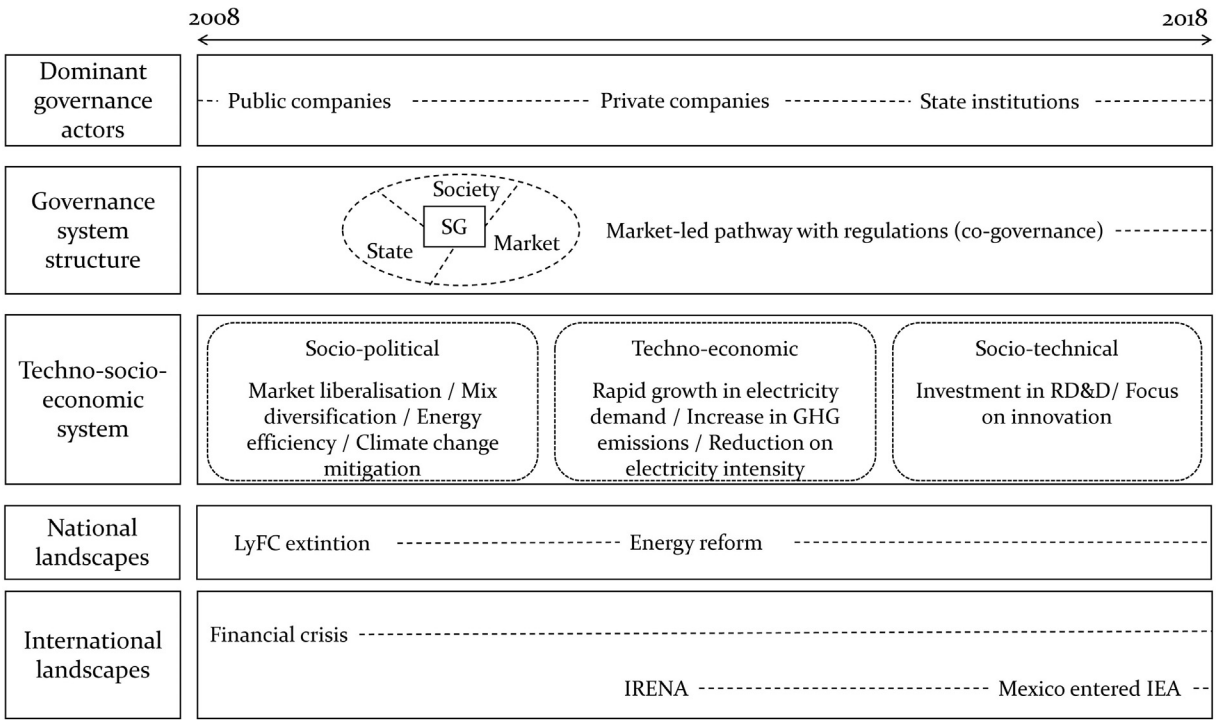


Fig. 23. Electricity system snapshot under the interactive governance approach (2008–2018) – system-to-be-governed, governance system, and external landscapes.

distributed generation (mainly solar PV) may represent a potential solution for grid congestion and thus reducing investment needed in new T&D lines. Mexico has a significant potential for distributed generation due to vast available natural resources throughout the country, and its further promotion may bring important social benefits to rural communities without access to electricity. It is worth noting that capacity for distributed generation in Mexico increased by 466% from 2012 to 2019 (from 14.86 to 692.86 MW), highlighting the interest in deploying this technology. However, financial mechanisms may be needed to facilitate accessibility to distributed generation in rural areas (e.g. temporary subsidies) (García Alcocer, 2021).

Support for clean energy RD&D has been extensively recognised as a key policy instrument to reduce GHG emissions and combat climate change (Garrone & Grilli, 2010; Koçak & Ulucak, 2019; Miremadi et al., 2019). The Mexican government considers RD&D as a key technology-push policy lever to reach clean energy, energy efficiency, and climate long-term targets (DOF, 2020a; DOF, 2012b). Significant progress has been made recently in this regard. For instance, innovation-focused systems (e.g. CEMIEs) have been strengthened and improved through specific policy instruments (e.g. public expenditure in RD&D). CEMIE-Sol can be taken as an example of technological progress in solar energy with 346 scientific publications, 7 business plans developed, 175 academic degrees obtained, 42 intellectual property applications submitted, and 29 technological packages reported by March 2019 (del Río Portilla & Morales Santiago, 2021). Also, the current administration has acknowledged the importance of investment in RD&D for clean energy technologies by setting a funding scheme in favour of clean energy technologies (at 65%/35% for clean energy/hydrocarbons) (DOF, 2021b), as previously suggested by the IEA (IEA, 2017). However, additional efforts focused on innovation are needed to overcome technical issues with nascent and emerging technologies (e.g. energy storage). Although public investment in RD&D for clean energy technologies started late (2010) in Mexico compared to other OECD/IEA members (1973), Mexico's international memberships (e.g. IEA, IRENA) represent a significant opportunity to advance innovation by taking advantage of technology diffusion and technological knowledge spillovers. In order to overcome technical and market barriers towards a clean energy transition in Mexico, the integration of technology-push and market-pull mechanisms (i.e. coordinated energy innovation policy mixes) are needed.

The electricity sector is expected to be the major contributor to GHG emissions reduction. The main policy instrument implemented by the government is a carbon tax. Fuels used for electricity generation are

Table 6
Electricity system snapshot under the interactive governance approach (2008–2018) – governing interactions (actor level).
Source: elaborated with information from (IEA, 2016, 2017; IRENA, 2015a; Jano-Ito & Crawford-Brown, 2016; Huacuz Villamar, 2016).

From	Interactions	To
Market	Pressure for increasing long-term investment in new capacity to meet demand. Pressure for competitive tariffs with respect to international benchmarks. Pressure for market liberalisation. Pressure for improving interconnexion for private producers. Pressure for strengthening innovation systems.	State
Market	Promotion of reduced tariffs for specific sectors (subsidies). Promotion of alternative solutions to satisfy specific needs (e.g. distributed generation). Pressure for adopting energy efficiency measures.	Society
State	Intervention on market liberalisation. Intervention on long-term energy planning. Intervention on climate change mitigation. Intervention on technology mix diversification. Intervention on energy efficiency. Regulation on electricity tariffs (subsidies adjustment).	Market
State	Promotion of better and more reliable supply services. Promotion of sustainable development. Intervention on energy efficiency measures.	Society
Society	Pressure for increasing government incentives (e.g. subsidies, tax reductions). Pressure for electricity access in remote zones. Pressure for strengthening environmental regulations.	State
Society	Pressure for reducing electricity tariffs. Pressure for enhancing supply services. Pressure for use of clean energy sources.	Market

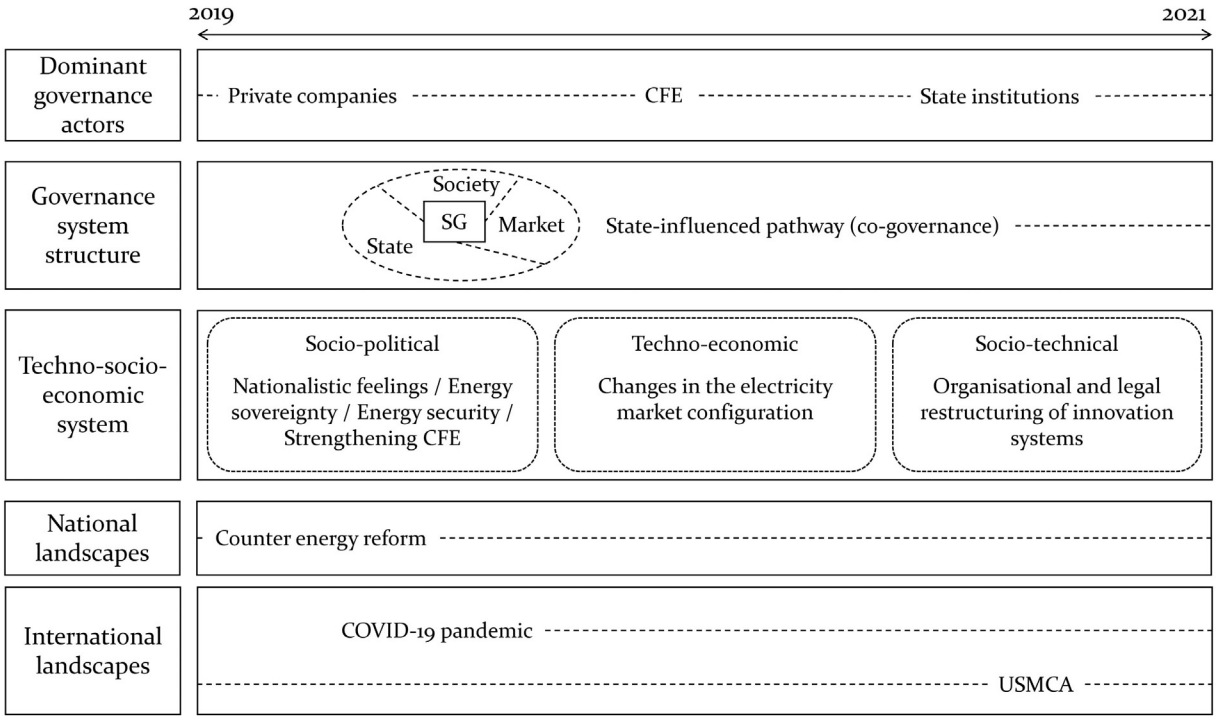


Fig. 24. Electricity system snapshot under the interactive governance approach (2019–2021) – system-to-be-governed, governance system, and external landscapes.

subject to the carbon tax. However, natural gas is zero-rated under this mechanism and it has been considered as the 'transition fuel' to comply with GHG emission reductions (Mundo Ayala, 2021). With decreasing domestic production and high dependence on imported natural gas, a gradual increase in carbon tax level (e.g. USD 50–100/tCO_2 by 2050) should be considered to better reflect the social cost of carbon and thus reduce carbon emissions from the electricity sector. In addition, a complementary Emissions Trading System (ETS) (also called cap-and-trade) may provide additional benefits by providing quantity certainty (additional to price certainty from a carbon tax) (Harvey et al., 2018). In 2020 a ETS test program stated operations in Mexico aimed at enhancing the quality of data on emissions and building capacity in emissions trading. The pilot phase (2020—2021) covers direct CO_2 emissions from entities in the energy and industry sectors. The energy sector includes electricity generation, transmission, and distribution, as well as fossil fuel extraction, production, transport, and distribution. The operational phase is expected to start in 2023 (Piquero, 2021). Additionally, carbon pricing policy instruments (e.g. carbon tax and/or ETS) may create economic incentives for carbon capture and storage (CCS) by reducing the cost of compliance (Harvey et al., 2018).

Table 7
Electricity system snapshot under the interactive governance approach (2019–2021) – governing interactions (actor level).
Source: elaborated with information from (DOF, 2020a; Percino-Picazo et al., 2021; DOF, 2021a; Ocampo, 2021; DOF, 2019; DOF, 2020b).

From	Interactions	To
Market	Pressure for clear and fair market rules for private participants. Pressure for a robust institutional framework (e.g. ensuring the independence of regulatory bodies). Pressure for non-discriminatory access to the networks. Pressure for strengthening sector competitiveness (e.g. through international trade agreements).	State
Market	Promotion of technology mix diversification. Promotion of climate change mitigation. Promotion of energy efficiency measures.	Society
State	Intervention on market configuration, promoting vertical integration led by CFE. Determination of electricity tariffs for specific population groups. Intervention on technology mix diversification, based on expansion plans and priority dispatch mechanisms. Pressure for investment in generation, transmission, and distribution to meet increasing electricity demand. Pressure for reducing operational inefficiencies.	Market
State	Promotion of reduced tariffs for specific sectors (subsidies). Promotion of better and more reliable supply services. Promotion of energy sovereignty. Promotion of energy security.	Society
Society	Pressure for increasing electrification in rural communities and marginalised urban areas. Pressure for economy recovery (e.g. creating jobs). Pressure for reducing climate pollutants.	State
Society	Pressure for reducing electricity tariffs. Pressure for improving supply services. Pressure for increasing electricity access in remote areas. Pressure for use of low-carbon energy sources.	Market

Historically Mexico's energy policy design has posed significant attention to the supply side rather than the demand side (de Buen-Rodríguez, 2007). Cross-sectoral energy efficiency policy instruments in Mexico have focused mainly on the residential and commercial sectors with the implementation of programs such as performance standards for buildings and appliances, replacement programs for refrigerators, air conditioning, and fluorescent lights, and a voluntary energy labelling program (FIDE stamp) (IEA, 2017). Although electricity accounts for around 31% of the total consumption in the industrial sector, energy efficiency measures have been limited to energy audits, technical recommendations, and data collection on energy consumption (IEA, 2017). Within the transport sector, 99.8% of the total fuel demand is fuelled by oil, with only a 0.2% share of electricity use. Thus, energy efficiency in the transport sector has been promoted mainly by improvements in light-duty vehicle standards (IEA, 2017).

Although Mexico has wide-ranging programs for energy efficiency, the Mexican society lacks awareness regarding their benefits. Energy efficiency policy instruments (e.g. industry energy efficiency standards, demand response) could play a stronger role in the policy mix to reach energy objectives. Thus, energy efficiency standards already in place should be constantly revised and updated according to new

Table 8
Targets, performance indicators, and main policy instruments for electricity mix diversification.
Source: elaborated with information from (Harvey et al., 2018; IEA, 2017; IRENA, 2015a; DOF, 2015, 2020a; SENER, 2017c, 2017d, 2017e, 2017f).

Objective: Electricity mix diversification					
Targets	2021	2024	2030	2050	Reference
Share of power generation from clean energy sources (%)	33.5	35.1	38.2	50	(DOF, 2020a)
Geothermal installed capacity (MW)		1025.4	1670.4		(SENER, 2017c)
Solar PV installed capacity (on-grid) (MW)		5000	9000		(SENER, 2017d)
Solar PV installed capacity (distributed generation) (MW)		2000	13 000		(SENER, 2017d)
Onshore wind installed capacity (MW)		14 000	21 000		(SENER, 2017e)
Ocean energy installed capacity (MW)	11 (by 2022)	80 (by 2026)	500–1000		(SENER, 2017f)
Performance indicators					
Share of electricity generation from clean energy sources (%)					
Installed capacity by source (MW)					
Electricity generation by source (TWh)					
Main policy instruments					
Clean energy portfolio standard					
Soft cost reduction					
Increase transmission and distribution (T&D) lines					
Reduce T&D losses					
Distributed generation					
Public investment in clean energy RD&D					

technological improvements and more efficient technologies available. Also, as energy-intensity industries are expected to rise in the coming years, increasing the efficiency of industrial equipment through performance standards should be included in the policy mix (e.g. fostering efficiency improvement in electric motors, pumps, and commercial boilers). Demand response mechanisms may bring significant benefits to the system by reducing demand during peak periods, lower capacity requirements, and increasing reliability. Although Mexico has not defined a clear demand response mechanism, an effective program requires solid measurement and verification elements to ensure cost savings for all participants.

With new actors in the system (e.g. new industry players, new regulators, a new system operator) the state should install a new data collection system focused on keeping the supply-demand balance (IEA, 2017). Mexico has an online database where information on energy supply and demand is published, the Energy Information System (Sistema de Información Energética, SIE). However, some data are not accurate and have not been updated regularly, creating uncertainty around electricity demand. A particular issue is that data on electricity consumption is not completely collected and/or uniformly reported (rather it is estimated), affecting the reliability of data on energy efficiency (IEA, 2017). Thus, improvements in data collection,

Table 9
Targets, performance indicators, and main policy instruments for climate change mitigation.
Source: elaborated with information from (IEA, 2017; DOF, 2012b; DOF, 2013; Ministry of the Environment and Natural Resources (SEMARNAT), 2020; Gobierno de México, 2015, 2016; SEMARNAT, 2013).

Objective: Climate change mitigation			
Targets	2030	2050	Reference
GHG and Short-Lived Climate Pollutants (SLCPs) emissions reduction	25–40% from business as usual (BAU) (from 1128 to 846–677 $MtCO_2e$)		(SEMARNAT, 2020; Gobierno de México, 2015, 2016)
GHG emissions reduction	22–36% from BAU (from 991 to 773–634 $MtCO_2e$)	50% from 2000 levels (Max. 320 $MtCO_2e$)	(DOF, 2012b; DOF, 2013; Ministry of the Environment and Natural Resources (SEMARNAT), 2020)
Black carbon emissions reduction	51–70% from BAU (from 137 to 67–41 $MtCO_2e$)		(DOF, 2012b; Ministry of the Environment and Natural Resources (SEMARNAT), 2020; Gobierno de México, 2015)
Reduction in emissions intensity	40% from 2013 levels		(DOF, 2012b; Ministry of the Environment and Natural Resources (SEMARNAT), 2020)
Reach emissions peak in 2026			(DOF, 2012b; Ministry of the Environment and Natural Resources (SEMARNAT), 2020)
GHG emissions reduction from electricity generation	31% from BAU (from 186 to 128 $MtCO_2e$)		(Gobierno de México, 2016; Gobierno de México, 2015)
Performance indicators			
GHG emissions by pollutant ($MtCO_2e$/year)			
GHG emissions by sector ($MtCO_2e$/year)			
Emissions intensity ($MtCO_2e$/GDP)			
Carbon intensity from electricity generation (tCO_2/MWh)			
Main policy instruments			
Carbon tax			
Emissions Trading System (ETS)			
Carbon Capture and Storage (CCS)			

Table 10
Targets, performance indicators, and main policy instruments for energy efficiency.
Source: elaborated with information from (Harvey et al., 2018; IEA, 2017; DOF, 2020a; DOF, 2015).

Objective: Energy efficiency improvement				
Targets	2030	2035	2050	Reference
Reduction in final energy intensity rate		2.2% from 2020 to 2035	2.5% from 2035 to 2050	(DOF, 2020a)
Reduction in total final energy consumption	24.7% from BAU (from 7120 to 5363 PJ)	30.1% from BAU (from 7843 to 5485 PJ)	43% from BAU (from 9621 to 5480 PJ)	(DOF, 2020a)
Reduction in electricity demand	29.7% from BAU (from 428 to 301 TWh)	34.6% from BAU (from 492 to 322 TWh)	46.8% from BAU (from 723 to 385 TWh)	(DOF, 2020a)
Performance indicators				
Final energy intensity (toe/GDP)				
Total final energy consumption (PJ)				
Total electricity demand (TWh)				
Electricity intensity (kWh/GDP)				
Main policy instruments				
Performance standards (e.g. buildings and appliances standards, industry energy efficiency standards)				
Demand side management – Demand response				
Reduction of electricity subsidies				
Electrify transportation sector				

management, and analysis are needed to appropriately track energy efficiency progress.

Mexico has historically relied on an expensive and distorting tradition of electricity subsidies (electricity tariffs for farmers and households are subsidised by 60–70% of the total cost). As tariff is a key driver for behavioural change, artificially low electricity prices should be phase out and replaced with other policy instruments (e.g. promoting distributed generation and energy efficiency measures). The wholesale and retail markets under fair competition may help in reducing generation costs and facilitate a smooth process of phasing-out subsidies without an extraordinary increase in prices (IEA, 2017). For instance, power auctions in Mexico have indicated that private companies can supply electricity from solar and wind technologies at highly competitive prices (as low as USD 17 per MWh for wind and USD 19 per MWh for solar PV in the third LTPA) (del Río, 2019). Although retail electricity prices remain a politically sensitive issue, reducing subsidies may help to increase consumer's awareness of efficiency and thus to buy more efficient products, while bringing long-term budgetary benefits for the government (net subsidies to end users accounted for USD 37.6 billion from 2010 to 2015) (IEA, 2017).

The transportation sector is the largest energy consuming sector and the largest CO_2 emitter in Mexico (IEA, 2017), powered mainly by oil. Thus, as the carbon intensity of the electricity sector decreases, one promising policy strategy for decarbonising the economy is the electrification of the transportation sector (through subsidies for electric vehicles, development of charging infrastructure, and consumer education) (Harvey et al., 2018). Although electric vehicles are an emerging technology that must compete against oil-fuelled matured technologies (i.e. conventional vehicles) the state has considered EV deployment as a key energy efficiency strategy towards a clean energy transition (DOF, 2020a).

Discussion and conclusions

Electricity is fundamental for meeting societal needs and supporting economic development. However, the electricity sector contributes to a significant share of greenhouse gas emissions. Power generation from clean energy sources may help to meet societal needs such as increasing electricity demand while enabling deep carbon reductions. The aim of this paper was to describe the development of clean energy technologies in Mexico from 1879 to 2021 using a multi-perspective approach. A series of qualitative storylines were synthesised in an analytical framework under the interactive governance approach. The empirical application of the framework proposed in Section 2 revealed that the ever-growing electricity demand in Mexico have called for exploring different technologies and available energy sources over time. The decline in hydrocarbons domestic production, increasing environmental concerns, and international agreements on climate change mitigation have been the main drivers for deploying clean technologies and adopting energy efficiency measures in Mexico. However, clean energy technologies have faced important barriers.

First, domestic available resources have played a crucial role in directing the pace and pathway of electricity generation in Mexico (i.e. path-dependence). In the early stages of the power sector in Mexico, the vast water resources allowed that most of the electricity produced came from hydropower technologies. However, access to a vast oil and gas resources promoted a transition to fossil-fuel power generation since 1971, reinforcing the position of fossil-fuel incumbent regimes and displacing clean energy technological niches. For instance, with a boom in oil production in the 1970's, the state encouraged the use of fuel oil (produced by PEMEX) for power generation, creating a carbon lock-in effect. Although Mexico has abundant renewable energy resources and clean energy development has been promoted by the government since 2008, little progress has been achieved to date due to technological and socio-economic barriers (e.g. economies of scale from large-scale fossil fuel generation, political and institutional influence). A decrease in hydrocarbons national production since the mid-2000's may represent an opportunity for clean energy development. For instance, resource depletion may lead to a rise in extraction costs and thus may prompt technology shifts, use of more efficient equipment, or reduce consumption. However, technological lock-in has been (a will remain) a significant challenge for clean energy technologies if the state promotes the development of incumbent regimes (e.g. electricity production from conventional technologies) due to socio-political interest (e.g. by maintaining aging and inefficient power plants that burn fuel oil produced by PEMEX).

Second, although Mexico has a remarkable potential on renewable sources (e.g. wind, solar, geothermal, bioenergy), the lack of investment in RD&D and innovation for clean energy technologies have limited their development. Mexico has recently taken important steps towards boosting innovation on clean energy technologies (e.g. CEMIEs). However, historically the country has been rather a technological follower/adopter (i.e. periphery country) than a technological leader (i.e. core country). As discussed in Section 3, the lack of economic resources led to knowledge obsolescence and lack of interest in clean energy development at their early stages. However, technology diffusion and technological learning processes have played (and would play) a relevant role for the development of these technologies.

Third, policy paradigms have shifted based on (dynamic) societal needs and socio-political interests. As a result, governance structures (and their interactions) have change over time to satisfy these needs and interests. The state-led pathway adopted after the nationalisation of the electricity industry brought several benefits to society (e.g. reduction in electricity prices) but at the same time multiple economic and financial issues (e.g. financial constraints to expand the system). Thus, a policy paradigm shift towards the liberalisation of the sector was adopted since the 1990's. The opening of the market has led to the use of more attractive power generation technologies, from a cost perspective (mainly natural gas-fired technologies). Although private investors have shown significant interest in building clean energy power plants (mainly wind and solar PV) after the 2013 energy reform, the current administration of Andrés Manuel López Obrador (elected in 2018) has focused on strengthening CFE by increasing its generation capacity and recover its self-sufficiency. This policy paradigm shift may jeopardise the development of clean energy technologies by creating political uncertainty and posing financial challenges to the expansion of the system.

Multiple policy instruments to overcome these barriers and allow a transition towards a clean energy system in Mexico have been identified and discussed in Section 4 (some already implemented by the government). These policy instruments aim at providing promising mechanisms to achieve current policy objectives identified by the application of the proposed analytical framework. Some policy mixes are more suited for countries under development. Electricity systems in developing countries have some common characteristics: continuous structural changes, the need for infrastructure expansion due to rapid growth in electricity demand, and significant (deep) uncertainties regarding future conditions (Castrejon-Campos et al., 2020). The development of the clean energy market may be affected by factors outside the control of policymakers such as fuel prices for electricity production (mainly natural gas), technological progress, price-demand elasticities, economic growth, and investment preference structures adopted by private generator companies. Based on the particular characteristics of the Mexico's electricity system described in this study, the exploration of different policy mixes considering different uncertain factors is proposed for future research. Thus, a quantitative analysis on future scenarios is needed to gain insights on what could be the most robust policy alternatives to efficiently meet the rapid growing demand, reach the long-term target of generating 50% of electricity with clean energy technologies by 2050 (compared to 20% in 2019), and meet international climate change commitments. Energy models can be used to explore the performance of different policy mixes. Additional to policy objectives presented in Section 4, the costs/savings of implementing alternative policy mixes should be considered by policymakers.

Different drivers and barriers for developing clean energy technologies in Mexico have been identified and discussed in this study. Also, current policy objectives, specific targets, performance indicators, and potential policy instruments towards a clean energy transition in Mexico were discussed. The use of concepts from a multi-perspective analytical framework and policy mixes for sustainability transitions were useful to understand the role of social actors, policy mixes, the system's performance, and technological change processes in the development of clean energy technologies. Also, the interactive governance theory was useful to synthetise the qualitative storylines derived from the multi-perspective analysis into a broader theoretical construct as suggested in previous studies.

The last period of analysis covered by this study (i.e. 2019–2021) may be considered as a partial (incomplete) representation of the ongoing structural transformations that have been taking place in recent years due to two main reasons. First, electricity transitions are characterised by long-term, complex, evolving processes of structural change where adaptations to policy mixes usually occur due to external and internal tensions in the system. Second, the lack of available data for some sustainability concepts used in this study (e.g. electricity generation, GHG emissions) limits the development of comprehensive storylines under the multi-perspective analytical framework described in this study. Thus, the application of the proposed theoretical framework (see Section 2) using updated relevant data offers an important avenue for future research. In addition, future research can be made by using additional complementary concepts from these or other analytical frameworks to generate alternative narratives about transformation processes not covered here. Also, a broader analysis of the energy sector as a whole may aid to better understand energy transitions in developing countries.

Declaration of competing interest

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix D Publications related to Chapter 4

Co-author authorisation form

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A. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Full title	Effects of learning curve models on onshore wind and solar PV cost developments in the USA		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate researcher's contribution (%)	75		
Status	☒ Published ☐ Accepted and In-press ☐ In progress		
Journal or book name	Renewable and Sustainable Energy Reviews		
Volume/page numbers (if published)	160/112278	Date accepted/ published (if relevant)	Available online 1 March 2022

B. CO-AUTHOR'S DECLARATION *(to be completed by the collaborator)*

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- the graduate researcher contributed greater than 50% of the content of the publication and is the "primary author" ie. the graduate researcher was responsible primarily for the planning, execution and preparation of the work for publication.

Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Felix Kin Peng Hui		18 March 2022

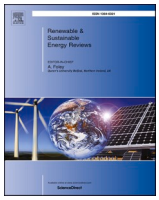
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Effects of learning curve models on onshore wind and solar PV cost developments in the USA

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ABSTRACT

Technological innovation planning for developing and deploying clean energy technologies plays a key role in reducing greenhouse gas emissions and transition to a low-carbon future. Learning curve theory has been adopted as a common framework for exploring the relationship between endogenous technological learning and technology cost developments. The aim of this article is to analyse the effects of selecting different learning curve approaches (i.e. model formulations) to describe energy technology cost changes over time. Experience and knowledge stock are chosen as the sources of learning to be considered. A new definition of experience was developed to account for the interaction between global and local experience. The new definition of experience also accounts for learning sub-processes (i.e. learning-by-doing, learning-by-using, and experience spillovers) to estimate total experience gained through technology deployment. An integrative model is developed for estimating the effects of learning-by-deploying and learning-by-researching on cost developments for onshore wind and solar PV in the USA. Publicly available data from government departments and organisations were utilised. It was found that technology cost developments are better explained when: (1) experience is defined as a function of global and local experience; (2) knowledge stock is also considered in the model formulation; and (3) technological processes affect only a fraction of the total capital cost. The findings suggested that the application of learning rates for model-based energy planning is context-dependent and how technological factors are explicitly defined may have significantly different policy implications (i.e. different technology costs predictions based on alternative model formulations).

1. Introduction

It is widely recognised that technological innovation in low-carbon technologies plays a substantial role in combating climate change and reducing greenhouse gas (GHG) emissions without compromising economic growth [1]. Energy-related policymakers have developed and applied diverse policy strategies to promote clean energy transitions. These policies include technology-push (e.g. public investment in energy research and development) and market-pull (e.g. carbon pricing, feed-in tariffs) mechanisms [2,3]. Technological learning has been identified as a key driver for moving towards low-carbon energy systems [4].

Technological learning is widely accepted as a mechanism that leads to technology cost reductions over time [5]. Electricity generation costs from renewable energy technologies have dropped rapidly over the last decade. These reductions have been driven by several factors such as cumulative manufacturers experience, technological innovation, economies of scale, among others. Cost reductions are reflected in clean energy technology deployment with renewables accounting for 82% of all new capacity additions worldwide in 2020, leading with solar photovoltaic (PV) and onshore wind additions [6]. Thus, understanding how costs of electricity generation technologies change over time due to technological change processes is crucial for energy analysts, planners, and policymakers.

The most common framework for investigating the relationship between technological learning and technology costs changes is the learning curve approach [5,7]. However, what sources of learning and key parameters to include as explanatory variables to technology cost changes has been identified as a paramount source of uncertainty within this approach [8,9]. Technological experience and technological knowledge stock, hereafter referred as experience and knowledge stock, are the most common sources of learning that have been modelled within energy-economic models. Nonetheless, alternative definitions of

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Nomenclature

Symbols

a	domestic knowledge dissemination policies factor (−)
C	capital cost ($ kW^{-1})
CC	cumulative installed capacity (MW)
E	experience (MW)
KS	knowledge stock ($m)
KP	international knowledge pool ($m)
LM	learning multiplier (−)
LR	learning rate (−)
PR	progress ratio (−)
RDnD	public RD&D spending ($m)
SPILL	international knowledge spillovers ($m)
X	learning source (−)
Z	new knowledge creation ($m)

Greek Symbols

α	share of the total technology capital cost affected by learning processes (%)
β	share of domestic content (%)
ρ	annual depreciation rate of knowledge stock (%)
γ	experience spillover coefficient (−)
δ	domestic absorption capacity of international knowledge spillovers (−)

Subscripts

g	time lag between the RD&D activity and its effects (a)
lbdo	learning-by-doing
lbu	learning-by-using
n	country
spill	experience spillovers
t	technology
y	timestep (a)

Superscripts

b	public RD&D spending elasticity
c	knowledge stock elasticity
d	international knowledge spillover elasticity
ℓ	learning index
lbd	learning-by-deploying elasticity
lbr	learning-by-researching elasticity

Abbreviations

1FLC	One-factor learning curve
2FLC	Two-factor learning curve
GHG	Greenhouse gas
IEA	International Energy Agency
LbD	Learning-by-Deploying
LbR	Learning-by-Researching
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
R&D	Research and development
RD&D	Research, development, and demonstration
RMSE	Root mean square error
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

these factors are found in the literature making it difficult to develop policy recommendations for decision makers regarding the role of technological learning processes on future cost developments.

The aim of this article is to analyse the influence of selecting different technological learning model structures (i.e. alternative definitions of explanatory variables) to describe renewable energy technology costs developments. Onshore wind and solar PV are the two renewable energy technologies with the fastest-growing electricity generation in the world and are of particular interest for energy transitions studies [10,11]. In 2020 the United States of America (USA) represented 32% and 21% of the Organisation for Economic Co-operation and Development (OECD) installed capacity for onshore wind and solar PV, respectively [12]. Thus, the focus in this article is on onshore wind and solar PV electricity generation technologies in the USA.

The article builds on existing learning curve literature by analysing the role of alternative approaches when modelling technological learning as a function of experience and knowledge stock as the main sources of learning. Due to different definitions of experience and knowledge stock, an integrative technological learning model has been developed by integrating multiple approaches to modelling technological learning. By changing key parameters within this integrative model, the impact of model definitions is explored as suggested by Ref. [13]. Thus, this article reveals the relative contributions of different variables to reducing capital costs for selected renewable energy technologies and provides an in-depth critical discussion on the implications of their use to inform energy policymaking. Also, the study contributes to the literature by providing a new definition of experience aimed at investigating the relative contribution of local and global experience on technology cost changes and accounting for different learning processes as suggested by previous studies [11,13]. Similarly, knowledge stock is modelled as a combination of global and local data to explore the relative contribution of domestic public energy R&D expenditures and international knowledge spillovers as suggested by Ref. [11]. The present investigation is targeted at energy analysts, researchers, planners, and energy innovation policymakers.

The remainder of this article is organised as follows. Section 2 sets the background of the research by describing the role of learning curve theory in estimating future technology costs. An integrative technological learning model is presented and explained in Section 3. Data sources employed, parameter value settings, and alternative model structures are described within this section. In Section 4 estimated learning rates by applying different model structures are presented. Findings of the analysis, policy implications, limitations and potential future research are discussed in Section 5. The conclusions follow in Section 6.

2. Endogenous technological change in energy modelling

Neoclassical growth models, fundamentally derived from Solow [14], have usually considered technological change as an exogenous phenomenon to the economy. This approach suggests that technological change is an autonomous process that do not depend upon other variables (e.g. economic, policy, social, or environmental factors); a perspective with important limitations for policy analysis [15]. In energy modelling literature, it has been advocated that technological change should be modelled as a result of the interactions of other interrelated processes, such as government-funded research and development (R&D), private technology investment, and economy-of-scale effects [16]. Thus, the use of learning curves has been adopted for energy and environmental technology analysis to gain knowledge about the process of learning in energy systems [17]. This is particularly important in the context of energy and innovation policy analysis to determine whether resources to be allocated to foster renewable energy technologies are better spent on technology diffusion or innovation policies [15,18]. The learning curve theory has been applied to analyse the effect of induced technological change in electricity generation technologies. Recent reviews may be found in Refs. [9,11,13,19].

2.1. Learning curve theory

Efforts on quantitative explanation of technological change dated from the 1930's when it was observed that the production cost of military airplanes declined at a semi-constant rate for each doubling of aircraft produced [20]. This correlation is known as the learning curve. Learning curves are generally used to empirically estimate the cost of a given technology as a function of technological learning [21]. The learning curve theory relies on the assumption that future technology costs decline as technological learning increases. In the energy sector the learning curve theory is commonly applied to estimate future costs of electricity generation technologies as a function of learning processes [9–11,13,22]. Learning processes in energy systems may occur through various channels [11]. When the focus is on experience gained by technology diffusion (i.e. learning-by-deployment [11]), learning may increase through experience attained during the production process of a technology (learning-by-doing [23]), through the operation or use of a technology (learning-by-using [24]), and via exchange of experience-based knowledge derived from interactions among different stakeholders or regions (learning-by-interacting [25] or experience spillovers [26]). On the other hand, when the focus is on innovation, learning may increase through knowledge creation during research activities (learning-by-researching or learning-by-searching [27]).

A variety of geometric model formulations have been proposed within the learning curve literature to describe the relationship between technological learning processes and technology cost reductions (a review may be found in Ref. [28]). Among learning curve studies on energy technologies, the log-linear model is the most common method applied due to its simplicity and generally good fit to historical data [29]. Thus, this model formulation has become a common method of representing technological learning in energy-economic models for policy analysis [4]. However, significant different policy implications may be obtained (e.g. different values for learning rates) based on the selection of learning sources (e.g. experience and knowledge stock) and assumptions to define technological progress in energy models [10]. How technological progress influences future electricity generation technology costs has been analysed through diverse energy models such as WITCH [30], MESSAGE [31], ReMIND-R [32], NEMS [33], and EPA-MARKAL [34]. A comprehensive review of efforts aimed at incorporating endogenous technological change in energy-economic models may be found in Ref. [35]. Also, research implications on endogenizing technological change in energy-economic models are discussed in Ref. [13]. It has been argued that endogenizing technological change in energy system models has a significant influence on the cost of climate policy actions based on learning sources used to describe technological processes [13].

One-factor learning curve (1FLC) models, often called experience curves [36], use experience as the only learning source to explain technology cost developments over time. The definition of experience in the case of electricity generation technologies may vary due to several empirical reasons (e.g. scope of the study, geographical delimitation, data availability). The most common definition of experience is cumulative installed capacity of the technology of interest [9,11]. However, electricity generated or number of plants (or parts of plants) built have been identified as the most frequent alternative definitions [9]. Other definitions have been proposed as proxies for experience for particular energy technologies, such as cumulative PV modules shipments for solar PV [37] and number of turbines in the case of wind [38]. Alternative definitions used for experience in electricity generation technologies may be found in Refs. [9,11].

In order to better represent technological change processes, two-factor learning curves (2FLCs) have been developed in Refs. [27,30,39,40]. The 2FLC approach was first proposed by Ref. [27] to include R&D expenditures, as a proxy for knowledge stock, as a second source of learning and thus adding a policy variable to the learning curve model. While it is widely accepted that both private and public investment in R&D activities may contribute to technology cost reductions, 2FLCs often include only public R&D expenditure, as private data generally are not publicly available [41]. Thus, learning-by-researching processes may incorporate public R&D expenditures or patents as the most common proxies for cumulative knowledge stock [15,42]. Alternative definitions for knowledge stock used for solar PV and wind may be found in Ref. [11]. Several studies have empirically tested 2FLC models to explore the impact of knowledge stock in technology cost developments (see, for instance, Refs. [15,21,39]). Results have shown that the contribution of knowledge stock compared to experience vary across different technologies and stages of development [11,41].

Multi-factor learning curves models (MFLC), including three or more factors, have been proposed in the literature. These include technology imports (i.e. learning-by-importing), economies-of-scale effects, supply-chain dynamics, input prices for materials, efficiency improvements, among many others [8,11]. However, multi-factor learning curves present major limitations such as difficulty to construct due to data limitations or high levels of multicollinearity [9,10,43,44].

2.2. Limitations of current learning curve models

The application of 1FLC models for predicting future technology cost developments has been extensively debated in the literature (see Refs. [9,13,15,45,46]). A key criticism of 1FLC models is the high level of aggregation to represent learning processes regarding technology deployment [9,11,13]. For instance, the relative role of learning-by-doing, learning-by-using, and experience spillovers cannot be revealed by using a traditional 1FLC approach [9,11]. Thus, it is argued that little explanation is offered by the statistical correlation between reductions in technology costs and cumulative installed capacity, used as a proxy for experience, when the process of technological learning is investigated using 1FLC models [8,46]. Considered as a partial model for technological learning processes, 1FLCs may produce inaccurate estimates of learning-by-deployment rates [15]. Thus, it has been suggested that a quantitative exploration of drivers that may contribute to learning due to technological deployment is needed to avoid producing misleading conclusions about learning gained through experience [11,13].

In addition, some scholars have suggested that 1FLC models may overestimate the actual contribution of experience as this approach uses a single parameter (i.e. experience gained by technology deployment) to explain technology cost changes (i.e. omitted variable bias) [9,13]. Omitted variable bias occurs when alternative key cost-influencing factors (e.g. knowledge stock, spillover effects) are neglected from the analysis [9]. From a policy perspective, only market-pull recommendations may be developed while ignoring technology-push mechanisms if 1FLCs are applied in energy models [15]. If energy models miss critical pathways or inappropriately capture learning processes (e.g. poor representation of energy innovation processes), policymakers could potentially obtain incomplete or misleading policy conclusions [46]. Energy innovation-oriented policy strategies play a key role in learning processes and promoting technological development [47–50]. For instance, when the private sector is unable to capture the full social value of their R&D efforts, private underinvestment is evident (i.e. market failure) [51,52]. Thus, government interventions (e.g. through public investments in energy R&D) play a vital role to close this investment gap. Also, public support for R&D may aid to overcome other system failures [53]. For instance, innovation stakeholders may not be able to take advantage of the entire innovation potential if governments do not guarantee proper diffusion of new knowledge. Nevertheless, the risk of governmental failure exists when public investment in R&D is allocated based on policymakers' own interests or when the public investment is too high resulting in a crowd-out effect of private investment by public expenditures [54,55]. Thus, analysis of technological change processes including innovation-oriented policy strategies (e.g. public investment in energy R&D) is crucial to gain a deeper understanding on

how public resources are spent and the effects of that expenditure.

Furthermore, although learning curve theory is widely used to predict future energy technology costs, significant uncertainties have been identified around learning curve model formulations and their use in energy-economic models for policy analysis [8]. A common question that has emerged among scholars, analysts, and policymakers is: what is the 'best' model formulation to represent technological learning for a specific technology? There is no definitive answer to this question [8]. It has been argued that outputs obtained from long-term modelling exercises are highly sensitive to input assumptions [29,56]. For example, while learning curves may explain how technology costs have evolved in the past, they may provide limited insights regarding how these costs are likely to change in the future [4]. Thus, the selection of model formulations and assumptions to project future technology costs may have considerably different policy implications (e.g. different technology deployment levels, different costs of mitigation policies) [10]. Additional inquiries related to structural definition include: what sources of learning better explain costs changes? How those sources of learning are defined and formulated? [4]. The selection of 'appropriate' definitions of learning sources and parameters to explain technology cost developments is closely related to the conceptualisation of the learning system and the definition of its boundaries [9].

Although additional caveats of learning curves have been discussed in the literature (e.g. learning rates are commonly assumed to be positive and remain constant over time, not accounting for radical improvements) [9,13], this article focusses on addressing three key limitations: (1) high level of aggregation regarding learning-by-deployment by proposing a new definition of experience to account for different learning processes (i.e. learning-by-doing, learning-by-using, and experience spillovers); (2) omitted variable bias by including knowledge stock as a second source of learning; and (3) structural uncertainty by investigating the potential policy implications of choosing alternative learning curve approaches to describe technological learning processes.

3. Methods and data

Different review studies on the application of learning curve theory to energy technologies have been reported. These reviews encompass power generation technologies in general [9,10,19,57] and individual generation technologies in particular, such as solar PV [11,29,58–60], wind [11,39,61,62], and fossil fuel-based technologies [63]. Also, applications on energy efficiency [7], and energy demand technologies [64] have been investigated. A wide range of learning rates for energy technologies have been reported in past studies using different model structures, data periods, and geographical locations (see Ref. [19] for an overview of 444 estimated learning rates). Based on previous reviews [9–11,13,19], Table 1 and Table 2 present a summary of estimated learning rates for onshore wind and solar PV for the USA, respectively.

The studies above suggest that the process of estimating learning rates for energy technologies is driven by several factors such as model structure, definition of the learning factors to be used, boundary of the learning system, time period, and variables to be considered [9,15]. Thus, the estimation of learning rates depends on the context of analysis and differs per situation [65]. In this article an integrative learning curve model has been developed by combining different learning curve methods to explore the relative impact of alternative model structures on technology capital cost developments. The integrative model is used to estimate learning rates for onshore wind and solar PV in the USA using different variables and time periods.

3.1. An integrative learning curve model

The integrative learning curve model developed in this work starts from the general learning curve model adapted from Ref. [81] and defined in this article as in Eq. (1):

$$C(\mathrm{X})_{t,y} = C(\mathrm{X}_0)_t \left(\frac{\mathrm{X}_y}{\mathrm{X}_0}\right)_t^{-\ell} \quad (1)$$

where $C(X)_{t,y}$ represents the capital cost of technology t at year y as a function of technological learning processes, X denotes the learning source (e.g. accumulation of technological knowledge or experience), $C(X_0)_t$ is the capital cost of technology t at time $y = 0$ (i.e. initial capital cost), and ℓ is the learning index (i.e. elasticity of learning to capital cost). The learning index is related to the learning rate (LR) by Eq. (2), adapted from Ref. [71]:

$$LR = 1 - 2^{-\ell} \quad (2)$$

The learning rate represents the percentage of capital cost reduction of a technology for every doubling of cumulative values of learning factor(s). The progress ratio (PR) is an alternative option for representing this relationship. PR represents the relative remaining capital cost of the technology after a doubling of the cumulative learning factor (s) considered and is expressed as in Eq. (3), adapted from Ref. [71]:

$$PR = 1 - LR \quad (3)$$

In Eq. (1) only one source of learning is considered (i.e. X). However, technological learning may occur through multiple channels as discussed in Section 2. When more than one source of learning is considered, the term 'learning multiplier' (LM) is introduced in the model to account for the change in technology capital costs due to technological progress through multiple factors. Thus, LM represents the combined learning effects on technology capital cost developments. Based on the

Table 1
Summary of learning rates for onshore wind in the USA using different model formulations and time periods.

No	Model	Period	Dependent cost variable	Experience metric	LbD rate %	Knowledge stock metric	LbR rate %	Ref.
1	1FLC	1985–1994	Cost of electricity ($ kWh^{-1})	Cumulative electricity production (TWh)	32	–	–	[66]
2	1FLC	1982–2004	Installed project cost ($ kWh^{-1})	Installed capacity (MW)	14.4	–	–	[67]
3	1FLC	1982–2006	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	16	–	–	[68]
4	1FLC	1982–2010	Installed project cost ($ kWh^{-1})	Installed capacity (MW)	8.3	–	–	[67]
5	1FLC	1982–2015	Installed project cost ($ kWh^{-1})	Installed capacity (MW)	6.5	–	–	[69]
6	1FLC	1990–2015	Electricity generation costs ($ kWh^{-1})	Cumulative electricity generation (kWh)	10	–	–	[70]
7	1FLC	2006–2010	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	−10	–	–	[68]
8	1FLC	2010–2020	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	40	–	–	[68]
9	2FLC	1981–1997	Capital cost ($ kW^{-1})	Cumulative capacity (MW)	14.2	Public R&D ($m)	18	[71]
10	2FLC	1985–1995	Generation costs ($ MWh^{-1})	Number of turbines installed	18	Public R&D ($m)	32	[72]
11	2FLC	1986–2002	Investment cost ($ kW^{-1})	Cumulative capacity (MW)	6.89	Public R&D ($m)	8.62	[73]
12	2FLC	2009–2016	Investment costs ($ kW^{-1})	Cumulative installed capacity (MW)	17.5	Public R&D ($m)	37	[74]
13	MFLC[a]	1999–2006	Wind energy price ($ MWh^{-1})	Generating capacity (MW)	4.19	–	–	[75]

[a] Additional learning sources were used in MFLC such as economies of scale, market demand dynamics, and supply change dynamics.

Table 2
Summary of learning rates for solar PV in the USA using different model formulations and time periods.

No	Model	Period	Dependent cost variable	Experience metric	LbD rate %	Knowledge stock metric	LbR rate %	Ref.
1	1FLC	1959–1974	Specific sale price ($ kW_p^{-1})	Cumulative installed capacity (MW)	22	–	–	[76]
2	1FLC	1976–1988	Factory price of PV module ($ W_p^{-1})	Cumulative PV sales (W_p)	22	–	–	[77]
3	1FLC	1976–1992	PV module selling price ($ W_p^{-1})	Cumulative PV sales (W_p)	18.4	–	–	[78]
4	1FLC	1979–2005	PV module price ($ W^{-1})	Cumulative production (MW)	19	–	–	[79]
5	1FLC	1990–2000	PV module cost ($ W^{-1})	Cumulative output (shipments)	23	–	–	[80]
6	1FLC	1990–2000	PV module price ($ W_p^{-1})	Cumulative output (shipments)	20	–	–	[80]
7	1FLC	1992–2000	PV module price ($ W_p^{-1})	Cumulated capacity (MW)	32	–	–	[80]
8	1FLC	1992–2000	PV module price ($ W_p^{-1})	Cumulated electricity (GWh)	28	–	–	[80]
9	1FLC	2007–2014	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	12	–	–	[68]
10	1FLC	2014–2020	Levelised cost of energy ($ MWh^{-1})	Cumulative installed capacity (GW)	45	–	–	[68]
11	2FLC	1975–2000	Capital cost ($ kW^{-1})	Cumulative capacity (MW)	18.4	Public R&D ($m)	14.3	[71]
12	2FLC	2009–2016	Investment costs ($ kW^{-1})	Cumulative installed capacity (MW)	6.78	Public R&D ($m)	75.21	[74]

two-factor learning curve model proposed by Ref. [39], technological learning is defined in this article as a function of experience (*E*) and knowledge stock (*KS*) as in Eq. (4). Definitions of experience and knowledge stock are detailed in Sections 3.1.1 and 3.1.2.

$$LM(E,KS)_{t,y} = \left(\frac{E_y}{E_0}\right)_t^{-lbd} \left(\frac{KS_y}{KS_0}\right)_t^{-lbr} \quad (4)$$

where *lbd* represents the learning-by-deployment elasticity, and *lbr* is the learning-by-researching elasticity. Thus, the change in technology capital cost is also defined in this article as a function of experience and knowledge stock as in Eq. (5).

$$C(E,KS)_{t,y} = C(E_0,KS_0)_t \cdot LM(E,KS)_{t,y} \quad (5)$$

In addition, in this work, not all the capital costs associated with a technology are affected by technological learning processes. As argued in the study conducted by Ferioli et al. [81], understanding cost structure is relevant because some cost components may not experience learning (e.g. financial or management costs) while other components do (e.g. domestic-produced and imported electricity generation equipment). For the case of renewable energy technologies (e.g. onshore wind and solar PV in the case of this study), electricity generation equipment (e.g. wind turbines and PV panels) may be affected by technological learning, usually known as 'hardware' costs [82], while other costs may not be reduced through technological learning processes (e.g. assembly, transportation, permitting). Thus, based on the component-based learning model developed by Ref. [81], the total technology cost in this article is split into diverse components where α is defined as the share of the total capital cost that can be affected by learning processes for technology *t*. Thus, the model proposed in this article focusses on the cost components affected by learning processes (i.e. technological-based capital cost) and it is redefined as in Eq. (6):

$$\alpha_t \cdot C(E,KS)_{t,y} = \alpha_t \cdot C(E_0,KS_0)_t \cdot LM(E,KS)_{t,y} \quad (6)$$

3.1.1. Definition of experience

Cumulative installed capacity of a particular energy technology is the most common variable used as a proxy in technological learning models to represent experience (see Tables 1 and 2). The model developed in this article also uses cumulative installed capacity to represent experience. Some studies on energy technologies emphasise that experience is a global public good [21,35,83]. This assumption implies that domestic experience (i.e. local installed capacity) may spill over worldwide and thus the estimated learning rates are valid only to the case where global experience (i.e. global installed capacity) doubles [21]. However, estimates of learning rates based only on international explanatory variables may not be valid in a local setting [22,84]. For instance, quantitative support was found for the argument that improving national learning conditions (e.g. stable regulatory frameworks, skilled workforce) may have a more substantial impact on cost reductions in developing countries than global experience [84]. Thus, technological experience should encompass both a local and a global component. For instance, a study conducted by Ek [21] suggested that in the case of onshore wind power generation plants in Europe, the wind turbine may represent the global component because it is usually acquired in the international market and constitutes around 70% of the total capital costs. Thus, 30% may be attributed to domestic activities such as installation, electric connections, and management [21]. Similarly, a study conducted by Huenteler et al. [84] identified that, for the case of solar PV in Thailand, 57% of the total technology cost corresponds to globally sourced parts (e.g. PV modules and inverters) while 43% accounts for locally sourced parts (e.g. balance of system).

The relative contribution of local and global technological learning to the cost reductions of renewable electricity technologies has been investigated in Refs. [22,84–86]. It has been argued that energy companies not only learn from previous internal experience but they may also benefit from external technology deployment and R&D expenditures, described as spillover effects [4,22,87]. Knowledge flow contributes to the spread of basic and applied scientific developments (i.e. knowledge spillovers) and the diffusion of energy technologies due to the economic benefits of innovation (i.e. experience spillovers) [40]. Knowledge and experience spillovers can be explained by different diffusion processes. For instance, the concept of *technology spillovers* refers to the case when different power generation technologies share one or more major components, which may be affected by technological learning (also known as *cluster effects* [4]). *Intra-industry spillovers* take place when knowledge is diffused among firms within the electricity industry in and within countries [35]. *Sectoral spillovers* occur when advancements in different sectors of the economy drive cost reductions in the power sector [88]. I*nternational spillovers* accounts for the knowledge diffused among countries [40]. Knowledge flow across countries is key in fostering technological innovation in regions different from where it was originally generated. In order to limit the scope of the article, technology and sectoral spillovers are not considered here.

International spillovers in energy systems consider that knowledge may flow across countries in two main forms: as tacit knowledge embodied in traded intermediate or final goods (e.g. solar panels, wind turbines) or information disembodied in patents, blueprints, exchange of ideas among researchers or scientific bodies, and imitation [40]. In order to account for the effect of embodied knowledge flow, the model proposed in this article splits experience into its local and global components, based on cumulative installed capacity (see Fig. 1). Disembodied knowledge stock is addressed in Section 3.1.2 through international knowledge spillover effects.

Local experience is defined in this article as the sum of experience gained through learning-by-doing (i.e. locally produced installed capacity) and learning-by-using (i.e. share of imported installed capacity that is used and assimilated locally). Experience spillovers are conceptualised as the share of external installed capacity that influence learning processes locally (i.e. external experience affecting local learning). The sum of local experience and external experience affecting local learning represents the total experience (i.e. learning-by-

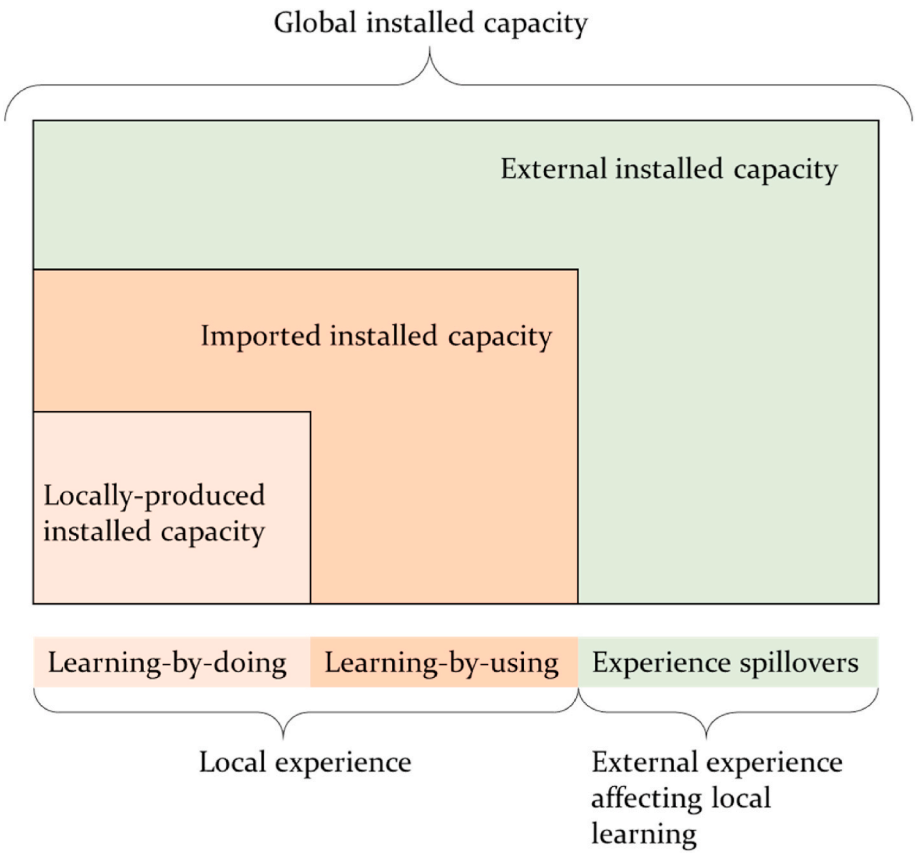


Fig. 1. Conceptualisation of experience based on local and global installed capacity and learning-by-deployment sub-processes.

deploying).

Experience gained though learning-by-doing (E_{lbdo}) for technology t at year y is defined in this article as in Eq. (7):

$$(E_{lbdo})_{t,y} = (\beta \cdot CC_Dom)_{t,y} \tag{7}$$

where β represents the share of domestic content (i.e. locally sourced resources), and *CC_Dom* accounts for domestic cumulative installed capacity for technology t at year y.

To account for experience gained through learning-by-using two concepts are used within the proposed model: industry experience pool and industry absorptive capacity. What an industry can learn from intra-industry spillovers is a function of both the amount of spillover available to be learned (i.e. industry experience pool, represented by imported installed capacity in this case) and the absorptive capacity of the industry [86]. The concept of absorptive capacity was introduced by Ref. [89] to model the flow of scientific and technological knowledge at the firm level [26]. Although absorptive capacity has been extensively applied at the firm level (see Ref. [90] for a review), the concept can be extended to a specific industry (i.e. industry absorptive capacity), or to an entire country (i.e. national absorptive capacity) [26]. Based on [91], industry absorptive capacity refers to a broad array of skills that reflect the need to deal with the tacit components of transferred technology and also the need to modify a foreign-sourced technology for domestic applications. Applying the concept of absorptive capacity from Ref. [91] to technological experience gained through learning-by-using, industry absorptive capacity is defined in this article as the ratio of locally produced installed capacity to the industry technological frontier, represented in this case as the total domestic installed capacity. Thus, learning by using (E_{lbu}) of technology t at year y is represented in this article as in Eq. (8):

$$(E_{lbu})_{t,y} = \left(\frac{\beta \cdot CC_Dom}{CC_Dom} \cdot [(1-\beta) \cdot CC_Dom]\right)_{t,y} \tag{8}$$

In addition, based on [26,86], the experience spillover effect is represented in this study as a function of the external installed capacity (i.e. external to the country of interest) and the absorptive capacity of the country. The absorptive capacity of the country is defined in this study as the ratio of domestic installed capacity to the global installed capacity (i.e. international technological frontier, represented by the cumulative installed capacity of the OECD countries). Thus, the experience spillover effect (E_{spill}) of technology t at year y is defined as in Eq. (9):

$$(E_{spill})_{t,y} = \left(\frac{CC_Dom}{CC_Glo} \cdot (CC_Glo - CC_Dom)\right)_{t,y} \tag{9}$$

where *CC_Glo* and *CC_Dom* represent global and domestic cumulative installed capacity, respectively. External installed capacity (*CC_Ext*) is defined as the difference between global and domestic installed capacity (i.e. external experience stock available). Based on the concept of national absorptive capacity [91], the experience spillover coefficient (γ) is introduced in the model developed to account for the ratio of domestic installed capacity to the international technological frontier as previously proposed by Refs. [26,86]. Thus, technological experience for technology t at year y is redefined in this article as in Eq. (10):

$$E_{t,y} = [\beta \cdot (2-\beta) \cdot CC_Dom]_{t,y} + [\gamma \cdot CC_Ext]_{t,y} \tag{10}$$

where the first term represents local experience, gained through both learning-by-doing and learning-by-using, and the second term accounts for experience spillover effects. When β and γ are set equal to 1, only global experience is used to represent experience. On the other hand, when $\beta = 1$ and $\gamma = 0$, only local experience is considered in the

definition of experience. A summary of the combination of values for these two parameters and their effects is presented in Table 3. This article focusses on exploring the relative impact of experience represented by global only (i.e. $\beta = 1$ and $\gamma = 1$), local only (i.e. $\beta = 1$ and $\gamma = 0$), and when global and local experience are considered (i.e. $0 < \beta < 1$ and $0 < \gamma < 1$).

3.1.2. Definition of knowledge stock

Knowledge stock has been modelled using different structures in the literature. In its simplest form, knowledge stock is represented by cumulative R&D expenditures, as proposed by Ref. [27]. However, a study conducted by Klaassen et al. [39] extended the knowledge stock concept by incorporating a depreciation rate of knowledge and the time lag between the actual R&D spending and their addition to the knowledge stock. Additionally, studies [30,40] proposed that new knowledge is produced not only by R&D expenditures and previous cumulative knowledge stock but also by international knowledge spillovers. The method used in this article to estimate cumulative R&D-based knowledge stock (*KS*) is based on [92]. Thus, KS of technology t in year y is estimated as in Eq. (11):

$$KS_{t,y} = (1 - \rho_t) KS_{t,y-1} + Z_{t,y} \tag{11}$$

where ρ ($0 \leq \rho \leq 1$) is the annual depreciation rate of KS of technology t in year *y-1* (i.e. cumulative previous KS), and $Z_{t,y}$ is defined as the process of new knowledge creation for technology t at year y. Eq. (11) considers that previous knowledge depreciates (i.e. becomes more irrelevant) with time due to several factors such as staff turnover, retirement, and rapid innovation [39]. Each energy technology may have a different rate of depreciation (see Section 3.3.3). Knowledge creation can be modelled as a function of public research, development, and demonstration (RD&D) spending, cumulative previous KS, and international knowledge spillovers as developed in Refs. [30,40,92]. Thus, based on [92], $Z_{t,y}$ is defined in this study as in Eq. (12):

$$Z_{t,y} = a \cdot RDnD^{b}_{t,y-g} \cdot KS^{c}_{t,y-1} \cdot SPILL^{d}_{t,y-g} \tag{12}$$

where parameter a reflects the domestic knowledge dissemination policies factor, g represents the time lag between the RD&D activity and its effects, *RDnD* denotes RD&D investment in technology t in year *y-g*, *KS* is the cumulative knowledge stock of technology t at year *y*-1, *SPILL* is the international knowledge spillover effect, and b, c, and d denotes the elasticities of the creation of new knowledge to the independent variables. These elasticities are between 0 and 1 [92]. Also, empirical studies have shown that creation of new knowledge in the energy RD&D sector exhibits diminishing returns (i.e. $b + c + d < 1$) [40,93].

Eq. (12) takes into account that RD&D expenditures, both domestic and international, do not have an instantaneous effect on learning, thus it may lead to tangible results after some time (i.e. parameter g). Also, it considers that new knowledge created through public investment RD&D in energy technologies is a 'public good' and therefore it can be applied by almost everyone, with the background and resources needed, as soon as it is publicly available (i.e. knowledge spillovers) [55]. Knowledge dissemination policies (e.g. promotion of institutional collaboration, fostering open-source publications, or improving national innovation systems) may facilitate or hinder the assimilation of new knowledge created. If countries do not invest in building technological capabilities, they may not have the capacity to absorb new knowledge created in other countries [94].

The potential effects of international RD&D-based spillovers on the energy sector have been reported in the literature (see Refs. [40,92]). Based on [92], two variables are used in this article to estimate RD&D-based international spillover effects: international knowledge pool (*KP*) and domestic absorption capacity of international knowledge spillovers (δ). Public RD&D-based knowledge is generated globally, either by country-specific efforts or by international cooperation, and it may be available to all countries (i.e. the public-good aspect of public RD&D). However, the process of knowledge creation does not follow the same dynamics and pace everywhere. Thus, countries are exposed to a pool of knowledge generated by other countries where a portion of this knowledge can be absorbed by follower countries [92]. The knowledge gap between the sum of global KS and the country of interest's KS is defined as the international knowledge pool (i.e. the knowledge available to the country of interest). Based on [92], this difference is represented in this study as the distance between domestic public investment in RD&D and the technology frontier. Similar to Ref. [30], the technology frontier is denoted by the knowledge stock generated by the OECD countries in the model developed in this study. The absorption capacity of a country represents the portion of the available international knowledge pool that the country of interest may be able to absorb. This value depends on various factors such as specialised human resources, laboratories, patents, energy innovation research groups and institutions, which are influenced by public investment in RD&D of energy technologies [95,96]. Thus, based on [92], international knowledge spillovers (*SPILL*) for technology t in country n at year y is estimated in this article as in Eq. (13):

$$\begin{aligned} SPILL_{t,n,y} &= \delta_{t,n,y} \cdot KP_{t,n,y} \\ &= \frac{RDnD_{t,n,y}}{\sum_{n \in OECD} RDnD_{t,n,y}} \left(\sum_{n \in OECD} RDnD_{t,n,y} - RDnD_{t,n,y} \right) \end{aligned} \tag{13}$$

Thus, the technological-based capital cost of technology t in a country n at year y is redefined in this article using an integrated learning curve model as in Eq. (14):

$$\alpha_t \cdot C(E, KS)_{t,n,y} = \alpha_t \cdot C(E_0, KS_0) \left(\frac{E_y}{E_0} \right)^{-lbd}_{t,n} \left(\frac{KS_y}{KS_0} \right)^{-lbr}_{t,n} \tag{14}$$

where E is defined as in Eq. (10) and *KS* as in Eq. (11).

Using a logarithmic transformation, Eq. (14) can be expressed as in Eq. (15):

$$\begin{aligned} \log[\alpha_t \cdot C(E, KS)]_{t,n,y} = \log[\alpha_t \cdot C(E_0, KS_0)] - ldb \cdot \log \left[\left(\frac{E_y}{E_0} \right)_{t,n} \right] \\ - lbr \cdot \log \left[\left(\frac{KS_y}{KS_0} \right)_{t,n} \right] \end{aligned} \tag{15}$$

Eq. (15) is used to investigate the relative impact of using different technological learning approaches on technological-based capital costs for onshore wind and solar PV in the USA. The relative impact is revealed by estimating the corresponding learning rates. Learning-by-deploying (LbD) and learning-by-researching (LbR) rates are estimated based on the relationship between technological-based cost developments as a dependent variable, and experience (using cumulative installed capacity as a proxy) and knowledge stock (using public RD&D expenditure as a proxy) as independent variables.

Table 3
Values for parameters used to represent experience.

β[a]	γ[b]	Experience is represented by
1	1	Global installed capacity
1	0	Domestic installed capacity
0	1	External installed capacity (no domestic experience is assumed)
0	0	No experience is assumed
0–1	0–1	Global and domestic installed capacity

[a] Share of domestic content.
[b] Experience spillover coefficient.

3.2. Data sources and periods of analysis

To estimate experience and knowledge stock, data collected on capital cost, cumulative installed capacity, and public expenditures in

Table 4
Data collected for onshore wind and solar PV.

Item	Unit	Period	References
Domestic (USA) cumulative installed capacity	MW[a]	1974–2020	[12,97]
Global (OECD countries including USA) cumulative installed capacity	MW	1974–2020	[12,97]
Domestic (USA) annual public RD&D expenses	$m[b]	1974–2020	[98–103]
Global (OECD countries including USA) annual public RD&D expenses	$m	1974–2020	[98–103]
Domestic (USA) capital cost	$ kW^{-1}[c]	1983–2020 (onshore wind) 1974–2020 (solar PV)	[6, 104–107]

[a] Megawatt (MW).
[b] Millions of USA dollars in constant 2020 prices and purchasing power parities rates ($m).
[c] 2020 USA dollars per Kilowatt (2020 $ kW^{-1}).

RD&D for onshore wind and solar PV are summarised in Table 4.

Monetary values were reported in 2020 USA dollars. They were estimated accounting for inflation based on the average annual consumer price index (CPI) in the USA [108]. A brief overview of the data used to estimate experience and knowledge stock is described in this section.

3.2.1. Onshore wind

Installed wind power project costs over time in the USA, based on capacity-weighted average, are depicted in Fig. 2. Data collected by the Lawrence Berkeley National Laboratory include 1128 completed onshore wind projects accounting for around 88% of total land-based wind power generation installed capacity in the USA at the end of 2020 [107].

In Fig. 2, a declining trend in installed wind power project costs is observed from the 1980's (i.e. the beginning of the wind industry in the USA) to the early 2000's. However, from 2004 to 2010 costs increased significantly. This trend is attributed mainly to an increase in the cost of imported wind turbine components due to a weakening U.S. dollar, rising labour costs, changes in warranty provisions among turbine manufacturers, and increasing commodities and energy prices [106,109]. From 2010 to 2020 a new decreasing trend in costs values can be observed in Fig. 2. Some empirical studies have suggested that historical cost changes for specific technologies may be better explained by two or more periods with different learning rates (see Refs. [61,68,110]). This may be shown as learning curves with discontinuities [9]. Following this idea, this article estimates learning rates for onshore wind power generation technology for three different periods: 1989–2004 (first period of cost reduction trend), 2004–2010 (cost increase trend), and 2010–2020 (second period of cost reduction trend). Although data on installed wind power project costs are available from 1983 in Ref. [107], 1989 is selected as the initial modelling value due to data availability on cumulative installed capacity for onshore wind technologies for the USA (see Fig. 3).

As the definition of experience in this article is based on global and local installed power generation capacity, the development of onshore wind cumulative installed capacity is depicted in Fig. 3. Although wind energy utilisation dates back more than five thousand years ago [111], available data regarding onshore wind power capacity within the IEA Electricity Information Statistics database [112] start from 1981 for OECD countries (1 MW) and 1989 for the USA (1337 MW domestic and 1650 MW international at the time). In 2020, the OECD installed capacity for wind was 368 GW, while USA domestic installed capacity accounted for 118 GW (around 32% of the OECD installed capacity) [12].

In order to estimate knowledge stock, the analysis of public investment in RD&D is needed. Fig. 4 shows the development of annual public investment in RD&D for wind energy for the OECD countries and USA from 1974 to 2020. It is worth noting that the effects of different global and domestic events are visually evident throughout the period analysed. For instance, increasing RD&D expenditures for wind technologies after the main energy crises (1973, 1979, and 2008) are clearly shown in Fig. 4. Furthermore, the effects of international agreements on environmental concerns (e.g. the UNFCCC treaty adopted in 1992, and the Paris Agreement and Mission Innovation adopted in 2015) are evident in the figure accounting for a rise in public investment in RD&D for clean energy technologies in general and wind technologies in particular. On the other hand, the low oil prices along the second half of the 1980's had a negative effect on annual public investment RD&D in alternative energy sources of fossil fuels, including wind.

3.2.2. Solar PV

Solar PV capital costs in the USA from 1974 to 2020 are depicted in Fig. 5. Unlike wind, the authors of this article did not have access to an integrative historical database for the whole period of analysis. Thus, learning rates for solar PV power generation technology are estimated

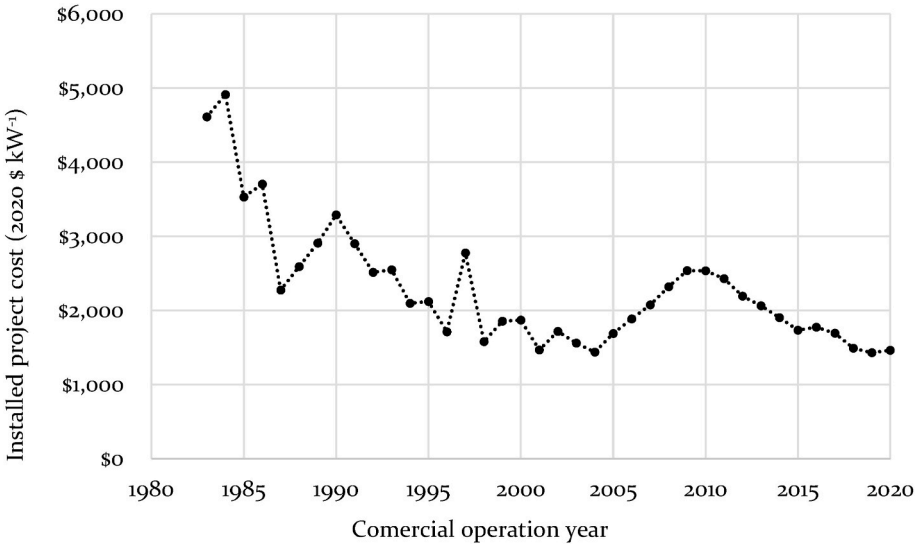


Fig. 2. Installed wind power project costs over time in the USA. Constructed with data from Refs. [106,107].

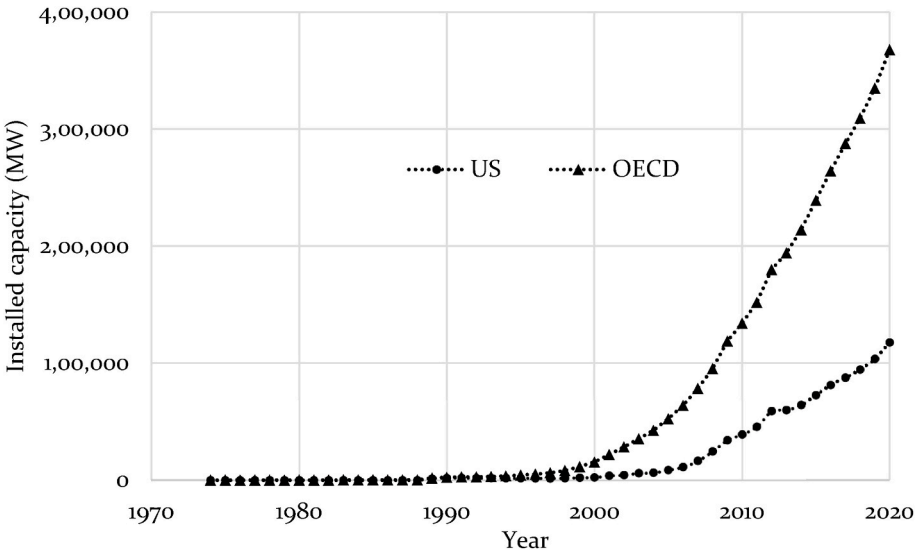


Fig. 3. Domestic (USA) and international (OECD) wind power generation installed capacity in MW. Constructed with data from Refs. [12,97].

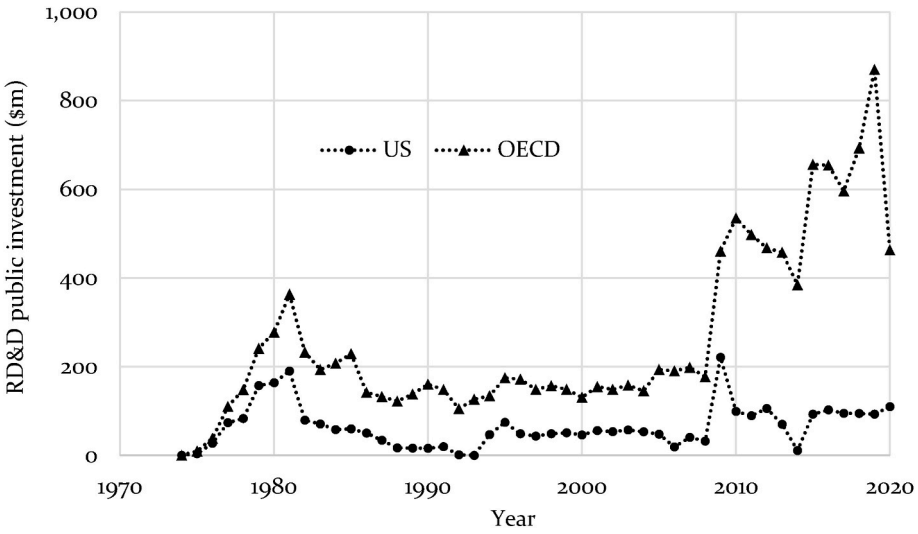


Fig. 4. Domestic (USA) and international (OECD) public investment in RD&D for wind technologies in 2020 $m and PPP. Constructed with data from Ref. [103].

for two different periods: 1992–2009 (based on data from Refs. [104,105]), and 2010–2020 (based on data from Ref. [6]). As for wind, the period of study for solar PV was defined based on data availability on installed capacity for both the USA and OECD countries (i.e. 1992 set as the initial modelling year).

Like onshore wind, power generation installed capacity for solar PV has rapidly increased in recent years (see Fig. 6). In 2020, the OECD installed capacity for solar PV was 344 GW, while USA domestic installed capacity accounted for 74 GW (around 21% of the OECD installed capacity) [6].

Fig. 7 shows the development of annual public investment in RD&D for solar PV energy for the OECD countries and the USA from 1974 to 2020. Similar to wind, the effects of global and domestic events are noticeable throughout the period analysed. It is evident that there is a decreasing trend in public RD&D expenditure for solar PV worldwide, and no expenditure at all in the USA from 2016 to 2020.

3.3. Parameters setting

To empirically estimate learning rates using Eq. (15), parameters considered in Eqs. (6)–(8) and (10)–(12) and (14) must be set. Thus, based on previous studies these parameters are set and explained as follows.

3.3.1. Capital cost structure

Total capital cost structure differs among electricity generation technologies. For instance, for land-based wind projects not only the cost of the turbine (i.e. rotor, nacelle, and tower) is considered but also balance of system (BOS) costs and 'soft' costs. BOS costs for a wind power plant refer to infrastructure components other than the turbines (e.g. wiring, substation hardware). Soft costs encompass non-infrastructure costs associated with the plant (e.g. permitting) [113]. Similarly, for utility-scale solar PV the PV modules and inverters integrate the main hardware costs, while racking and wiring are encompassed within BOS costs, and soft costs include installation labour, system design, permitting, among others [82,114].

In order to define the share of the total technology cost that can be affected by learning processes (i.e. α) the study distinguishes between technological-based costs and non-technological costs. The former account for those that are affected by technological learning processes and the latter encompass costs that may not have a direct change due to learning processes. In the case of onshore wind, this study assumes that

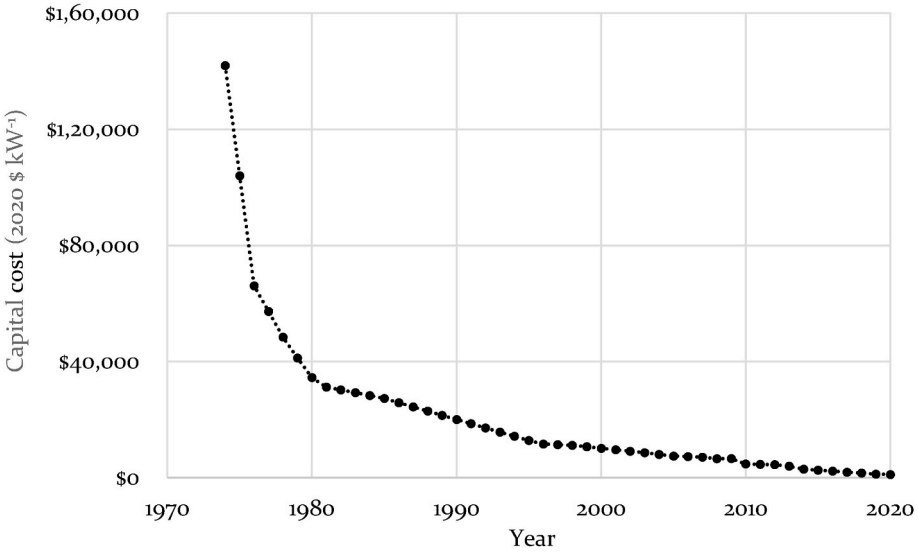


Fig. 5. Installed solar PV costs over time in the USA. Constructed with data from Refs. [6,104,105].

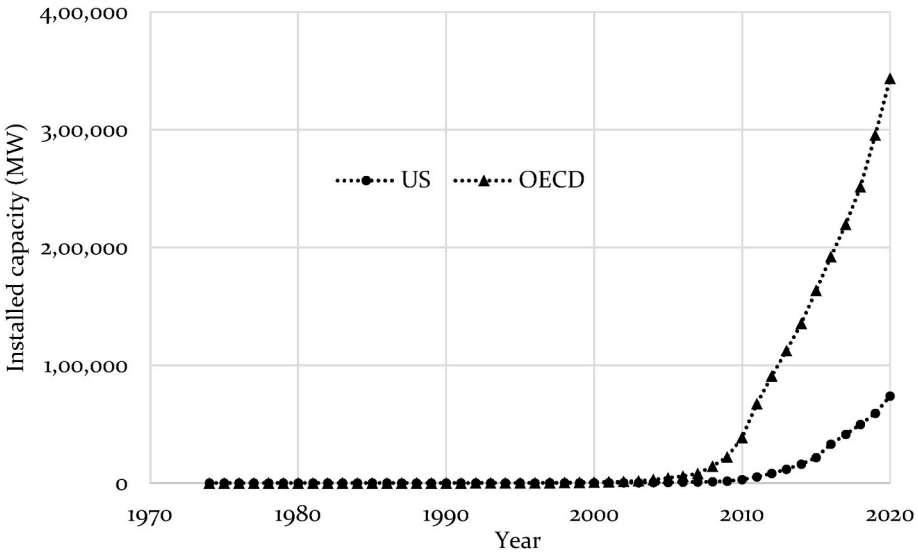


Fig. 6. Domestic (USA) and international (OECD) solar PV power generation installed capacity in MW. Constructed with data from Refs. [12,97].

technological-based costs include the turbine (i.e. rotor, nacelle, and tower) and electrical infrastructure, while non-technological costs encompass foundation, turbine transportation, site access and staging, assembly and installation, project management, development, construction finance, and contingency. Similarly, technological-based costs for solar PV include the module, inverter, and hardware balance of system, while non-technological costs include permitting, inspection and interconnection, engineering, procurement and construction, labour costs, and other soft costs. Based on historical reviews on the cost structure of wind and solar energy technologies [82,115–123], this study assumes that technological-based costs account for 78% (i.e. $\alpha = 0.78$) and 62% (i.e. $\alpha = 0.62$) of the total technology capital cost for onshore wind and solar PV, respectively (see Fig. 8).

3.3.2. *Domestic content and international trade*

The renewable sector in the USA is highly reliant on foreign supply chains. However, imported content varies widely depending on the technology and the type of components. For instance, due to high transportation costs, large components for wind technologies such as tower and blades are more likely to be manufactured domestically [113]. Although domestic manufacturing content in the USA is strong for some wind turbine components (e.g. towers, blades and hubs), the wind industry also relies significantly on imports for some equipment (e.g. most components internal to the nacelle) [107]. It has been reported that imports of wind-related equipment into the USA declined substantially from around 80% in 2006–2007 to approximately 30% in 2012–2013 [124]. To estimate the share of domestic content for onshore wind over time, this study followed the approach presented in Ref. [124] (p. 24), based on estimated imports of tracked wind-related equipment into the USA, and by using updated data from Ref. [107]. Estimated share of domestic content (i.e. parameter β) for onshore wind in the USA varies from 22% in 2007 to 68% in 2020 (see Fig. 9), which is consistent with values previously reported in Ref. [124]. Due to lack of available data, 22% is assumed for years before 2007.

In contrast to the USA wind industry, the USA solar manufacturing supply chain is mainly reliant on imports for key components (e.g. inverters, cells, wafers, and many balance-of-system components) [125]. Although the first PV device was invented in New Jersey (USA) in 1954 and the USA government supported its development and deployment through the implementation of different policies (e.g. public RD&D),

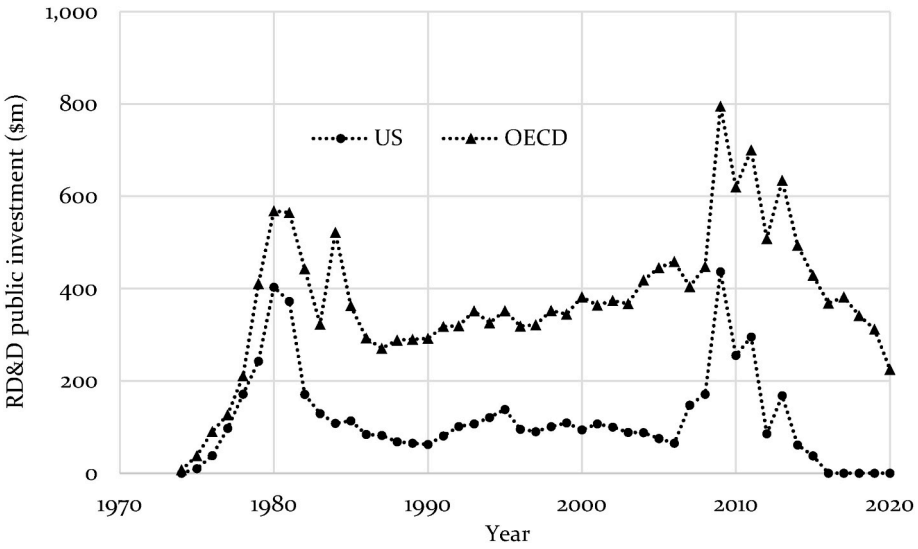


Fig. 7. Domestic (USA) and international (OECD) public investment in RD&D for solar PV in 2020 MM$ and PPP. Constructed with data from Refs. [98–103].

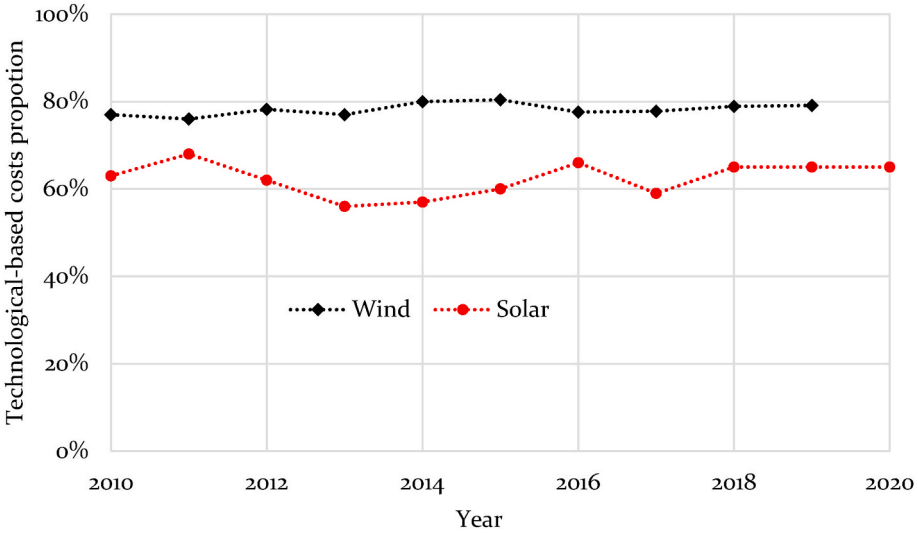


Fig. 8. Modelled trend of technological-based costs as a proportion of total capital cost for onshore wind and solar PV in the USA. Constructed with data from Refs. [82,115–123].

China became the dominant global player in the production of PV modules and cells since the 2010's, with significant help from government subsidies, affecting the global supply chain [126,127]. To estimate the share of domestic content for solar PV over time, this study used the ratio of USA solar PV annual production, obtained from Ref. [128], to the annual installed capacity of solar PV in the USA, presented in Ref. [97], from 1993 to 2012. Unlike onshore wind, the estimated share of domestic content for solar PV technologies in the USA declined from 100% in 2009 (i.e. all capacity was met domestically) to 27% in 2012 (see Fig. 9). Due to lack of available data, 27% is assumed for years after 2012.

3.3.3. *Annual depreciation rate of knowledge and time lag for RD&D investment effects*

Assumptions regarding annual depreciation rate of KS and time lag between energy RD&D expenditures and effects on KS are also needed to conduct this investigation. An examination of knowledge depreciation rates for the energy sector was carried out in a study conducted by Grubler et al. [129], where they found that typical rates ranges from 10% to 40%. However, in the case of renewable energy technologies these rates may be lower from the cited range. For instance, for wind technology, depreciation rates of 2.5% [71], 3% [43,130], 5% [39] and 10% [92] have been used in different studies.

In the case of the time lag between public investment RD&D in energy technologies and the gain of knowledge, most scholars have reported 2–5 years as the most suitable values for this parameter (see Refs. [39,43,71,131]). A sensitivity analysis regarding knowledge depreciation rates and time lags presented in Ref. [55], has found higher sensitivity of KS with respect to the obsolescence of knowledge among energy technologies (primarily due to changing innovation rates). However, 10% as the depreciation rate of previous KS and 3 years as the time lag between public investment in RD&D for energy technologies is commonly used in the literature (see Refs. [55,92]). Based on these previous studies, values of 10% for ρ and 3 year for g are assumed within this study.

3.3.4. *International knowledge spillover effects*

Constants and coefficients for international spillover effects have been empirically estimated and used in Refs. [40,92,132]. For instance, elasticity coefficients b, c, and d in Eq. (12) were set equal to 0.2, 0.55,

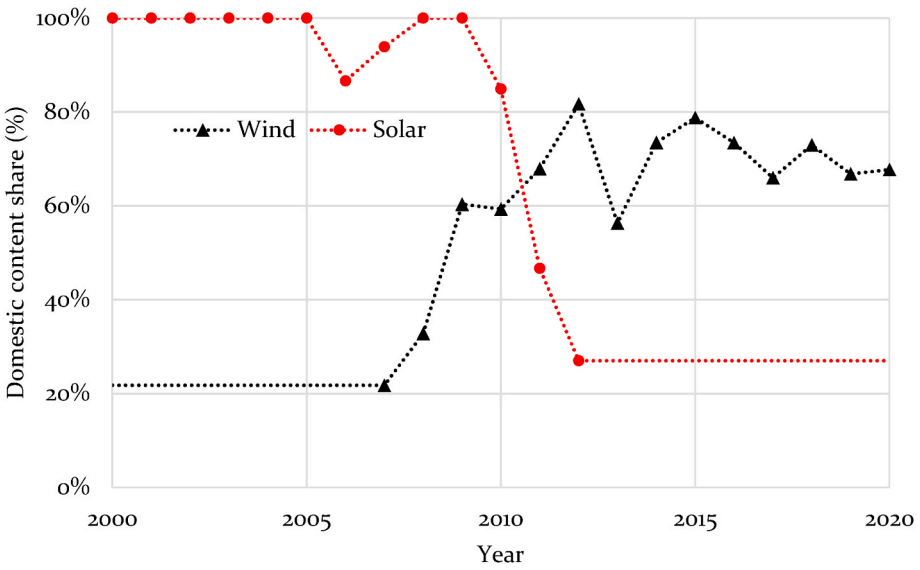


Fig. 9. Estimated share of national content for onshore wind and solar PV in the USA from 2000 to 2020. Constructed with data from Refs. [97,107,128].

and 0.15, respectively in Ref. [92] to investigate the influence of public RD&D and international spillover effects on the development of renewable energy sources. These elasticities represent the ratio of percentage change of the creation of new knowledge (i.e. *Z*) with respect to the change in the explanatory variables considered in Eq. (12) (i.e. *RDnD*, *KS*, and *SPILL*). When *d* is set to 0.15, an increment of 1% of international knowledge spillovers (*SPILL*) increases the output of *Z* (i.e. creation of new knowledge) by 0.15%.

A sensitivity analysis of the elasticity of new knowledge creation to international knowledge spillovers carried out in Ref. [92] revealed that 0.15 is a suitable value for *d*, as initially proposed in Ref. [40]. Due to lack of research on empirical foundation of the value of the elasticity of knowledge generation to international spillovers, this was chosen lower than the elasticity of knowledge production to domestic investments (e.g. equal to 0.18 in Ref. [40] and 0.20 in Ref. [92]), and about one third of the elasticity with respect to former KS (e.g. equal to 0.53 in the model without spillovers in Ref. [132] and 0.55 in Ref. [92]). Thus, to investigate the effect of international knowledge spillovers using the proposed model, parameters *b*, *c*, and *d* are set to 0.2, 0.55, and 0.15, respectively based on [92].

Due to lack of empirical evidence to define parameter *a*, this is set equal to 1 when KS is considered in the model. Thus, future research is suggested to gain knowledge regarding the quantitative role of innovation policies in the creation of new RD&D knowledge. Table 5 summarises the parameter setting assumptions used in this study.

Table 5
Parameter settings assumptions used to estimate experience and knowledge stock.

Parameter	Description (units)	Onshore wind	Solar PV
α	Share of the total technology capital cost affected by learning processes (%)	78	62
β	Share of domestic content (%)	22–82	27–100
γ	Experience spillover coefficient (−)	0–1	0–1
δ	Domestic absorption capacity of international knowledge spillovers (−)	0–1	0–1
ρ	Annual depreciation rate of knowledge stock (%)	10	10
g	Time lag between the RD&D activity and its effects (a)	3	3
a	Domestic knowledge dissemination policies factor (−)	1	1
b	Public RD&D spending elasticity (−)	1, 0.2	1, 0.2
c	Knowledge stock elasticity (−)	0, 0.55	0, 0.55
d	International knowledge spillover elasticity (−)	0, 0.15	0, 0.15

3.4. Alternative model structures definition

Model structures were defined to analyse the effects of alternative definitions for the learning factors. Model structures for the two selected renewable energy technologies are summarised in Table 6. Parameters were set based on Section 3.3. The first three model structures, 1FLC-A to 1FLC-C, assume experience as the only source of learning and only technological-based cost components are affected by this process. Model 1FLC-A assumes that only global experience (i.e. OECD installed capacity in this case) leads the process of learning. Model 1FLC-B assumes that only local experience (i.e. domestic installed capacity) affects learning processes. Model 1FLC-C estimates the joint effect of global and local learning by considering learning-by-doing, learning-by-using, and international experience spillovers, based on the new definition of experience explained in Section 3.1.1. The last two models in Table 6, 2FLC-D and 2FLC-E, include knowledge stock as a second source of learning. Following the definition of experience from Model 1FLC-C, Model 2FLC-D was used to analyse the impact of domestic public investment in RD&D for onshore wind and solar PV technologies, while Model 2FLC-E also considers the effect of international knowledge spillovers.

3.5. Estimated experience and knowledge stock

Experience and knowledge stock for onshore wind and solar PV in the USA are estimated using the model structures defined in Section 3.4. Fig. 10 depicts estimated experience based on global, local, and considering a joint effect of global and local cumulative installed capacity (i.e. model structures 1FLC-A to 1FLC-C) for (a) onshore wind, and (b) solar PV (see Section 5.1 for a discussion on this variable).

Fig. 11 shows the estimated knowledge stock based on domestic public investment in RD&D only (i.e. 2FLC-C) and including international knowledge spillover effects (i.e. 2FLC-D) for (a) onshore wind, and (b) solar PV (see Sections 5.2 and 5.3 for a discussion on this variable).

Estimated technological experience and knowledge stock were used as input variables to estimate the corresponding LbD and LdR rates using Eq. (15). Learning rates were estimated by applying an ordinary least-squares (OLS) method of regression analysis using Python 3.8.

Table 6
Alternative model structures definition and specifications. See Section 3.3 for a description of each parameter.

Model	Description	Purpose	α	β	γ	ρ	g	a	b	c	d
1FLC-A	Only global experience leads to learning/Learning processes affect some components	To analyse the impact of global experience	0–1	1	1	–	–	–	–	–	–
1FLC-B	Only local experience leads to learning/Learning processes affect some components	To analyse the impact of local experience	0–1	1	0	–	–	–	–	–	–
1FLC-C	Local and global experience lead to learning/Learning processes affect some components	To analyse the impact of local and global experience	0–1	0–1	0–1	–	–	–	–	–	–
2FLC-D	Local and global experience, and knowledge stock lead to learning/Learning processes affect some components	To analyse the impact of RD&D-based knowledge stock	0–1	0–1	0–1	0.1	3	1	1	0	0
2FLC-E	Local and global experience, and knowledge stock lead to learning/Learning processes affect some components/ International knowledge spillovers effect is included	To analyse the impact of RD&D-based knowledge stock and knowledge spillover effects	0–1	0–1	0–1	0.1	3	1	0.2	0.55	0.15

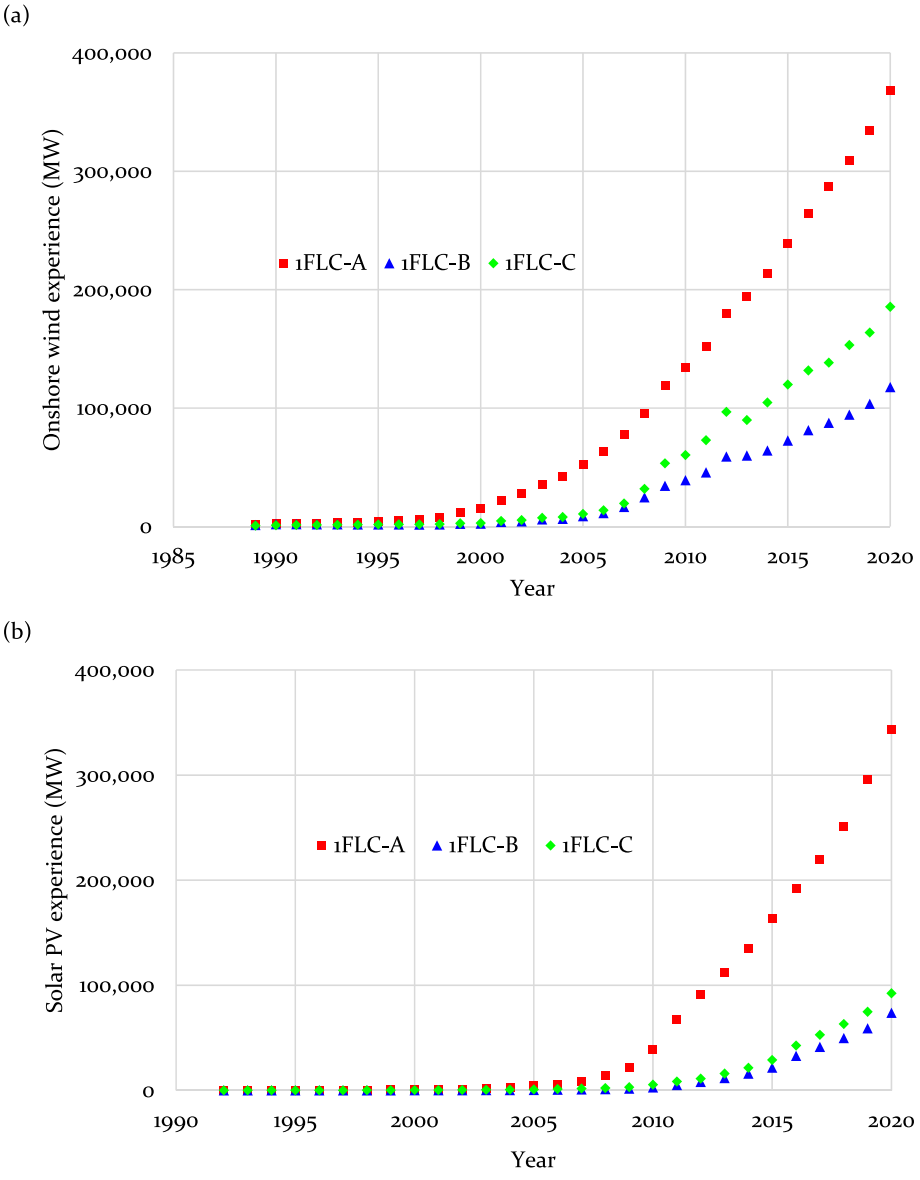


Fig. 10. Estimated experience for (a) onshore wind and (b) solar PV in the USA, using alternative model structures. Constructed with data from Refs. [12,97,107,128].

4. Results

The regression results for onshore wind and solar PV in the USA are presented and described in this section. These include estimated values for learning-by-deploying (LbD) and learning-by-researching (LbR) rates for the different periods analysed, adjusted R-squared values for each model structure, significance levels, as well as the root mean square errors (RMSEs) for estimated learning rates were used to estimate technological-based costs over time.

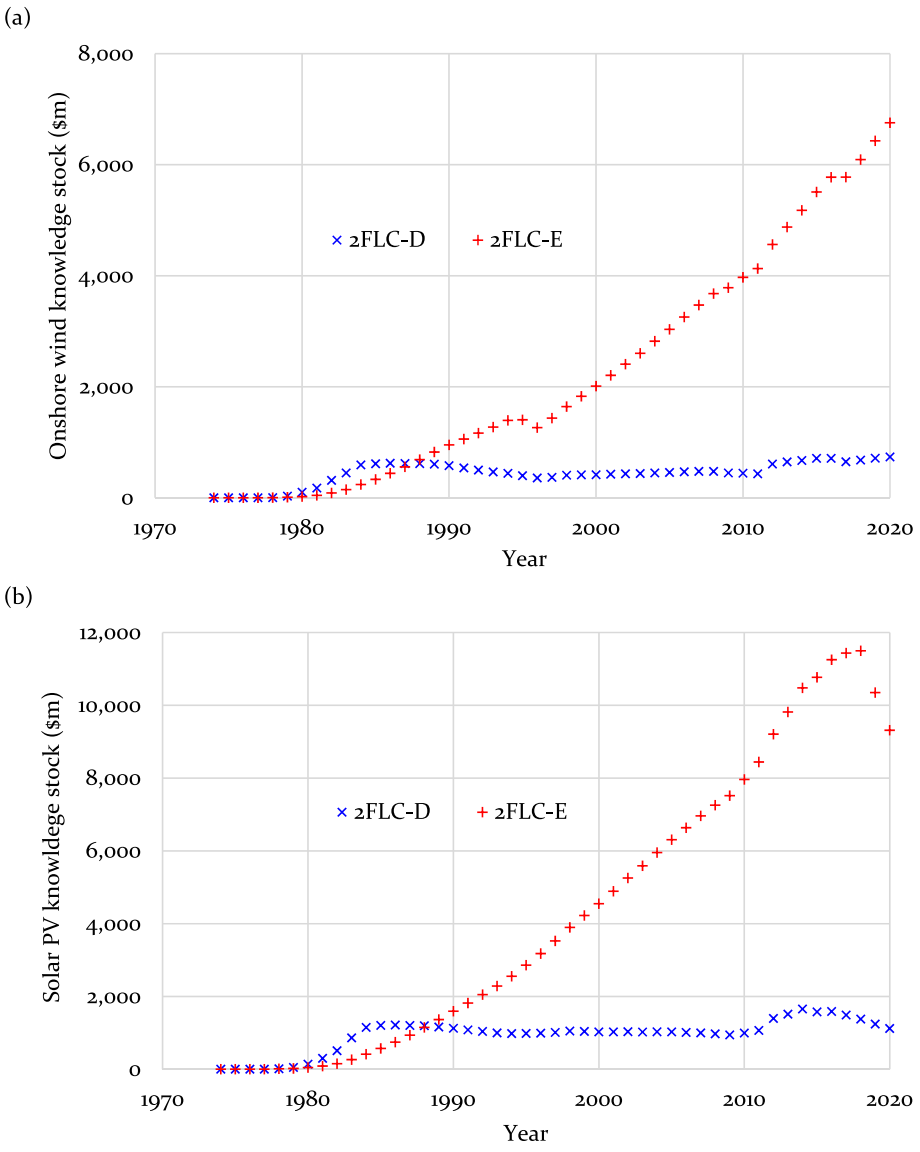


Fig. 11. Estimated knowledge stock for (a) onshore wind and (b) solar PV in the USA, using alternative model structures. Constructed with data from Refs. [92,98–103].

Table 7
Empirical test results for onshore wind in the USA.

Model	Year	LbD[a] elasticity (−)	(p)[b]	LbR[c] elasticity (−)	(p)[b]	Adj. R^2 (−)	LbD rate (%)	LbR rate (%)	RMSE[d] ($ kW^{-1})
1FLC-A	1989–2004	−0.2164	(0.000)***	–	–	0.685	13.93	–	250.41
	2004–2010	0.4991	(0.000)***	–	–	0.970	−41.34	–	88.27
	2010–2020	−0.5986	(0.000)***	–	–	0.968	33.96	–	46.73
1FLC-B	1989–2004	−0.3703	(0.005)***	–	–	0.409	22.64	–	401.21
	2004–2010	0.3054	(0.000)***	–	–	0.967	−23.58	–	100.78
	2010–2020	−0.5702	(0.000)***	–	–	0.948	32.65	–	70.28
1FLC-C	1989–2004	−0.3237	(0.000)***	–	–	0.663	20.10	–	258.25
	2004–2010	0.2641	(0.000)***	–	–	0.935	−20.09	–	142.07
	2010–2020	−0.5587	(0.000)***	–	–	0.946	32.11	–	83.53
2FLC-D	1989–2004	−0.2711	(0.000)***	0.5644	(0.060)*	0.727	17.13	−47.88	305.65
	2004–2010	0.2779	(0.000)***	1.5476	(0.014)**	0.985	−21.24	−192.34	55.88
	2010–2020	−0.5432	(0.000)***	−0.0335	(0.842)	0.939	31.38	2.30	85.02
2FLC-E	1989–2004	0.0775	(0.768)	−0.7805	(0.133)	0.697	−5.52	41.78	264.70
	2004–2010	0.0296	(0.709)	1.5338	(0.031)**	0.978	−2.07	−189.54	58.87
	2010–2020	−0.0422	(0.836)	−1.0398	(0.029)**	0.968	2.89	51.36	41.46

[a] LbD = learning-by-deploying.
[b] *, ** and *** denote significance levels better than 10% (i.e. $0.05 \leq p < 0.1$), 5% (i.e. $0.01 \leq p < 0.05$), and 1% (i.e. $p < 0.01$), respectively.
[c] LbR = learning-by-researching.
[d] RMSE = Root Mean Square Error.

4.1. Onshore wind

The empirical test results for onshore wind in the USA for different periods and different model structures are summarised in Table 7. The range of values empirically estimated for the learning rates varies considerably. When experience was considered as the only source of learning (i.e. 1FLC models), LbD rates varied from 13.93% to 22.64% for the period 1989–2004. When KS was also included within the model formulation (i.e. 2FLC models), LbD rates ranged from −5.52% to 17.13%, and LbR rates varied from −47.88% to 41.78% for the same period. Negative learning rates, estimated based on empirical data, represent an increase in costs and negative impacts on technology diffusion. Thus, for the period 2004–2010 all values for estimated learning rates were negative (see Table 7). On the other hand, estimated LbD rates presented less variability for the period 2010–2020 when only experience was considered in the model formulation, ranging from 32.11% to 33.96%. However, when KS was also included, LbD rates varied significantly from 2.89% to 31.38%, and LbR rates from 2.30% to 51.36%.

Fig. 12 depicts observed (solid line) and estimated (dotted lines) technological-based costs for onshore wind in the USA for three periods: (a) 1989–2004, (b) 2004–2010, and (c) 2010–2020. Estimated cost

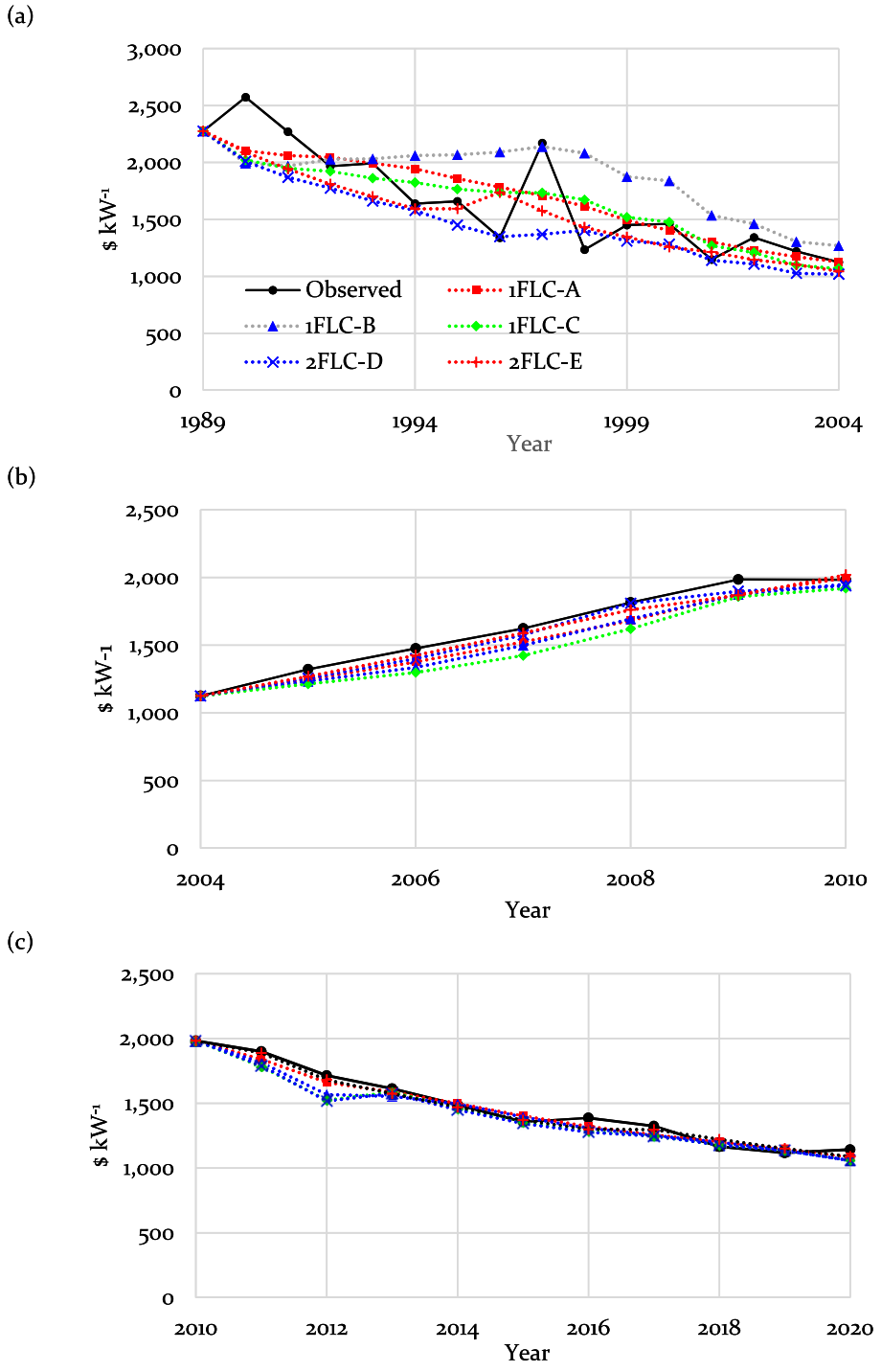


Fig. 12. Technological-based costs for onshore wind in the USA for: (a) 1989–2004, (b) 2004–2010, and (c) 2010–2020. Observed (solid line) and estimated (dotted lines).

developments were obtained by using the alternative model structures defined in Section 3.4.

4.2. Solar PV

Estimated learning rates for solar PV in the USA for different periods and alternative model structures are summarised in Table 8. In the case of solar PV, estimated LbD rates vary from 11.20% to 16.04% for the period 1992–2009 if experience is encompassed as the only source of learning. When KS was also included, LbD rates varied from 3.96% to 15.72%, and LbR rates varied from 31.51% to 46.19% for the same period analysed. For the period 2010–2020, LbD rates ranged from 28.30% to 40.38% when only experience was considered, and from 33.19% to 36.66% when also KS was included. Furthermore, LbR rates varied from −127.91% to 46.19% for the same period.

Fig. 13 depicts observed (solid line) and estimated (dotted lines) technological-based costs for solar PV in the USA for two periods: (a) 1992–2009 and (b) 2010–2020. Estimated cost developments were obtained by using the alternative model structures defined in Section 3.4.

5. Discussion

The aim of this article is to investigate the potential impact of diverse sources of learning and the definition of explanatory variables on technological-based capital cost changes for onshore wind and solar PV. Thus, findings on the relative contribution of different sources of learning and definitions of these factors are presented and discussed one by one in this section. Also, previous literature is discussed considering the findings derived from the empirical results presented in Section 4.

5.1. Impact of local, global, and combined experience

To investigate the relative potential effects of global and local experience on technological-based cost changes three model structures have been analysed and compared for both renewable technologies (i.e. models 1FLC-A, 1FLC-B, and 1FLC-C). When LbD rates were estimated based on global experience only (i.e. $\beta = 1$ and $\gamma = 1$) and local experience only (i.e. $\beta = 1$ and $\gamma = 0$), a remarkable difference can be highlighted between the two technologies. In the case of onshore wind, global experience better explains technological-based cost changes (i.e. higher Adj. R^2 values with similar significance levels and smaller statistical error). On the contrary, cost changes are better explained by local experience in the case of solar PV. The contrasting behaviour between technologies is consistent with the portion of domestic content to international trade found in the literature (see Section 3.3.2).

Although the most common approach used for the estimation of learning rates has been when global experience is assumed as the only source of learning that explains technology cost changes for onshore wind and solar PV (see Ref. [11] for a review), the findings presented in Section 4 suggest that the definition of experience should include both a national and an international component, as previously discussed by Ref. [133]. Thus, a new definition of experience has been developed in this article to account for learning through local and global learning processes, and the interaction between them (see Section 3.1.1). The new definition encompasses three learning sub-processes: learning-by-doing, learning-by-using, and international experience spillovers. Based on experience gained through these three complementary sub-processes, total experience may increase in relation to domestic capabilities and external experience affecting local learning processes. Findings suggest that if the country of interest possesses a strong domestic supply chain (i.e. manufacturing capability) and leads the development of the technology under study (i.e. the country is a technological leader), experience may be better represented by global experience (i.e. global installed capacity in this case). However, if the country's supply chain significantly relies on imports and follows technological trends (i.e. the country is a technological follower), experience may be limited to its domestic capacity. By applying the new definition of experience, this distinction is evident in Fig. 10: a strong domestic manufacturing capacity and relatively strong domestic absorptive capacity lead to 'more experience' in the case of onshore wind (see Fig. 10 (a)), while a dependent supply chain and a relatively weak domestic absorptive capacity in the case of solar PV result in 'less experience' gained through learning-by-deploying processes (see Fig. 10(b)). Thus, the results obtained and presented in Section 4, empirically validate that technological-based cost changes may be better explained when both sources of experience are explicitly included within the model formulation (i.e. $0 < \beta < 1$ and $0 < \gamma < 1$) compared to global-only or local-only settings (i.e. similar Adj. R^2 values with similar or higher significance levels and similar or smaller statistical errors). Also, these findings may be relevant when policymakers are interested in exploring the effects of implementing regulations regarding domestic content for renewable energy technologies. Furthermore, the new definition of experience proposed in this article, quantitatively accounts for the relative contribution of learning-by-doing, learning-by-using, and experience spillovers in total experience gained through learning-by-deploying processes.

5.2. Impact of RD&D-based knowledge stock

When knowledge stock was modelled as a second source of learning, using domestic public RD&D expenditures as a proxy (i.e. model 2FLC-D), a better goodness of fit was found compared to 1FLC models (i.e. higher Adj. R^2 values with similar significance levels). However, insights, derived from the empirical results presented in Section 4, vary between the two renewable technologies when KS was included in the model. LbD rates in the case of solar PV tend to increase compared to

Table 8
Empirical test results for solar PV in the USA.

Model	Year	LbD[a] elasticity (−)	(p)[b]	LbR[c] elasticity (−)	(p)[b]	Adj. R^2 (−)	LbD rate (%)	LbR rate (%)	RMSE[d] ($ kW^{-1})
1FLC-A	1992–2009	−0.1714	(0.000)***	–	–	0.944	11.20	–	1170.30
	2010–2020	−0.7461	(0.000)***	–	–	0.861	40.38	–	673.17
1FLC-B	1992–2009	−0.2523	(0.000)***	–	–	0.938	16.04	–	1212.01
	2010–2020	−0.4799	(0.000)***	–	–	0.900	28.30	–	544.22
1FLC-C	1992–2009	−0.2405	(0.000)***	–	–	0.944	15.35	–	1135.74
	2010–2020	−0.5461	(0.000)***	–	–	0.931	31.51	–	455.84
2FLC-D	1992–2009	−0.2468	(0.000)***	−0.8942	(0.161)	0.948	15.72	46.19	1260.53
	2010–2020	−0.5820	(0.000)***	−0.6761	(0.001)***	0.980	33.19	−59.79	218.98
2FLC-E	1992–2009	−0.0583	(0.045)**	−0.5459	(0.000)***	0.986	3.96	31.51	340.75
	2010–2020	−0.6590	(0.000)***	1.1885	(0.010)**	0.968	36.66	−127.91	318.33

[a] LbD = learning-by-deploying.
[b] *, ** and *** denote significance levels better than 10% (i.e. $0.05 \leq p < 0.1$), 5% (i.e. $0.01 \leq p < 0.05$), and 1% (i.e. $p < 0.01$), respectively.
[c] LbR = learning-by-researching.
[d] RMSE = Root Mean Square Error.

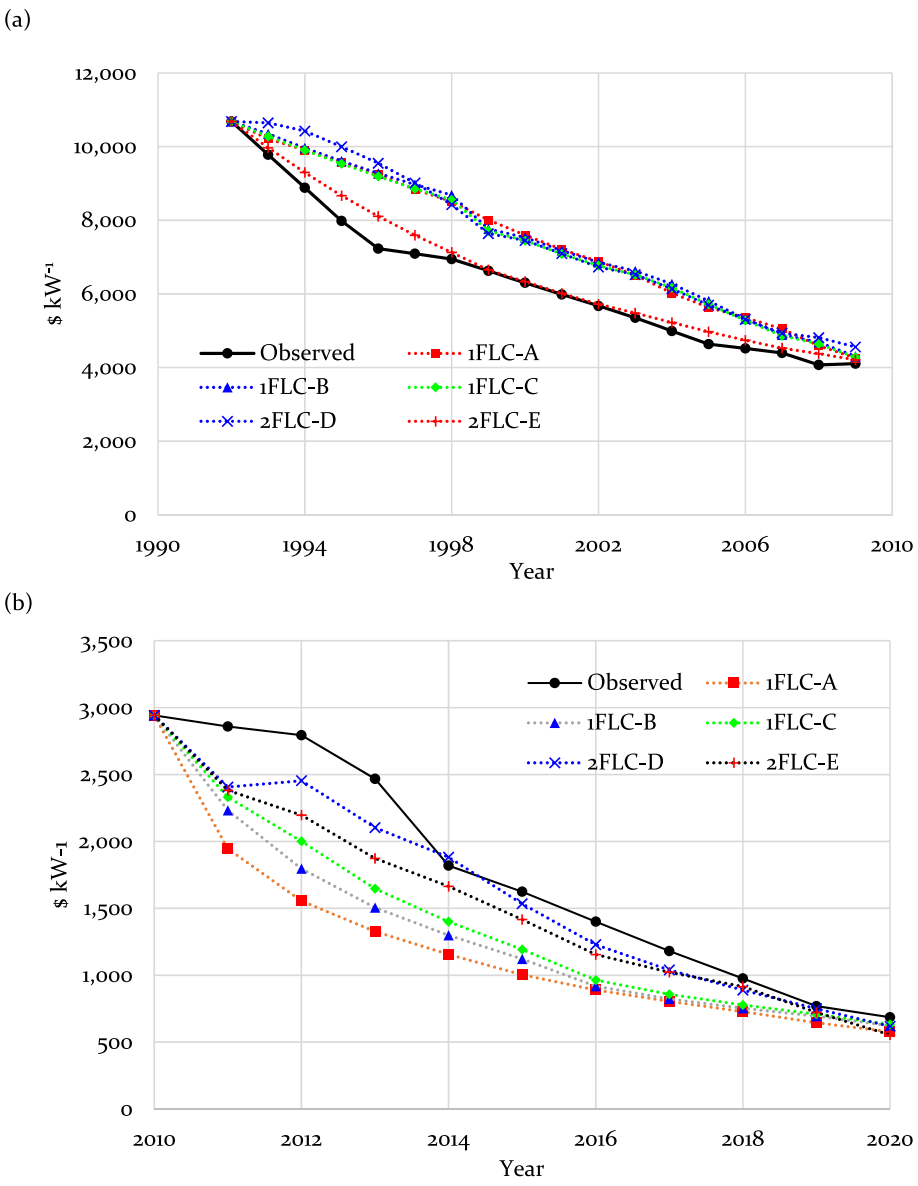


Fig. 13. Technological-based costs for solar PV in the USA for: (a) 1992–2009 and (b) 2010–2020. Observed (solid line) and estimated (dotted lines).

1FLC models, while LbR shows a positive effect on cost reductions in the period 1992–2009 and a negative effect in recent years (i.e. a negative LbR rate in the period 2010–2020). On the other hand, LbD rates for onshore wind tend to decrease when KS is included in the model formulation, while LbR had a negative impact on cost reductions from 1989 to 2010 and a positive impact in the period 2010–2020. It is worth noting that almost all LbD rates were found to be positive, except for the period of increasing costs for onshore wind from 2004 to 2010. These findings show that, for onshore wind and solar PV in the USA, experience often has had a positive impact on costs reductions, while domestic knowledge stock has had different impacts on these technologies depending on the period of analysis. This may be explained by the fact that public RD&D expenditures have increased just for specific periods of time (e.g. after energy crises), while installed capacity has followed an increasing trend over time. If no RD&D is allocated for a specific technology, KS decreases over time due to knowledge depreciation, creating a negative effect on costs reductions for that specific technology (see Section 3.5). Thus, poorly developed or delayed innovation policy adoption could have a negative impact on the rate of cost reduction [11]. Further research is needed to investigate the impact of stable funding for clean energy technologies as previously suggested by Ref. [47].

5.3. Impact of RD&D expenditures and spillovers

When not only domestic public RD&D expenditures but also international knowledge spillover effects are explicitly modelled (i.e. 2FLC-E), results also vary between the two technologies. Although LbD rates tend to increase through the different periods analysed for both technologies, LbR rates increased for onshore wind, from 41.8% in the period 1989–2004 to 51.4% in the period 2010–2020; and decreased for solar PV, from 31.5% in the period 1992–2009 to −128% in the period 2010–2020 (i.e. a negative effect in cost reductions). Also, compared to the 2FLC-D model, better statistical explanation was found for solar PV (i.e. higher Adj. R^2 values with similar significance levels and smaller statistical errors) and 'worse' statistical explanation for onshore wind (i.e. lower Adj. R^2 values with lower significance levels yet smaller statistical errors).

When compared to 1FLC models, estimated learning rates using the 2FLC-E model show larger variability with relatively lower significance levels (see Section 4). However, this model formulation outperformed the 1FLC models in terms of explanatory power (i.e. higher Adj. R^2

values). This finding shows that international knowledge flows between countries may play a key role in fostering the development of renewable energy technologies, empirically demonstrated in this article by observing higher Adj. R^2 values with smaller statistical error compared to 1FLC models. However, the way KS is defined and modelled needs further attention to improve the statistical significance obtained within this article, based on parameter settings presented in Section 3.3.4.

5.4. Impact of periods analysed

In this article, the periods of analysis were chosen based on technology cost trends and data availability (see Section 3.2). These periods include different technological development stages. The analysis in this article includes demonstration stage, market formation, and full commercialisation for wind onshore and solar PV in the USA, based on the stages of development suggested by Ref. [11]. Estimated LbD rates for both technologies suggest that an accelerated learning process has taken place in more recent years (i.e. during the full commercialisation stage). Empirical results obtained in the last period of analysis (i.e. 2010 to 2020) show higher learning rates for both technologies compared to previous periods. For instance, using the 1FLC-A model for the first period of cost reductions for onshore wind (i.e. 1989-2004), the technological-based cost declined 13.93% per each doubling of cumulative installed capacity; and during the second period of cost reductions (i.e. 2010-2020) the LbD rate was estimated to be higher (i.e. 33.96%), showing a more rapid decline in technological-based costs for each doubling of experience. Similarly, the estimated LbD rate for solar PV from 1992 to 2009 using the 1FLC-B model formulation was found to be 16.04%, while from 2010 to 2020 was 28.33%. Estimated LbD rates follow this pattern in all model formulations used in this analysis (see Tables 7 and 8). These findings suggest that learning does not necessarily decrease as technologies mature, as has been suggested by other recent study [68].

Empirical findings suggest that learning factors (i.e. experience and knowledge stock) may have different effects on cost changes depending on the development stage of the technology. When learning rates are employed to forecast future cost projections, the estimations based on historical cost changes may be misleading if development stages of the technology are not considered. For instance, when KS was considered in the model formulation (i.e. 2FLC models) to estimate learning rates for solar PV from 1992 to 2009, learning-by-researching presented a larger effect on cost reductions than learning gained by experience (i.e. higher LbR rates compared to LbD rates). On the contrary, in the period from 2010 to 2020, learning-by-researching had a negative impact on cost reductions (i.e. negative LbR rates) and thus, based on the empirical results, learning-by-deploying has led cost reductions in recent years. Similarly, when the 2FLC-D model was used to estimate learning rates for onshore wind, the empirical results show that experience has had a stronger effect on cost reductions (i.e. LbD rate of 31.38%) than knowledge stock (i.e. LbR of 2.30%) in recent years (i.e. period from 2010 to 2020). These findings highlight the relative importance of public investment in RD&D for energy technologies during the early stages of technological development, while investments from the market may play a more significant role during more advanced technological stages, as previously suggested by Ref. [1]. However, a generalisation of these findings may not be applicable to all periods and all model structures conducted in this study. For instance, when the 2FLC-E model is used to estimate learning rates for onshore wind from 2010 to 2020, KS presented a larger effect on cost reductions than experience (i.e. LbD rate of 51.36% compared with a LbR rate of 2.89%, but not statistically significant).

5.5. Policy implications

Learning curves are often used in energy-economic models to predict future technology cost developments and investigate plausible trajectories of energy systems. Policymakers can use learning curves as an analytical tool to explore the potential effects of public investment decisions aimed at guiding technology deployment and transformations in energy systems [1]. For instance, future technology cost developments, estimated by using learning curves, may be used to design the change of subsidies to emerging technologies (e.g. offshore wind, solar thermal) to attain a competitive level and plan a phasing-out strategy for these incentives during the full commercialisation stage of the technologies [1]. Also, the use of learning curves may help decision makers to guide public and private investments in RD&D throughout the different technological development stages. However, model-based investment decisions may vary significantly based on the definition of endogenous technological change. As presented in Section 4, what learning factors to consider and how these are formulated may result in a large range of values for learning rates and thus in different technology cost predictions. Findings in this article suggest that the application of historical learning rates to specific technologies may result in arguably misleading policy decisions if context-dependent sources of learning and parameters are not previously analysed and defined accordingly within the model formulation. For instance, if a learning rate estimated based on data from one country (e.g. USA) or a specific technology (e.g. onshore wind) is used to estimate future cost developments for another country (e.g. India) or another technology (e.g. geothermal) with different technological dynamics, unrealistic results are likely to be obtained. When learning curves are used for policy analysis it is paramount to explicitly establish what sources of learning are to be included and how they are formulated. Thus, reliable contextual-based estimates of learning rates are needed if energy systems models are used to generate meaningful policy-oriented results [134].

The empirically estimated learning rates presented in this study exhibit large variability when the two selected sources of learning are explicitly modelled (i.e. experience and knowledge stock), and alternative definitions of these learning factors are formulated. These learning rates include positive and negative values (i.e. increasing and decreasing trends) showing cost variations over time. As estimations are affected by the model structure (i.e. inclusion of different sources of learning and explanatory variables) no single estimation can be considered robust for all cases. However, the 2FLC-D model generally outperformed compared to other model structures when looking at goodness of fit (i.e. Adj. R^2 values), significance levels (i.e. p-values), and the statistical error when estimated learning rates were used to forecast technological-based cost developments (i.e. RMSEs) for both technologies at different periods in time (i.e. see empirical results in Section 4). This finding suggests that, when data are available, the 2FLC-D model structure may be used to explore the effects of learning processes on future technological-based cost developments. Thus, the impact of technological progress on cost reductions can be explored by accounting for different learning sub-processes, global and local experience, and domestic public investment in RD&D for energy technologies. Although it has been argued that learning-by-deploying and learning-by-researching effects are challenging to be separated, it also has been recognised that the impact of R&D on future technology costs can have a large added value, mainly in early development stages of the technology [19,135,136], as empirically demonstrated with solar PV in this study. Also, consideration of public investment in RD&D for energy technologies adds a controllable policy variable to the model and reduces, to some extent, the issue of bias due to omitted variables compared to 1FLC models, as previously discussed in Ref. [15].

5.6. Limitations and potential future research

Although valuable insights, derived from the empirical results presented in Section 4, have been discussed within this article, the analysis conducted has some limitations. First, this article has investigated the effects of alternative model structures on technological-based cost developments based on the share of the total technology cost that can be

affected by learning processes (i.e. parameter α). However, non-technological costs (e.g. soft costs) also play a role in the total technology capital cost and they should be included in model-based energy policy analysis. Non-technological costs may follow different dynamics and may vary in different regions, explained by other processes (e.g. paperwork requirements, permitting processes). Thus, future research may be oriented towards integrating complementary approaches (e.g. endogenous learning processes and exogenous administrative processes) to explain the complete picture of technology capital cost developments over time. Furthermore, parameter α may vary based on the definition of technological-based capital costs (i.e. components to be affected by learning processes). Although this parameter was set based on historical reviews on the cost structure of wind and solar energy technologies in the USA (see Section 3.3.1), different values may lead to different future technology cost predictions (see the sensitivity analysis provided in Appendix A).

Second, the exploration of alternative approaches to model technological progress has revealed the relative effects of different learning sources and explanatory variables on technological-based cost developments over time for onshore wind and solar PV in the USA. However, the analysis may be also applied to other countries or regions by explicitly establishing the learning sources and periods of analysis to be used for the investigation. Also, its application may be extended to different energy technologies at different technological maturity stages (e.g. offshore wind, clean hydrogen). In addition, the approach adopted in this study may be used as an analytical tool to conduct comparative research between countries, technologies, and periods to extend its applicability and improve the generalisability of the findings.

Third, by untangling learning-by-deploying sub-processes (i.e. learning-by-doing, learning-by-using, and experience spillovers), valuable insights on technological experience were discussed in Section 5.1. However, the new definition of experience proposed in this article integrates the three sub-processes to quantitatively estimate total experience and then estimate LbD rates. Future research can focus on investigating the relative contribution of each one of these sub-processes in cost developments. For instance, learning-by-doing, learning-by-using, and experience spillover rates (e.g. *lbdo*, *ldu*, *spill*) may be estimated separately by applying a Cobb-Douglas production function, rather than a single learning rate derived from total experience (i.e. learning-by-deploying rate).

Fourth, while the 2FLC approach can improve the understanding of technological processes, data availability has been found to be an issue [8,10]. Data on private investment in RD&D for energy technologies are usually not publicly available. Thus, the 2FLC approach often encompasses public RD&D expenditures only. The inclusion of private expenditures in the 2FLC formulation may reveal how private and public RD&D expenditures affect technology cost projections at different stages of development. Thus, including private RD&D investment within the model formulation and investigating its relationship with public RD&D expenses is an important task for future research.

Fifth, technological progress in energy systems is driven by complex dynamic interactions involving multiple factors. Apart from experience and knowledge stock, there may be other factors to be considered when informing policy-making decisions. Future research could be oriented to investigate the possible impact of those factors on energy systems (e.g. societal influences). For instance, societal factors such as opposition to a specific technology or public acceptability to specific policies (e.g. carbon pricing) may strongly influence the pace of learning and diffusion of energy technologies [8,137].

In addition, although future technology changes may be estimated using quantitative methods, such as the learning curve approach, complementary qualitative methods (e.g. expert elicitation, energy policy analysis studies) may help to better explain the effects of technological progress on technology cost developments [11,138]. A promising mixed approach (i.e. quantitative and qualitative analyses) to deal with structural and parametric uncertainty by investigating diverse model structures based on historical developments may be found in Ref. [139].

6. Conclusions

Learning curves have been used extensively to estimate technology cost developments over time. Multiple factors and their interactions may influence technological progress in renewable energy development towards a low-carbon future. This article investigated the plausible effects of technological learning processes on technology cost changes over time by using alternative model structures. Technological experience and knowledge stock were chosen as the main sources of learning. Learning-by-deploying and learning-by-researching rates were estimated for onshore wind and solar PV in the United States of America using different learning curve approaches. The findings suggest that alternative explicit definitions of learning sources may have significantly different policy implications when learning rates are used for model-based energy policymaking.

The empirical results presented within this article revealed the relative impact of diverse variables on reducing technological-based capital costs for selected renewable energy technologies. An integrative technological learning model has been developed based on various approaches to endogenous learning and relevant data on onshore wind and solar PV technologies. By choosing how different sources of learning and key parameters are defined, the influence of alternative approaches was explored. A new definition of experience was developed and presented in this study to account for the interaction between global and local experience. The findings presented in this study empirically validate that technological-based capital cost developments may be better explained when both sources of experience are explicitly modelled. The new definition of experience also accounts for learning sub-processes (i.e. learning-by-doing, learning-by-using, and international experience spillovers) to estimate total experience gained through technology deployment. This new definition may be useful for energy policymakers to investigate the impact of domestic content regulations on energy technology cost developments.

Learning through researching is of critical relevance for innovation policymakers when the effects of energy RD&D are to be investigated. When knowledge stock was modelled as a second source of learning, a relatively better statistical explanation was found for technological-based cost changes over time. Alternative definitions of learning sources and the investigation of their impact is suggested as further work. The analysis carried out within this article may support energy policymakers and innovation institutions to actively try to influence the pathway and pace of energy-related technological progress at different stages of development.

Credit author statement

Omar Castrejon-Campos: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualisation. **Lu-Aye:** Validation, Resources, Writing - review & editing, Visualisation, Supervision, Project administration, Funding acquisition. **Felix Kin Peng Hui:** Supervision, Writing - review & editing.

Data availability

Datasets related to this article can be found at https://dx.doi.org/10.17632/82nfwvcgdz.12, an open-source online data repository hosted at Mendeley Data [140].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Sensitivity analysis on share of total technological capital costs affected by learning processes (i.e. parameter α)

As discussed in Section 5.6, there is some uncertainty around parameter α (i.e. share of total technological capital costs affected by learning processes). As discussed in Section 3.3.1, parameter α depends on the selection of components that may be affected by technological learning processes. For instance, it is assumed that the total capital cost may be affected by learning processes if α is set to one (i.e. $\alpha = 1$). On the other hand, when α is assumed to be 0.5 only half of the total capital cost may be affected by learning processes. Although estimated learning rates do not vary based on the value assigned to this parameter (see Eq. (6)), root mean square errors (RMSEs) varied when these learning rates were used to estimate technological-based costs. Thus, a sensitivity analysis was performed relative to assumed values presented in Section 3.3.1.

Figures A1 and A2 present the change in RMSE relative to assumed values for onshore wind and solar PV, respectively. These figures suggest that technological cost developments are highly sensitive to assumed values for parameter α. The higher the value assumed for this parameter the greater the statistical error. Thus, a previous analysis of what components may be affected by learning processes is needed, as discussed in Section 3.3.1.

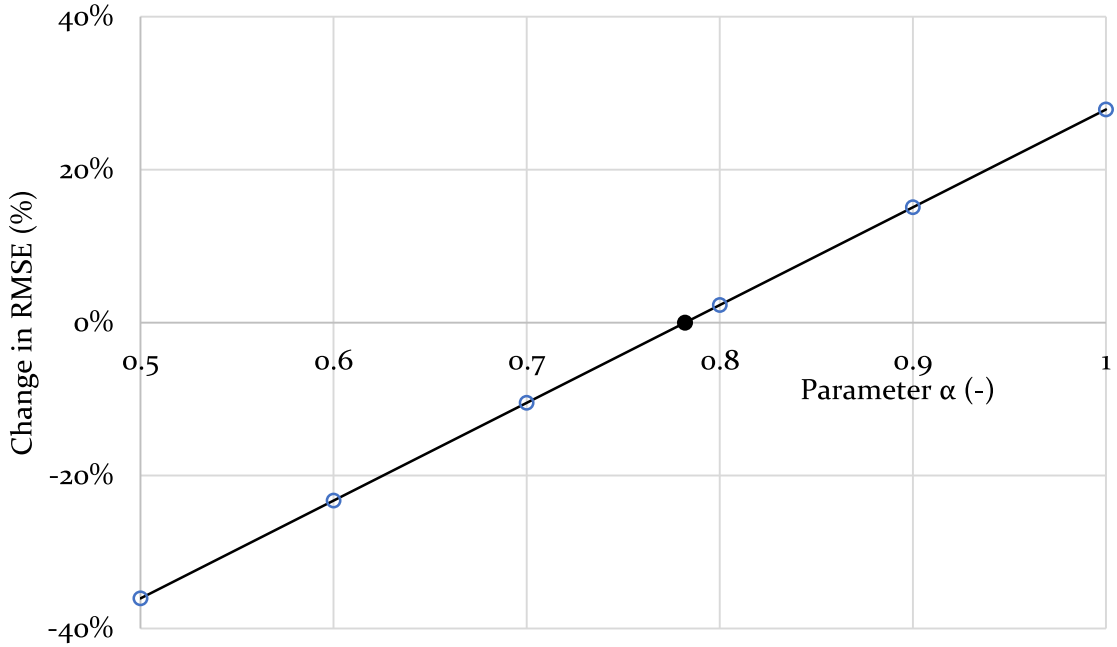


Fig. A1. Relative change in RMSE for different values assigned to parameter α for onshore wind in the USA. Change in RMSE was estimated relative to values assumed in this study (i.e. the black dot).

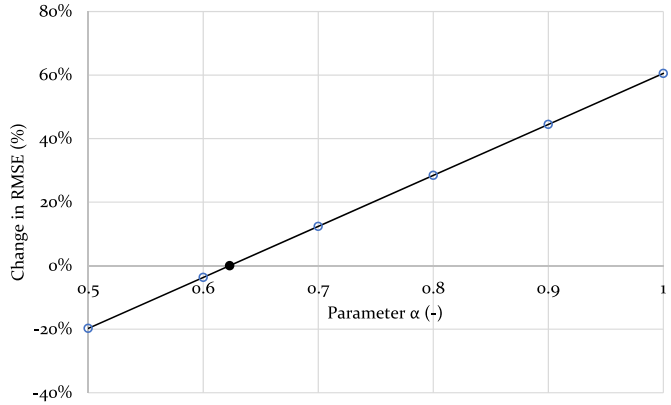


Fig. A2. Relative change in RMSE for different values assigned to parameter α for solar PV in the USA. Change in RMSE was estimated relative to values assumed in this study (i.e. the black dot).

Appendix B. Sensitivity analysis on share of domestic content (i.e. parameter β)

As discussed in Section 3.3.2, values for parameter β (i.e. share of domestic content) for both technologies were assumed to be constant for specific

periods of analysis due to lack of available data. Thus, a sensitivity analysis was performed around these assumed values. Upper and lower bound were set to 0.1 and 0.5, respectively. Figures B1 and B2 show the relationship between parameter β and estimated learning rates for onshore wind and solar PV in the USA at different periods (i.e. from 1989 to 2004 for onshore wind and from 2010 to 2020 for solar PV). The sensitivity analysis shows that learning rates are relatively sensitive to values assumed for parameter β. Thus, further research is needed to realistically set values for this parameter across all periods of analysis and thus improve the reliability of the findings presented in this study (see Section 5.1 for a discussion on this issue).

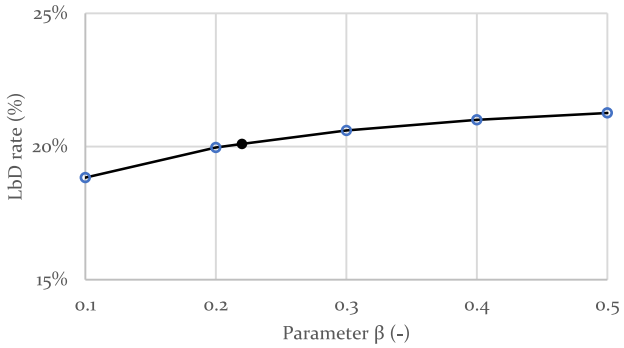


Fig. B1. Estimated learning-by-deploying (LbD) rates for different values assigned to parameter β for onshore wind for the USA in the period 1989–2004. Estimated LbD rate using the value assumed in Section 3.3.2 is highlighted as a black dot.

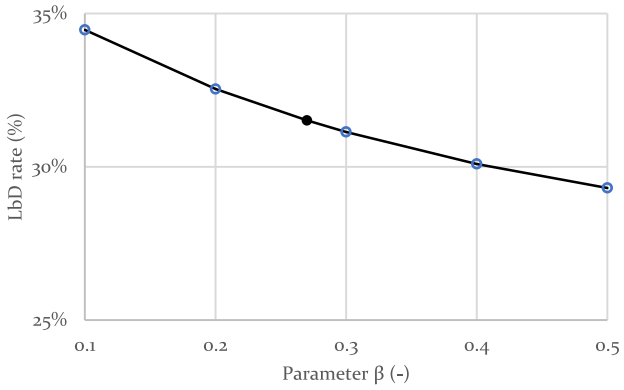


Fig. B2. Estimated learning-by-deploying (LbD) rates for different values assigned to parameter β for solar PV in the USA for the period 2010–2020. Estimated LbD rate using the value assumed in Section 3.3.2 is highlighted as a black dot.

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A. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Full title	Dataset on effects of learning curve models on onshore wind and solar PV cost developments in the USA (Version 2)		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui		
Graduate researcher's contribution (%)	75		
Status	☒ Published ☐ Accepted and In-press ☐ In progress		
Journal or book name	Mendeley Data		
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Felix Kin Peng Hui		18 March 2022

Dataset on effects of learning curve models on onshore wind and solar PV cost developments in the USA

Authors

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Abstract

This dataset includes input data to estimate learning-by-deploying (LbD) and learning-by-researching (LbR) rates for onshore wind and solar PV in the United States of America (USA). Using different learning curve approaches the simulated technological-based cost developments are also presented. Coefficient of determination (R squared) and Root Mean Square Error (RMSE) were applied for quantification of the agreement between simulated and observed technological-based costs.

Keywords

Clean energy investment
Technological experience
Knowledge stock
Renewable energy
Technological learning

Specifications table

Subject	Renewable Energy, Sustainability, and the Environment
Specific subject area	Technological innovation and diffusion
Type of data	Text, Tables
How data were acquired	Cumulative installed capacity (domestic and global) in megawatts (MW): IEA Electricity Information Statistics database [1], and IRENA Renewable Capacity Statistics 2021 [2]. Annual public RD&D expenses (domestic and global) targeting each clean energy technology in millions of US dollars in 2020 values and purchasing power parities rates ($m): IEA Energy Technology RD&D Statistics database [3], and DOE's solar technologies market reports [4–8]. Domestic (US) capital cost in US dollars per kilowatt (2020 $ kW^{-1}): IRENA Renewable Power Generation Costs in 2020 [9], 2018 Wind Technologies Market Report [10], Land-Based Wind Market Report: 2021 Edition [11], US Department of Energy report [12], and Lawrence Berkeley National Laboratory report [13]. Monetary values are reported in 2020 US dollars. They were estimated accounting for inflation based on the average annual consumer price index (CPI) in the US [14]. Software tools: Microsoft Excel, Python, PyCharm.
Data format	Raw and processed
Parameters for simulation	Capital cost structure: Cost of Wind Energy Reviews [15–23] and US Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020 [24]. Domestic content and international trade: IEA Electricity Information Statistics database [1], US Solar Photovoltaics Production, 1976-2012 [25], and Land-Based Wind Market Report: 2021 Edition [11]. Annual depreciation rate of knowledge and time lag for RD&D investment effects: Innovation in the energy sector: Lessons learnt from R&D expenditures and patents in selected IEA countries [26], and The influence of public R&D and knowledge spillovers on the development of renewable energy sources: The case of the Nordic countries [27]. International knowledge spillover effects: The influence of public R&D and knowledge spillovers on the development of renewable energy sources: The case of the Nordic countries [27].

Description of data	*Input data collected* Data collected on installed capacities (MW), public investments in research, development and demonstration (2020 $m), capital costs in the USA (2020 $ kW^{-1}), and domestic content (-) from 1974 to 2020 for energy technologies selected are included in the two following files: Wind <Onshore_Wind_US2.csv> Solar PV <Solar_PV_US2.csv> *Simulated data* Input data are used to estimate learning-by-deploying (LbD) and learning-by-researching (LbR) rates for onshore wind and solar PV in the USA. First, technological-based costs, experience, and knowledge stock for selected energy technologies are estimated using the model structures defined in the study. Then, a log-log linear regression analysis is performed by applying an ordinary least-squares (OLS) method. The regression analysis is performed based on the relationship between technological-based cost as a dependent variable, and experience (using cumulative installed capacity as a proxy) and knowledge stock (based on public RD&D expenditures) as independent variables. Data obtained from the regression analysis are used to estimate learning rates. Predicted technological-based cost values are simulated based on estimated learning rates. Finally, observed and predicted values are compared to calculate the Root Mean Square Error (RMSE) for each model formulation (i.e. different learning curve approaches). Using Python (programming language) 3.8.2 (32-bit) and PyCharm 2020.1.1 (Community Edition) as an integrated development environment (IDE) the previous process was conducted. Python code applied <Learning_Curves2.py> *Summary of simulation results* The following Excel file contains a summary of observed and simulated technological-based costs, learning rates, coefficient of determination (R squared), and RMSE for each one of the energy technologies selected, periods of analysis, and model formulations proposed within the study: <Wind_and_SolarPV_summary2xlsx>
Data source location	USA and OECD
Data accessibility	CC BY 4.0 You can share, copy and modify this dataset so long as you give appropriate credit, provide a link to the CC BY license, and indicate if changes were made, but you may not do so in a way that suggests the rights holder has endorsed you or your use of the dataset. Note that further permission may be required for any content within the dataset that is identified as belonging to a third party.

Value of the data

This dataset adds to credibility of the methods and discussions provided in the study while maximising the usefulness of the conducted research. By free access to the data, the users may benefit from a more in-depth understanding of the methods and results. The users may gain insight on the methods of data preparation and processing applied in the study and may also conduct further analysis of the results.

Simulation Design, Materials, and Methods

Simulation design, materials, methods, assumptions made, and their justifications are provided in the study.

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This dataset was developed in the University of Melbourne – Department of Infrastructure Engineering as a part of PhD thesis of Omar Castrejon-Campos, who has been supported by the CONACYT-SENER-Energy Sustainability Fund (grant number: 708667).

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this dataset.

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A. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Full title	Economic and environmental impacts of public investment in clean energy RD&D		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui Paulo Vaz-Serra		
Graduate researcher's contribution (%)	65		
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Journal or book name	Energy Policy		
Volume/page numbers (if published)	168/113134	Date accepted/ published (if relevant)	Available online: 01 July 2022

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Full title	Economic and environmental impacts of public investment in clean energy RD&D		
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui Paulo Vaz-Serra		
Graduate researcher's contribution (%)	65		
Status	☒ Published ☐ Accepted and In-press ☐ In progress		
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Volume/page numbers (if published)	168/113134	Date accepted/ published (if relevant)	Available online: 01 July 2022

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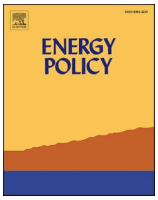
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Economic and environmental impacts of public investment in clean energy RD&D

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ABSTRACT

Learning curve theory has been adopted for investigating the relationship between technological learning and technology cost developments. The aim of this paper is to explore the impacts of public investment in clean energy research, development, and demonstration (RD&D) on future technology cost developments by using a two-factor learning curve approach. Learning-by-deploying and learning-by-researching were chosen as the main sources of learning. The focus is on onshore wind and solar photovoltaics in the United States of America. By using publicly available data, we estimated learning-by-deploying rates of 31.4% and 27.6%; and learning-by-researching rates of 2.3% and 4.7% for onshore wind and solar PV, respectively. By adopting a logistic curve approach, an additional $1322 and $819 mil. were forecast to be spent by 2050 in RD&D for onshore wind and solar PV, respectively. We explored the plausible long-term effects of diverse RD&D investment scenarios on electricity generation and greenhouse gas (GHG) emissions using a system dynamics model. The findings reveal that public investment in RD&D for clean energy technologies may play a key role in the pace of capital cost reductions and technology diffusion. However, relatively little long-term effects of RD&D efforts alone were found on market dynamics and GHG emissions.

1. Introduction

Innovation is a central driver of growth in all economic sectors (Wiesenthal et al., 2012). Innovation researchers seek to understand how technological progress may benefit society, and how policy strategies can be framed accordingly to meet economic and societal needs while complying with contemporary global challenges (e.g. climate change) (Bettin, 2020). Thus, a more comprehensive understanding of the role of the state to enable (or hinder) innovation processes for energy technologies is paramount for policy analysis (Bettin, 2020). One of the main drivers behind innovation in the energy sector is research, development, and demonstration (RD&D) (Bointner, 2014). Support for energy RD&D has been extensively recognised as a key policy strategy to reduce greenhouse gas (GHG) emissions (Garrone and Grilli, 2010; Koçak and Ulucak, 2019; Miremadi et al., 2019). However, the relationship between investment in energy RD&D and GHG emission reductions is highly uncertain (Anadón et al., 2017; Harvey et al., 2018). Thus, insights on the potential impacts of RD&D on technology cost reductions, and therefore reduction on emissions due to market dynamics, may aid policymakers and energy analysts to recognise the long-term implications of short-term policy actions.

Learning curve has been adopted as a widely applied technological forecasting framework for investigating the relationship between endogenous technological learning and technology cost developments (see (Castrejon-Campos et al., 2022a; Elia et al., 2021; Samadi, 2018; Thomassen et al., 2020)). The aim of this article is to explore the potential impacts of public investment in energy RD&D on future renewable technology cost developments under the learning curve approach. The focus is on onshore wind and solar photovoltaics (PV) in the United States of America (USA) as these are the two renewable energy technologies with the fastest-growing electricity generation capacity worldwide and are of particular interest for sustainable energy transitions (Rubin et al., 2015).

The main contribution of this article is the prospective exploration of the relative effects of diverse innovation-oriented policy strategies on capital cost developments for selected clean energy technologies, as well as their plausible long-term impacts on market dynamics (i.e. installed capacity and electricity generation) and environmental concerns (i.e. GHG emissions). Although the impact of RD&D has been discussed in

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Nomenclature

Symbols

C	capital cost ($ kW^{-1}), $ reported in this article are US dollars
CC	cumulative installed capacity (MW)
Dom	domestic (−)
E	experience (MW)
Ext	external (−)
KS	knowledge stock ($ mil.)
LM	learning multiplier (−)
LR	learning rate (−)
RDnD	public RD&D spending ($ mil.)

Greek Symbols

α	share of the total technology capital cost affected by learning processes (%)
β	share of domestic sourced resources (%)
ρ	annual depreciation rate of knowledge stock (%)
γ	experience spillover coefficient (−)

Subscripts

g	time lag between the RD&D activity and its effects (a)
t	technology
y	time-step (a)

Superscripts

lbd	learning-by-deploying elasticity (−)
lbr	learning-by-researching elasticity (−)

Abbreviations

1FLC	One-factor learning curve
2FLC	Two-factor learning curve
ABM	Agent-based modelling
BAU	Business as usual
BNEF	Bloomberg New Energy Finance
CPI	Consumer price index
DEM	Discrete event modelling
EPS	Energy Policy Simulator
GHG	Greenhouse gas
IEA	International Energy Agency
ITC	Induced technological change
lbd	Learning-by-deploying
lbr	Learning-by-researching
LCOE	Levelised cost of electricity
LIN	Low innovation
MW	Megawatt
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary least-squares
PV	Photovoltaics
R&D	Research and development
RD&D	Research, development, and demonstration
RMSE	Root mean square error
SD	System dynamics
SDM	System dynamics modelling
USA	United States of America

diverse retrospective studies (using historical data), finding future costs to extrapolate its learning effects has been identified as a key challenge for prospective studies (Thomassen et al., 2020). Thus, this article builds on a previous retrospective study that explored the effects of technological learning processes on technology cost developments over time by using alternative model structures (Castrejon-Campos et al., 2022a). The previous study revealed valuable insights regarding the relative effects of different learning sources and explanatory variables on historical cost developments. The motivation of this article is to extend its applicability to prospective studies by exploring diverse RD&D investment scenarios, and therefore it provides new insights for model-based energy policy analysis for clean energy transitions. In addition, this article empirically contributes to existing learning curve literature and energy systems modelling by comparing the relative effects of innovation processes when technological learning is modelled as a function of technological experience only (using installed capacity as a proxy) and when RD&D-based knowledge stock is included as a second source of learning (using cumulative public RD&D expenditure as a proxy). The research provides an in-depth critical discussion of their implications to inform model-based energy policymaking. This article targets at energy innovation policymakers, innovation researchers, and energy analysts.

The rest of this article is organised as follows. Section 2 sets the background of the research by briefly describing the learning curve theory and the role of RD&D in technology cost developments. The analytical structure is presented and explained in Section 3. Data sources employed, learning parameters, and input data needed for the modelling and simulation processes are also described in this section. In Section 4 simulation results are presented and discussed based on the diverse scenarios explored. Findings of the analysis, limitations, and potential future research are also discussed within this section. Conclusions and policy implications are presented in Section 5.

2. Technological learning for model-based policy analysis

Neoclassical models of economic growth, fundamentally derived from the Solow's neoclassical school (Solow, 1956), have suggested that technological progress is exogenous to the economic process (Verspagen, 1992); an approach with significant limitations for policy analysis (Jamasb, 2007). Romer (1986), based on macroeconomic growth theory and technological change theory, proposed an alternative approach by suggesting that technological progress in economic growth models should be modelled endogenously. In energy modelling literature, Grubb et al. (2002) advocated that technological progress should be modelled endogenously deriving from the interactions of interrelated economic, social, and policy processes, including economies of scales derived from technology deployment, and private and government-funded investment in research and development activities. Thus, the application of learning curve theory has been adopted in energy policy analysis to gain a better understanding of learning processes in energy systems (Miketa and Schrattenholzer, 2004). The application of learning curves is relevant for energy and innovation planning if limited financial resources may be better allocated to diffusion or innovation policy strategies towards clean energy transitions (Jamasb, 2007).

2.1. Learning curve theory

Quantitative explanation of technological progress dated from the 1930's when it was observed that the cost of producing military aircrafts declined at a semi-constant rate for each doubling of airplanes produced (Wright, 1936). This correlation is commonly explained in terms of a learning process taking on the form of a learning curve. The learning curve approach suggests that future technology costs decline as technological learning increases. Multiple structural models have been proposed within the learning curve literature. However, the log-linear model is the most commonly structural formulation used in diverse

studies because of its simplicity and good fit to historical data (Nemet, 2006). This model formulation has become a common method to integrate endogenous technological change in energy-economic models for policy analysis (EPRI, 2013). Learning curves are used to empirically estimate technology costs as a function of learning processes (Ek and Söderholm, 2010). The learning curve theory has been applied to explore the impact of technological learning on cost developments for electricity generation technologies (Hayward and Graham, 2013; Kamp et al., 2004; Rubin et al., 2015; Samadi, 2018). Recent reviews may be found in (Elia et al., 2021; Samadi, 2018; Thomassen et al., 2020).

Diverse (learning) sources may drive learning progress within energy systems, such as technological experience and knowledge stock (Elia et al., 2021; Yeh and Rubin, 2012). When the focus is on experience gained through production processes (i.e. technology diffusion) learning may increase through learning-by-doing (Arrow, 1962), learning-by-using (Rosenberg, 1982), and/or learning-by-interacting (Lundvall and Andersen, 1988). Alternatively, when the focus is on innovation processes, learning may rise through learning-by-researching (also known as learning-by-searching (Kouvaritakis et al., 2000)).

One-factor learning curves (1FLCs), often called experience curves (Junginger et al., 2010), uses (only) experience as the independent variable to explain technology costs developments over time. The application of a 1FLC approach has been extensively debated in the literature (see (Jamasb, 2007; Jamasb and Köhler, 2007; Nordhaus, 2009). From a policy perspective, if a 1FLC approach is applied only market-pull policy strategies (e.g. carbon tax, renewable portfolio standards) may be developed while ignoring technology-push mechanisms (e.g. R&D investment) within learning processes (Castrejon-Campos et al., 2022a). Considered as a partial model for representing technological progress, 1FLCs may produce inaccurate estimates of learning rates and therefore incomplete, erroneous, or misleading policy conclusions (Jamasb, 2007; Nordhaus, 2009). Thus, in order to better represent innovation processes, two-factor learning curves (2FLCs) have been developed (Bosetti et al., 2006, 2008; Klaassen et al., 2005; Kouvaritakis et al., 2000). The 2FLC approach was first proposed by Kouvaritakis et al. (2000) to include R&D expenditures as a second source of learning, adding a policy variable to the learning curve model. Learning through researching is of critical relevance for innovation policymakers when the effects of energy RD&D are to be investigated.

2.2. The role of public investment in RD&D for energy technologies

Public companies tend to limit their RD&D investment to low-risk, short-term projects (e.g. demonstration plants) (Anadón, 2012). The low RD&D intensity of utilities can be explained because of electricity-generation technologies rarely provide differentiated or additional services (i.e. electricity generation technologies generate a homogeneous output, so end-users rarely care where the electricity comes from) and operate in a heavy regulated sector (Anadón, 2012). When the private sector cannot capture the full social value of their RD&D efforts, private underinvestment may be revealed due to market dynamics (i.e. market failure) (Jaffe et al., 2005). Public investments in energy RD&D may play a strategic role in closing this investment gap. Thus, analysis of technological learning processes is of particular interest to gain a deeper understanding on how public resources could be spent to promote clean energy development without harming the environment (Anadón, 2012; Lee and Shih, 2011).

The design of energy RD&D investment portfolios has followed commonly a two-staged analytical process. The first stage comprises analysing how future technology costs could be affected by RD&D expenditures and then, the second stage focuses on investigating how technology costs affect energy and climate policies (Anadón et al., 2017). Policy mixes can activate innovation processes and trigger structural change, but at the same time, these changes may influence policy decisions (Bettin, 2020; Rogge and Reichardt, 2016). In this article, the focus is on decisions regarding public investment in energy RD&D (i.e. former stage). How technological change influences future electricity generation technologies costs has been analysed through diverse energy-economic models such as WITCH (Bosetti et al., 2006), MESSAGE (Messner and Strubegger, 1995), ReMIND-R (Luderer et al., 2010), NEMS (DOE, 2019), EPA-MARKAL (Shay et al., 2006), and EPS (Energy Innovation, 2021). A comprehensive review on endogenous technological change in energy-economic models may be found in (IPCC, 2007).

Although multiple studies have discussed the potential effects of public investment in energy RD&D for sustainable development (see (Thomassen et al., 2020) for a review), the prospective exploration of learning through researching processes has been seldom addressed in the literature because of diverse reasons. For instance (Rubin et al., 2015), argued that finding historic data to estimate learning-by-researching effects is a significant challenge. In addition (Thomassen et al., 2020), showed that the extrapolation of these learning effects is even more challenging if reliable data is not available to estimate future values. However, it has been advocated that when data are available, learning-by-researching should be included to explore the effects of learning processes on technology cost changes over time (Castrejon-Campos et al., 2022a; Thomassen et al., 2020). The relative effects of different learning sources and explanatory variables on historical cost developments have been recently explored by using publicly available data from government departments and international organisations (Castrejon-Campos et al., 2022a). It was found that technology cost developments may be better explained when learning through deployment and learning through researching are included in energy models. In this article, we extended the application of the 2FLC model developed in (Castrejon-Campos et al., 2022a) to explore the potential effects of learning-by-researching on future technology cost developments.

3. Methods and data

To investigate the potential economic and environmental impacts of public investment in energy RD&D, a process of six complementary phases was adopted in this study (see Fig. 1). During the initial (and continuing) phase, a literature review on innovation and technological learning was conducted. The aim of this phase was to identify relevant approaches to model endogenous technological learning and innovation processes for energy policy analysis. During Phase 2, data on domestic (USA) and international (Organisation for Economic Co-operation and Development −OECD−) installed capacity, domestic and international annual public RD&D expenses, and domestic capital cost for onshore wind and solar PV were collected from the sources described in Section 3.2. In addition, learning parameters needed to estimate empirically learning rates (e.g. domestic content, knowledge depreciation rate, time lag between investment in RD&D and its effects) were established in this section. Learning rates were estimated in Phase 3 based on the accumulation of experience (learning-by-deploying) and knowledge stock (learning-by-researching) in Section 3.3.1. Also, future RD&D public investment was forecasted based on historical data, as described in Section 3.3.2. Estimated learning rates and forecasted RD&D expenditures were used as input data in the simulation model to investigate the potential effects of public investment in energy RD&D on future cost developments. A system dynamics (SD) modelling approach was adopted in this study to implement the model structure (Phase 4). The simulation model, implemented in Vensim DSS (available at https://vensim.com/), is briefly described in Section 3.4. During Phase 5, the main outputs of interest were selected, and simulation was conducted using the SD model. To investigate the effects of variations in RD&D expenditures, two scenarios were proposed as described in Section 3.5. Last, results were analysed and discussed in Phase 6.

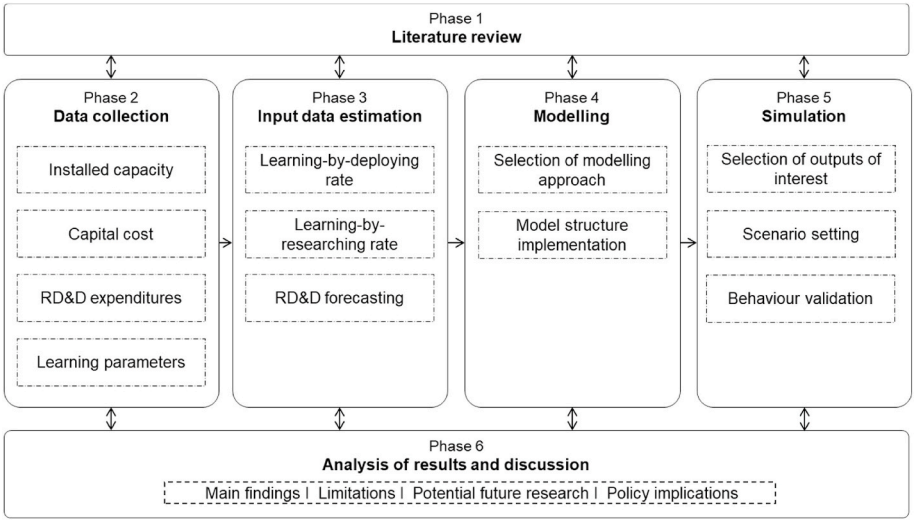


Fig. 1. Research design followed by this investigation.

3.1. A learning curve model for electricity generation technologies

Estimating learning rates is driven by several factors such as variables to be considered, definition of learning factors, model structure, geographical delimitation, and period of analysis (Castrejon-Campos et al., 2022a; Jamasb, 2007; Samadi, 2018). The application of learning curve theory to energy technologies has been widely reviewed and discussed in the literature. Thus, a broad range of values for learning rates in the energy sector has been reported in previous studies. These studies comprise energy technologies in general (McDonald and Schrattenholzer, 2001; Rubin et al., 2015; Samadi, 2018; Thomassen et al., 2020) and individual electricity generation technologies in particular, such as wind (Castrejon-Campos et al., 2022a; Ibenholt, 2002; Klaassen et al., 2005; Wiser and Millstein, 2020) and solar PV (Castrejon-Campos et al., 2022a; Elshurafa et al., 2018; Mauleón, 2016; Nemet, 2006; Yu et al., 2011).

An integrative learning curve model was developed in (Castrejon-Campos et al., 2022a) to explore the relative impact of alternative model structures (based on diverse learning curve approaches) on historical capital cost developments for onshore wind and solar PV in the USA. By exploring diverse periods of analysis and how multiple sources of learning and key parameters were defined, the study found that technology cost developments may be better explained when: (1) technological processes affect only a fraction of the total capital cost (i.e. technological-based capital cost), (2) experience is defined as a function of local and global experience, and (3) knowledge stock is also included in the model structure (Castrejon-Campos et al., 2022a).

Based on the empirical findings presented in (Castrejon-Campos et al., 2022a), technological learning is defined in this article as a function of experience (*E*) and knowledge stock (*KS*) as the main sources of learning (see Eq. (1)).

$$\alpha_t \cdot C(E,KS)_{t,y} = \alpha_t \cdot C(E_0,KS_0)_t \cdot LM(E,KS)_{t,y} \quad (1)$$

where α_t is defined as the share of the total capital cost that can be affected by learning processes for technology *t*, $C(E,KS)_{t,y}$ represents the technological-based capital cost of technology *t* at year *y* as a function of technological learning processes (i.e. based on experience and knowledge stock), $C(E_0, KS_0)_t$ denotes the initial capital cost of technology *t* at year $y=0$, and $LM(E,KS)_{t,y}$ represents the combined learning effects on technology capital cost changes for technology *t* at year *y* (i.e. known as the learning multiplier (Castrejon-Campos et al., 2022a)).

Based on the two-factor learning curve model proposed by (Klaassen et al., 2005), *LM* is defined in this article as in Eq. (2):

$$LM(E,KS)_{t,y} = \left(\frac{E_y}{E_0}\right)_t^{-lbd} \left(\frac{KS_y}{KS_0}\right)_t^{-lbr} \quad (2)$$

where *lbd* represents the learning-by-deployment elasticity, and *lbr* is the learning-by-researching elasticity.

Based on (Castrejon-Campos et al., 2022a), technological experience (*E*) of technology *t* at year *y* is defined in this article as a function of local experience and external experience affecting local learning, using installed capacity as a proxy, and is represented as in Eq. (3):

$$E_{t,y} = [\beta \cdot (2-\beta) \cdot CC_Dom]_{t,y} + [\gamma \cdot CC_Ext]_{t,y} \quad (3)$$

where parameter β ($0 \leq \beta \leq 1$) represents the share of domestic content (i.e. locally sourced resources), *CC_Dom* accounts for domestic installed capacity of technology *t* at year *y*, parameter γ ($0 \leq \gamma \leq 1$) is defined as the experience spillover coefficient which accounts for the ratio of domestic installed capacity to the international technological frontier, and *CC_Ext* represents the external installed capacity (i.e. difference between global and domestic installed capacity) of technology *t* at year *y*. The first term in Eq. (3) represents local experience, gained through learning-by-doing and learning-by-using, and the second term accounts for experience spillover effects (also known as learning-by-interacting (Lundvall and Andersen, 1988)). A detail description of the mathematical definition of experience and an in-depth discussion on the relative contribution of these learning sub-processes within the learning-by-deploying process may be found in (Castrejon-Campos et al., 2022a).

In addition, the method used in this article to estimate cumulative RD&D-based knowledge stock (*KS*) of technology *t* in year *y* is based on (Klaassen et al., 2005). Thus, KS is estimated as in Eq. (4):

$$KS_{t,y} = (1-\rho_t) KS_{t,y-1} + RDnD_{t,y-g} \quad (4)$$

where ρ ($0 \leq \rho \leq 1$) is the annual knowledge depreciation rate of previous technological knowledge stock (i.e. KS of technology *t* in year *y-1*), parameter *g* represents the time lag between the RD&D activity and its effects, and *RDnD* denotes public RD&D expenditures in technology *t* in year *y-g*. The term '*y-g*' indicates that public RD&D expenditures in year *y* do not have an instantaneous effect on learning, thus it may lead to tangible results after some time (i.e. parameter *g*). Also, Eq. (4) considers that previous knowledge becomes more irrelevant or even obsolete with time (i.e. parameter ρ) due to several factors such as rapid innovation, staff turnover, and retirement (Klaassen et al., 2005).

Based on the definition of experience (Eq. (3)) and knowledge stock

(Eq. (4)), technological-based capital cost of technology t at year y is defined in this article as in Eq. (5):

$$\alpha_t \cdot C(E, KS)_{t,y} = \alpha_t \cdot C(E_0, KS_0)_t \cdot \left(\frac{E_y}{E_0}\right)_t^{-lbd} \left(\frac{KS_y}{KS_0}\right)_t^{-lbr} \quad (5)$$

By applying a logarithmic transformation to Eq. (5), Eq. (6) is used in Section 3.3 to estimate the learning-by-deploying and learning-by-researching rates for onshore wind and solar PV in the USA based on historical data and learning parameters described in Section 3.2.

$$\log[\alpha_t \cdot C(E, KS)]_{t,y} = \log[\alpha_t \cdot C(E_0, KS_0)_t] - ldb \cdot \log\left[\left(\frac{E_y}{E_0}\right)_t\right] - lbr \cdot \log\left[\left(\frac{KS_y}{KS_0}\right)_t\right] \quad (6)$$

3.2. Data collection

To estimate the accumulation of technological experience and knowledge stock, data collected for onshore wind and solar PV are summarised in Table 1. In addition, to estimate empirically learning rates (i.e. learning-by-deploying and learning-by-researching) using Eq. (6), parameters considered in Eqs. (1), (3) and (4) were established based on previous studies and they are presented in Table 2. A detailed description of data collected and learning parameters used within this investigation may be found in (Castrejon-Campos et al., 2022a, 2022b).

3.3. Input data estimation

To explore the potential impacts of technological learning on future technology cost developments, a two-factor learning curve approach is adopted in this investigation. Technological learning is modelled in this article as a function of technological experience and RD&D-based knowledge stock. Data collected and parameters described in Section 3.2 are used to estimate learning rates based on the accumulation of experience (learning-by-deploying) and knowledge stock (learning-by-researching). In addition, future RD&D public investment is forecasted following a logistic curve approach based on historical data as described in this section.

3.3.1. Learning rates estimation

Learning rates were estimated based on the relationship between technological-based cost changes as a dependent variable, and experience (using installed capacity as a proxy) and knowledge stock (using public RD&D expenditure as a proxy) as independent variables. Using the model formulation described in Section 3.1, learning rates were estimated by applying an ordinary least-squares (OLS) method of regression analysis using Python 3.8.2 as explained in (Castrejon-Campos et al., 2022b). A summary of the results is presented in Table 3. The period of analysis for each technology was selected based on four main reasons. First, during the 2000's onshore wind and solar PV technologies reached the full-commercialisation stage in the USA (Elia et al., 2021). Second, 10–12 years' worth of historical data has been suggested to achieve stable estimates on learning rates (Santhakumar et al., 2021). Third, an increasing interest in electricity generation diversification through public RD&D investment can be observed in 2008 (see Fig. 2). Fourth, although it is widely accepted that technological learning leads to technology cost reductions over time (Wei et al., 2017), the estimation of learning rates should consider external market factors (e.g. market power, response to policies and regulations) that may cause market-structural change (e.g. increase in technology costs for onshore wind from 2004 to 2010 due to market dynamics) (Castrejon-Campos et al., 2022a; Santhakumar et al., 2021). A sensitivity analysis for alternative periods of analysis is presented in Appendix A.

Table 1
Data collected to estimate technological experience and knowledge stock for onshore wind and solar PV. Sources: (Castrejon-Campos et al., 2022a, 2022b).

Item	Unit	Period
Domestic (USA) installed capacity	MW[a]	1974–2020
International (OECD countries including USA) installed capacity	MW	1974–2020
Domestic (USA) annual public RD&D expenses	$ mil.[b]	1974–2020
International (OECD countries including USA) annual public RD&D expenses	$ mil.	1974–2020
Domestic (USA) capital cost	$ kW^{-1}[c]	1983–2020 (onshore wind) 1974–2020 (solar PV)

Monetary values were reported in 2020 US dollars. They were estimated accounting for inflation based on the average annual consumer price index (CPI) in the USA.
[a] Megawatt (MW).
[b] Millions of US dollars in constant 2020 prices and purchasing power parities rates ($ mil.).
[c] US dollars (2020) per Kilowatt (2020 $ kW^{-1}).

Table 2
Assumptions for learning parameters used to estimate learning rates for onshore wind and solar PV. Sources: (Castrejon-Campos et al., 2022a, 2022b).

Parameter	Description (units)	Onshore wind	Solar PV
α	Share of the total technology capital cost affected by learning processes (%)	78	62
β	Share of domestic content (%)	68	27
γ	Experience spillover coefficient (−)	0–1	0–1
ρ	Annual depreciation rate of knowledge stock (%)	10	10
g	Time lag between the RD&D activity and its effects (a)	3	5

3.3.2. Future trends in public investment in RD&D

Innovation diffusion has been one of the most researched issues in social sciences, albeit with multiple approaches (Bettin, 2020). Resources for energy RD&D are limited and how to better allocate them to develop and deploy energy technologies is a key policy issue (Kim et al., 2014). Different efforts to predict future energy RD&D public investment have been found in the literature (Kim et al., 2014; Miremadi et al., 2019; Usui et al., 2017). In this investigation, we adopted the logistic curve approach to model knowledge development and diffusion (based on energy RD&D expenses). This assumption has been made based on the rationale that RD&D investment plays a paramount role in advancing technological knowledge for emerging technologies, however the role of public and private funding is different throughout the diverse innovation stages. At the R&D stage, knowledge creation and spillovers are commonly sustained from government financial support with public investment (with little or no private R&D investment). When

Table 3
Estimated learning rates for onshore wind and solar PV for the US.

Technology	Learning factors	Period of analysis	Estimated learning rates	Model validation
Solar PV	Experience (MW) Knowledge stock ($ mil.)	2008–2020	lbd[a] rate = 27.56% lbr[b] rate = 4.72%	R-squared = 0.81 RMSE[c] = 484.44 ($ kW^{-1})
Onshore wind	Experience (MW) Knowledge stock ($ mil.)	2010–2020	lbd rate = 31.38% lbr rate = 2.3%	R-squared = 0.91 RMSE = 85.02 ($ kW^{-1})

[a] lbd = learning-by-deploying.
[b] lbr = learning-by-researching.
[c] RMSE = Root Mean Square Error.

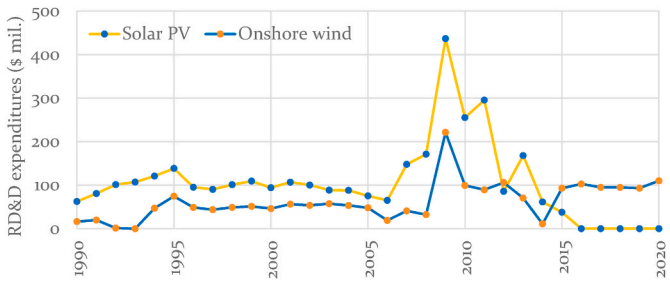


Fig. 2. RD&D public investment for solar PV and wind in the US from 1990 to 2020. Source: constructed with data from (IEA, 2021).

technologies reach a demonstration phase, usually private investors gain interest in expanding their businesses in new technological directions by adopting these new technologies. Thus, private investment complements public funding for demonstration (or pilot) plants. However, to overcome some pre-commercialisation technical and economic barriers, a continuous level of government support is needed. During the early technology diffusion stage, private RD&D investment may increase. Thus, new knowledge creation also occurs within industry (mainly leaders in the market), increasing the importance of private intellectual property (aiming at protecting their businesses). During this phase, experience gained by improvements in production, operation, and management (i.e. learning-by-deploying) gain more relevance as a key driver in technology deployment. To overcome technical issues and support technology niche markets, governments need to ensure a consistent long-term RD&D investment strategy. During the full-commercialisation stage, knowledge is created mainly at the industrial level and collaboration between companies. Thus, public investment decreases over time and learning-by-deploying usually turns the main driver for cost reduction and technology diffusion. The government's role during this stage usually focuses more on market-pull policies (e.g. improving regulatory processes, energy efficiency) and less on technology-push mechanisms (e.g. public investment in RD&D) (Elia et al., 2021).

The logistic curve model describes the diffusion of innovation as an S-shaped sigmoid curve that shows initial slow adoption, a sudden uptake, and a long stabilisation period (Bettin, 2020) (see Fig. 3). According to this model, diffusion of an energy technology can be described by using three parameters: L represents the maximum innovation adoption (or curve's maximum value), k denotes the speed of diffusion (or logistic growth), and x_0 that refers to the inflection point (the x value of the sigmoid curve midpoint).

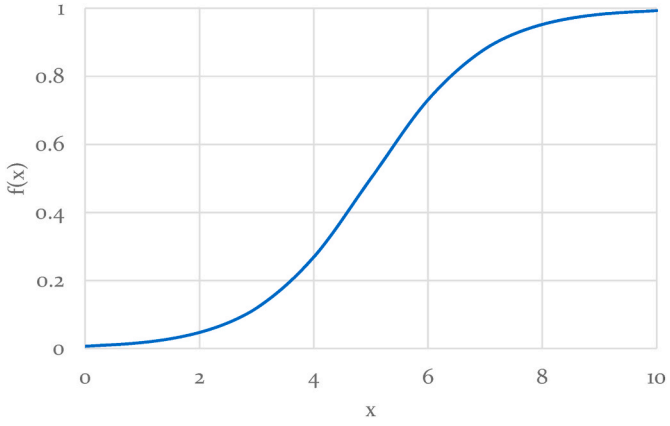


Fig. 3. Example of a logistic growth curve (with parameters: L = 1, k = 1, x0 = 5). Source: own elaboration.

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \tag{7}$$

The first step to predict future RD&D expenses was to analyse historical data for the clean energy technologies selected for this investigation. Then we conducted logistic regression in Python (using scipy.optimize package) to estimate the parameters of the logistic function (see Fig. 4 and Fig. 5). These parameters were used to predict future values for public RD&D investment for onshore wind and solar PV to 2050. The Python codes can be made available upon request.

3.4. Model description

Energy systems are characterised by dynamic complexities such as non-linearities among variables of the system, time delays, inter-temporal interactions, and side-effects between system variables (Castrejon-Campos et al., 2020). Interactions in energy systems can be analysed using different modelling approaches (e.g. Agent-Based Modelling (ABM), System Dynamics Modelling (SDM), or Discrete Event Modelling (DEM)). Following an endogenous approach, we have adopted System Dynamics (SD) (Sterman, 2000) as the simulation modelling approach. SD is used to formulate and test structural (energy and climate) policies. It is performed by modelling and simulating complex (energy) systems and analysing their resulting non-linear behaviour over time (Kwakkel and Pruyt, 2013). SD focuses on the use of simulation models to explore the relationship between a specific system structure and its dynamic behaviour, based on established assumptions (Kwakkel and Pruyt, 2015). SD has been selected due to three main reasons. First, it allows us to integrate explicit behavioural rules (i.e. policy instruments) via information feedback loops and delays in perception and adjustment (Bolwig et al., 2019). Second, the focus is on disequilibrium dynamics and feedback complexity rather than on equilibrium and optimal factor allocations (Gallagher et al., 2019). Third, it allows us to explore the behaviour of the system by considering interactions between both pricing and non-pricing policy instruments. Although alternative modelling techniques such as ABM or DEM can be applied to energy policymaking, they require a vast amount of historical or empirical data to simulate the behaviour of individual entities (Bolwig et al., 2019; Castrejon-Campos et al., 2020).

This article applied a modified configuration of the last version (3.3.1, released in January 2022) of the USA energy policy simulator (EPS) developed by Energy Innovation LLC (Energy Innovation, 2021). A public web-based version of the original model may be available at https://us.energypolicy.solutions/. The EPS is an open-source and peer-reviewed SD computer model aiming at quantifying the plausible effects of energy and climate policies on GHG emissions at a national or regional level. The EPS allows users to control multiple parameters that affect energy use and production, as well as GHG emissions (Austin and Denzinger, 2020). The EPS model has been used to explore the impact of

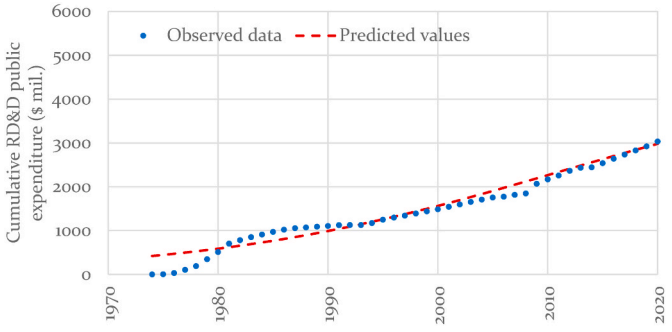


Fig. 4. Estimated logistic curve for wind based on historical data. L = 4675 ($ mil.), k = 0.06 ($ mil. a^{-1}), xo = 2011 (a), R-square = 0.96 (–), RMSE = 168.9 ($ mil.).

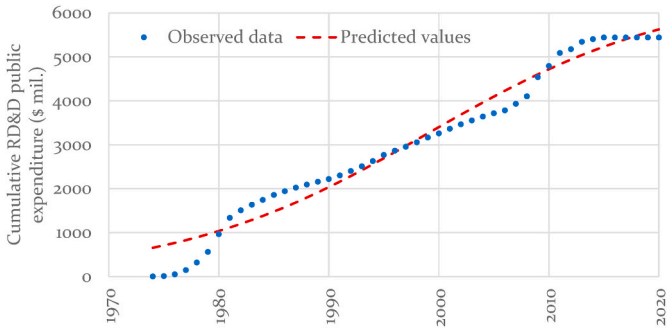


Fig. 5. Estimated logistic curve for solar PV based on historical data. L = 6519 ($ mil.), k = 0.09 ($mil. a^{-1}), xo = 1999 (a), R-square = 0.96 (−), RMSE = 317.7 ($ mil.).

different policy mixes in diverse regions such as Indonesia (Chandra Setiawan et al., 2021), China (Gallagher et al., 2019), Mexico (Stevens, 2020), and Alberta, Canada (Austin and Denzinger, 2020).

The EPS model uses a combination of exogenous and endogenous learning approaches to estimate technology cost developments depending on the maturity level of each technology (Energy Innovation, 2021). In case of endogenous learning, the EPS model adopts the one-factor learning curve (1FLC) approach being installed capacity the only driver for future technological-based cost developments in the case of wind and solar PV. We extended the approach to include knowledge stock as a second source of learning in order to explore its potential economic and environmental effects. In addition, although the effects of domestic and external (i.e. outside the modelled region) technology deployment has been considered in the last version of the EPS model (see Fig. 6), the value proposed to limit the contribution of deployment outside the modelled region to learning calculations lacks a well-grounded justification. Thus, modifications to the EPS model were implemented to account for technological experience based on diverse learning sub-processes (i.e. learning-by-doing, learning-by-using, and experience spillovers) and RD&D-based knowledge stock as suggested by (Castrejon-Campos et al., 2022a; Thomassen et al., 2020). Based on (Castrejon-Campos et al., 2022a), the main structural modifications within the EPS model for onshore wind and solar PV were implemented within the *Endogenous learning sheet* (see Fig. 7). The modified version of the EPS model can be made available upon request.

Knowledge stock is estimated based on domestic RD&D public investment. An additional policy was introduced to explore the role of additional public investment (or underinvestment) in energy RD&D for the electricity technologies selected. The model structure for estimating knowledge stock is presented in Fig. 8.

The variable labelled *This Year Solar and Wind Hard Costs as Fraction of First Year Hard Costs* (see Fig. 7) was replaced by the concept of *Learning Multiplier* (*LM*) defined in Section 3.1. This variable depends not only on the experience (estimated through domestic and external installed capacities) but also on technological knowledge stock created because of RD&D expenditures. The former was labelled as *Experience Multiplier* and the latter as *Knowledge Stock Multiplier* (see Fig. 9).

3.5. Simulation process

Input parameters in the EPS model undertake diverse data types (e.g. natural numbers, Booleans, real numbers divided into ten broad categories). Also, the EPS produces hundreds of output parameters within twelve broad categories (Energy Innovation, 2021). Thus, the selection of inputs and outputs relevant to the analytical enquiry of this investigation represents a key task. The model's inputs, outputs, and calculation flow are presented in Fig. 10.

To explore the impacts of annual energy RD&D expenditures and knowledge accumulated, three scenarios were developed: business as usual (BAU) scenario, induced technological change (ITC) scenario, and

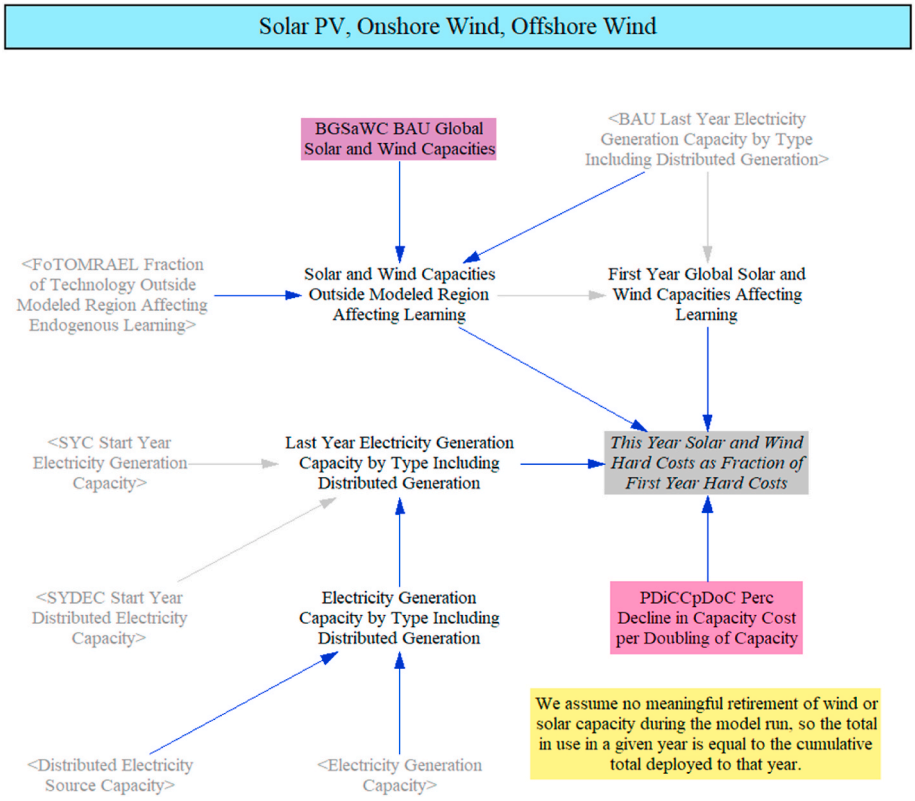


Fig. 6. Endogenous learning structure for selected energy technologies (original EPS model based on 1FLC). Source: (Energy Innovation, 2021). Description of coloured variables refer to (Energy Innovation, 2021).

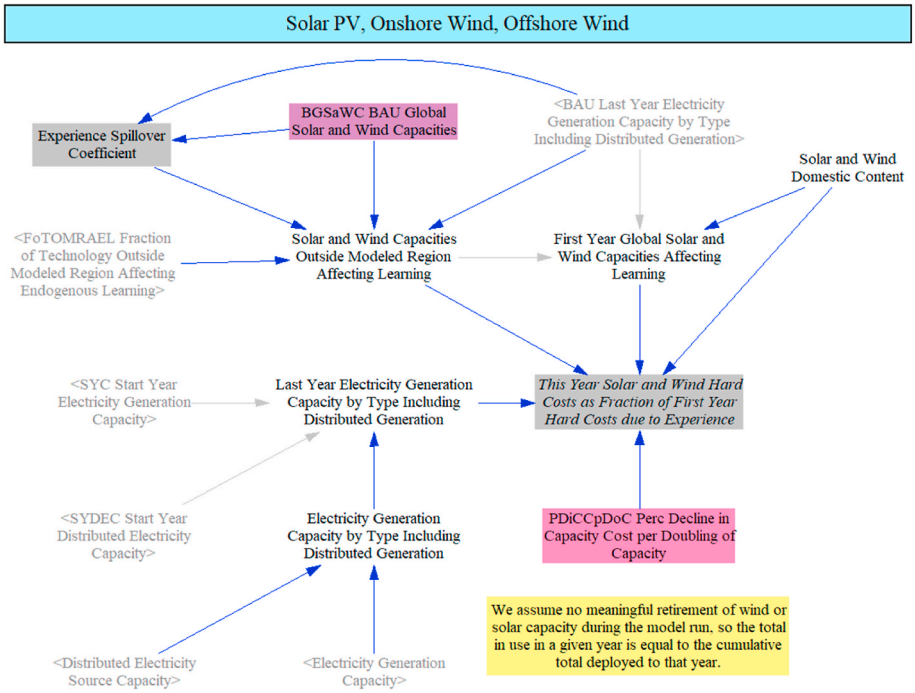


Fig. 7. Endogenous learning structure for selected energy technologies (modified EPS model based on a 2FLC approach). Description of coloured variables refer to (Energy Innovation, 2021).

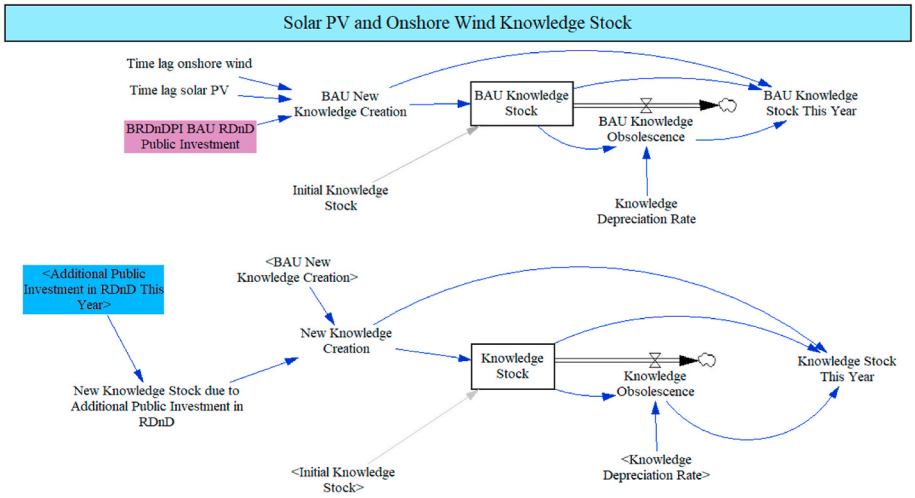


Fig. 8. Knowledge stock estimation for energy technologies selected. Description of coloured variables refer to (Energy Innovation, 2021).

low-innovation (LIN) scenario. Based on the 2FLC model formulation described in Section 3.1, the BAU scenario is used to explore the impact of knowledge stock as a second source of learning (i.e. when public RD&D expenses are included in the model formulation) compared to the experience-only (1FLC) approach adopted in the original EPS model. The ITC scenario is used to explore the effects of additional government-financed RD&D expenditures on capital cost developments (compared to the BAU scenario). The LIN scenario is used to explore the impact of limited (under)investment (i.e. if policymakers would decide to reduce RD&D expenses) compared to the BAU scenario. Values on additional investment and limited (under)investment were set based on a basis of ± 20% of cumulative investment under the BAU scenario from 2020 to 2050 (i.e. ±280 $ mil. and ± 180 $ mil. for onshore wind and solar PV, respectively). Implementing these (cumulative) investment strategies follows a S-curve shape along the simulation period.

4. Results and discussion

The aim of this article is to explore the potential effects of public energy RD&D expenditures on future technology cost developments, electricity generation, and electricity-sector GHG emissions. This section begins with a comparison between the BAU scenario applied by the original EPS model (1FLC approach) and the proposed BAU scenario which includes knowledge stock as a second source of learning (2FLC approach) to estimate future technology cost developments. It proceeds with exploring the effects of two RD&D-based innovation policy strategies on capital cost developments compared to the proposed BAU scenario: (1) if policymakers would decide to allocate additional RD&D investment to accelerate the speed of innovation processes (ITC scenario), and (2) if policymakers would decide to reduce investment in RD&D for renewable energy technologies (LIN scenario). Subsequently, the plausible effects of these innovation strategies on market dynamics

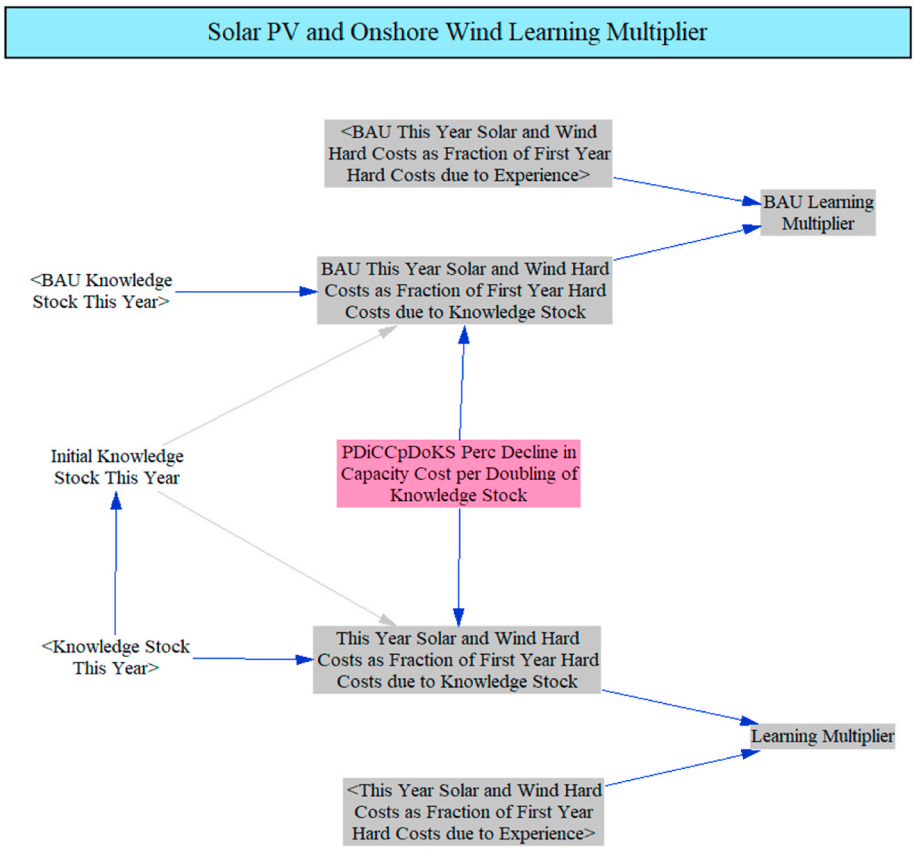


Fig. 9. Learning multiplier estimation for energy technologies selected. Description of coloured variables refer to (Energy Innovation, 2021).

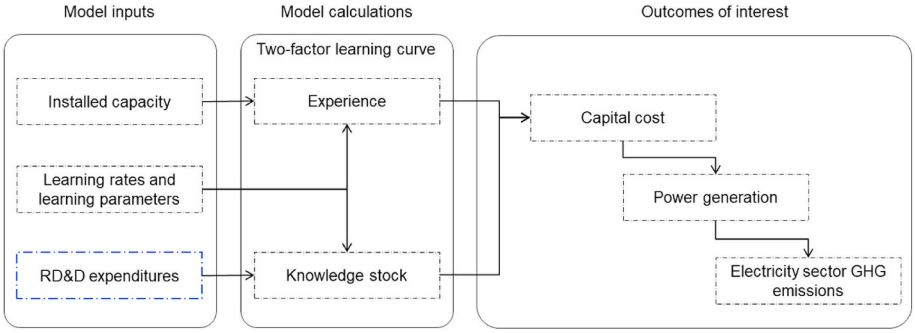


Fig. 10. Schematic diagram of the simulation process. Changes in RD&D public investment as a policy lever is the focus of this investigation (blue dashed rectangle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(i.e. installed capacity and electricity generation) and environmental concerns (i.e. power-sector GHG emissions) are explored and discussed. Last, limitations and potential future research are presented and discussed.

4.1. The impact of RD&D public investment

The original EPS model adopted an experience-only approach to include endogenous learning within the simulation process. The data source used for defining learning rates for wind and solar PV is the 'state of the clean energy industry' keynote presented at the Bloomberg New Energy Finance (BNEF)'s Future of Energy EMEA[1] Summit, held in London in 2017.[2] The document presented a learning-by-doing rate of 19% for wind (not distinguishing between onshore and offshore) and 24–28% for solar PV. However, how these learning rates were estimated is not clear within the document. Previous studies have suggested that the application of learning rates may cause misleading policy decision if sources of learning and learning parameters are not previously defined accordingly with the context of the study (Castrejon-Campos et al., 2022a). Thus, we have estimated the learning rates (learning-by-deploying and learning-by-researching) for onshore wind and solar PV in the USA based on historical data as described in Section 3.3.

[1] Europe, the Middle East, and Africa (EMEA).
[2] The keynote may be found in https://about.bnef.com/blog/michael-liebreich-state-industry-keynote-bnef-emea-summit-2017/.

Total experience gained through technology deployment (learning-by-deploying) has been estimated accounting for learning sub-processes (i.e. learning-by-doing, learning-by-using, and international experience spillovers) as presented in (Castrejon-Campos et al., 2022a). In the case of onshore wind, the learning-by-deploying (lbd) rate, estimated by using a 2FLC approach, is significantly higher than the learning-by-doing rate used in the original EPS model (i.e. 31.38% compared to 19%). On the other hand, the estimated lbd rate for solar PV resulted in a similar value used in the original EPS model (i.e. 27.56% compared to 24%). The empirical results obtained in this study (see Table 3) suggest that technological progress through technological experience (i.e. installed capacity additions) may play a more important role than knowledge stock (i.e. energy RD&D public investment) for these two renewable technologies (i.e. learning-by-deploying has a significantly larger impact than learning-by-researching). This finding is consistent with the technological maturity level of these technologies (i.e. mature technologies usually present high lbd rates and low lbr rates) as discussed in previous studies (see (Castrejon-Campos et al., 2022a; Thomassen et al., 2020).

The estimated learning rates were used within the modified version of the EPS model to estimate the *annualised construction cost per unit capacity*. For onshore wind and solar PV, endogenous learning affects only a portion of the costs, known as technological-based costs (Castrejon-Campos et al., 2022a). However, non-technological costs (e.g. soft costs such as permitting, transportation, and project management) also play an important role in the total technology capital cost. Although non-technological costs may follow different dynamics, they must be included in model-based energy policy analysis to explain the complete picture of capital cost developments. Thus, non-technological costs for technologies selected are handled via exogenous learning within the EPS model (Energy Innovation, 2021). By integrating these two complementary methods (i.e. exogenous administrative processes and endogenous learning processes) technology capital cost developments over time were estimated using the original EPS model (1FLC approach) and the adaptation presented in Section 3.4 (2FLC approach). A graphical comparison between these approaches is presented in Fig. 11 for onshore wind and Fig. 12 for solar PV.

When the 2FLC model formulation is applied to estimate technology capital cost developments from 2020 to 2050 for onshore wind and solar PV, a more accentuated reduction trend is observed for both technologies compared to the 1FLC approach. However, a larger gap can be observed for onshore wind (see Fig. 11) compared to solar PV (see Fig. 12). In the case of onshore wind, the 2FLC approach shows a reduction of 57% by 2050 from the initial cost of 63,767 $ MW^{-1} in 2020 compared to a 41% reduction within the 1FLC approach. On the other hand, a reduction of 55% from the initial cost (50,390 $ MW^{-1}) is expected to occur for solar PV under the 2FLC approach, compared to a 47% under the original approach (1FLC). The difference between the two technologies may be explained by the relative contribution of local and global learning processes and the interaction between them. As previously discussed in (Castrejon-Campos et al., 2022a), a dependent supply chain and a relatively weak domestic absorptive capacity may cause 'less' experience gained from learning-by-deploying processes and therefore less cost reduction in the case of solar PV, while a strong domestic manufacturing capacity and relatively strong domestic absorptive capacity may lead to 'more' experience for onshore wind.

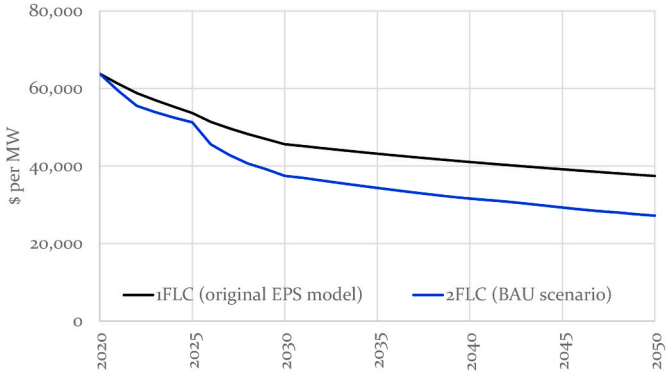


Fig. 11. Estimated annualised construction cost per unit capacity for onshore wind in the USA from 2020 to 2050.

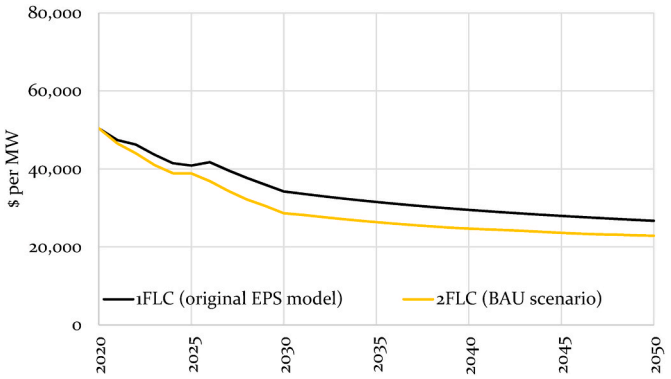


Fig. 12. Estimated annualised construction cost per unit capacity for solar PV in the USA from 2020 to 2050.

To decide how new capacity should be built to meet the total annual electricity demand, the model adopts a minimum cost approach by assigning priority to power plants based on the lowest cost (i.e. the power plant with lowest-cost is built first, then next-lowest cost plant, and so on). By representing the costs of each power plant type as a bell curve (i.e. normal probability distribution), the model estimates the 'optimal' capacity to be built per technology (for details see (Energy Innovation, 2021)). Simultaneously, the cost of energy technologies modelled using an endogenous learning approach (i.e. wind and solar PV) depends on the installed capacity built (i.e. technological experience) over the simulation period, creating a feedback loop. By simulating future installed capacity developments (see Fig. 13), we have found that capacity construction for onshore wind and solar PV may be broadened under the 2FLC compared to the 1FLC approach. However, due to market dynamics and physical constraints some of the renewable energy capacity may not be dispatched to meet electricity demand (i.e. curtailment), as discussed in Section 4.4.

4.2. Additional RD&D public investment

By 2020 the USA government had spent around $3000 and $5400 mil. in RD&D for wind and solar PV, respectively (based on historical data). Following the logistic function approach described in Section 3.5, we have estimated that under the (2FLC) BAU scenario an additional

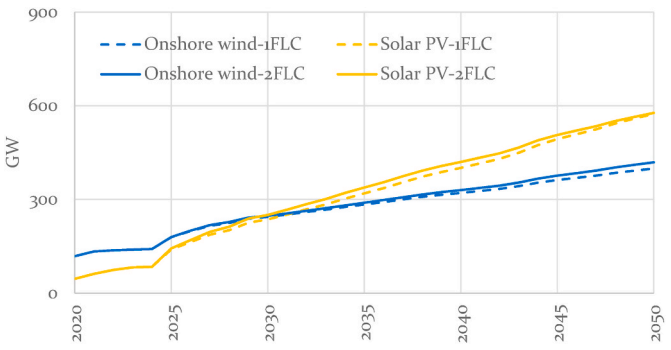


Fig. 13. Estimated installed capacity for wind and solar PV in the US from 2020 to 2050 under different approaches.

$1322 and $819 mil. dollars may be spent in RD&D by 2050 for onshore wind and solar PV, respectively. To explore the potential effects of additional RD&D public investment on technology capital cost developments, we have proposed the induced technological change (ITC) scenario (see Section 3.7). The ITC scenario assumes an additional $260 and $160 mil. dollars for onshore wind and solar PV respectively from the BAU scenario (around +20%). Implementing this innovation policy strategy follows an S-shaped curve through the model run (as opposed to a linearly implementation schedule or a scheme of full implementation from the first years like other policy instruments within the EPS model). A comparison between the BAU and ITC scenarios is presented in Fig. 14 for onshore wind and Fig. 15 for solar PV.

We can observe that for both technologies capital costs may decline further if additional RD&D expenditures are allocated for these renewable technologies. In the case of onshore wind, the ITC scenario shows a reduction of 60% by 2050 from the initial cost (compared to a 57% reduction within the BAU scenario). Similarly, for solar PV a reduction of 58% by 2050 is expected from the initial cost in the ITC scenario (compared to a 55% reduction in the BAU scenario). However, the effects of these innovation efforts are not immediate; instead we can observe a long-term impact on capital cost reductions, reflected by a visually larger effect after 2040. This behaviour may be explained by the S-shape implementation schedule then follows the innovation policy. Thus, the exploration of different implementation schedule curves is proposed for future research.

4.3. Limited RD&D public (under) investment

Following the same rationale of Section 4.2, we have proposed the limited innovation (LIN) scenario to explore the potential effects of RD&D underinvestment. The LIN scenario assumes a reduction of $260 and $160 mil. for onshore wind and solar, respectively from the BAU scenario (around −20%).

As could be expected, cutting RD&D expenditures may have the opposite effect (in the long term) on capital cost developments as the ITC scenario. In the case of onshore wind, the LIN scenario shows a decrease of 55% by 2050 from the initial cost (compared to a 57% in the BAU scenario). Similarly, for solar PV a reduction of 52% by 2050 is expected from the initial cost in the LIN scenario (compared to a 55% reduction in the BAU scenario).

In addition, the effects of public RD&D on installed capacity developments under the three scenarios proposed are depicted in Fig. 18. Based on the simulation results for installed capacities, three aspects can be highlighted in this study. First, the market may favour the deployment of solar PV in the long term, as this technology would be the cheapest technological option within the model runs. Second, although a relative difference in estimated annualised construction cost per unit capacity is observed between the BAU and LIN scenarios for onshore wind (see Fig. 16) and solar PV (see Fig. 17), no significant difference is perceived for predicted installed capacity for these technologies (see Fig. 18). This finding may be explained by the dynamic interaction between technology-push mechanisms (e.g. public investment in energy RD&D) and complementary market-pull policy strategies implemented within the model such as renewable portfolio standards, which requires a minimum share of electricity generation from renewable technologies (including onshore wind and solar PV). Third, following a 2FLC approach, learning-by-researching may have a large added value for renewable deployment in the long term as previously suggested in (Castrejon-Campos et al., 2022a; Thomassen et al., 2020).

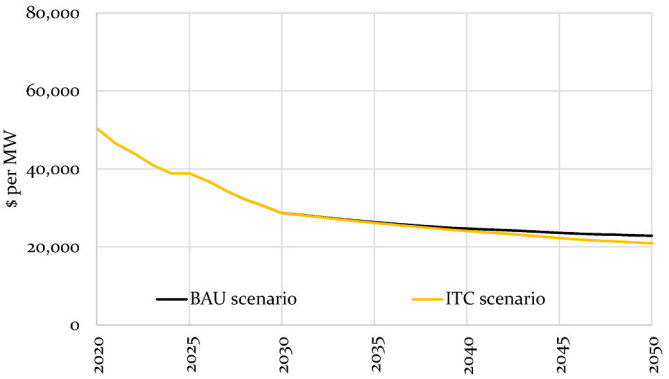


Fig. 15. Estimated annualised construction cost per unit capacity for solar PV in the USA from 2020 to 2050.

4.4. Effects of RD&D public investment on electricity generation

For energy technologies (as in many other sectors), cost is a key driver for increasing technology diffusion. As discussed in previous sections, public investment in RD&D may influence capital cost developments for renewable energy technologies. However, this is not the only cost considered within the simulation process. Following the levelised cost of electricity (LCOE) approach, the model estimates the cost per unit output for all energy technologies (considering fixed and variable costs) and electricity is dispatched through two main mechanisms: guarantied dispatch mechanisms and least-cost dispatch mechanism (Energy Innovation, 2021). Fig. 19 depicts the potential impacts on electricity generation of the two innovation policy strategies proposed in this study, compared to the BAU scenario. We can observe that under the ITC scenario, the market would favour the diffusion of solar PV and onshore wind in the long term. However, due to market dynamics in the electricity sector the behaviour of electricity generation may differ from the one observed for installed capacities of these technologies. This is, although more solar PV capacity is expected to be built compared to

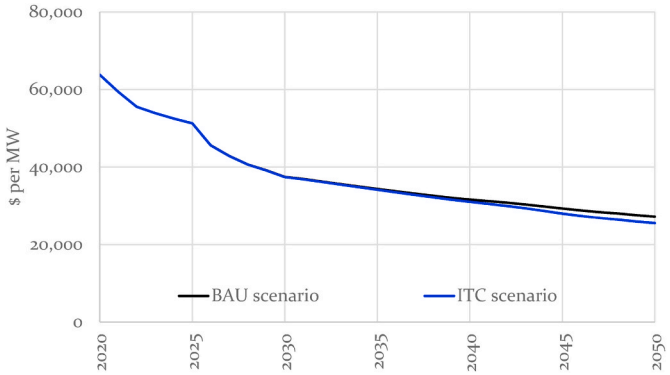


Fig. 14. Estimated annualised construction cost per unit capacity for onshore wind in the USA from 2020 to 2050.

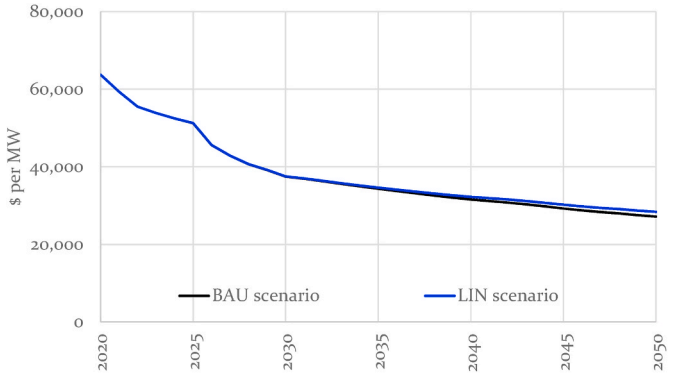


Fig. 16. Estimated annualised construction cost per unit capacity for onshore wind in the USA from 2020 to 2050.

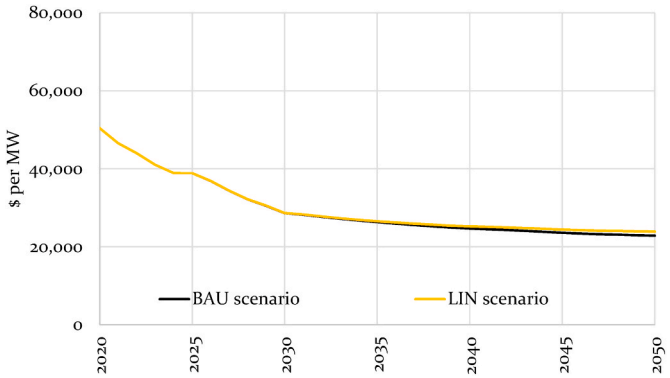


Fig. 17. Estimated annualised construction cost per unit capacity for solar PV in the USA from 2020 to 2050.

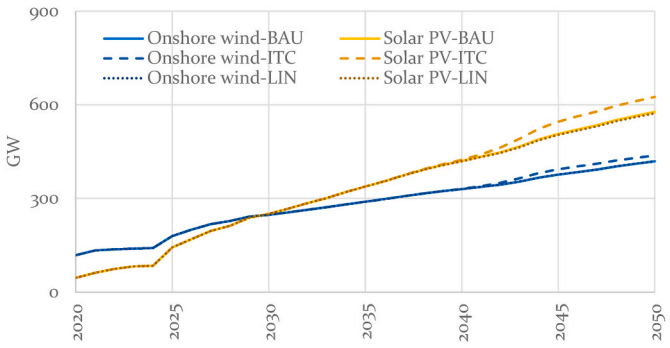


Fig. 18. Predicted installed capacity for wind and solar PV in the USA from 2020 to 2050 under diverse scenarios.

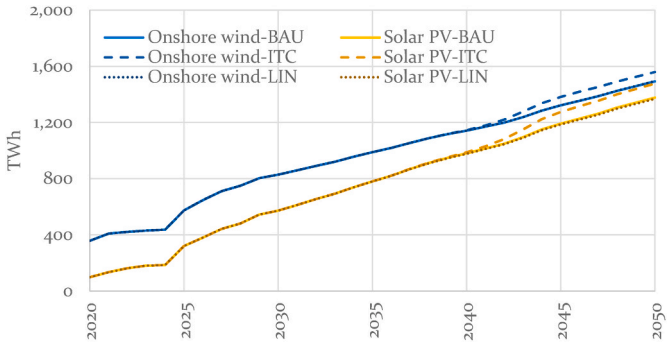


Fig. 19. Predicted electricity generation for wind and solar PV in the USA from 2020 to 2050 under diverse scenarios.

onshore wind capacity (see Fig. 18), the simulation results show that the market may favour the diffusion of onshore wind and constrain the penetration of solar PV in the long term (see Fig. 19). This may be explained because of renewable energy diffusion heavily dependents on natural and physical constraints such as availability of natural resources or infrastructure. Thus, the variable aspect of these technologies and the not-yet-economically characteristic of energy storage as a complement for renewable generation, lead to curtailments. Even if solar PV and onshore wind reach high levels of deployment, electricity demand and market dynamics may guide the process of curtailment for these variable technologies.

It is worth mentioning that under both scenarios, onshore wind may be the cheapest electricity generation technology with an average LCOE of \$19.4 per MWh^{-1} (followed by solar PV with an average LCOE of \$19.5 per MWh^{-1} and natural gas combined cycle with an average LCOE of \$29.4 per MWh^{-1}).

4.5. Effects of RD&D public investment on GHG emissions

The model estimates pollutant emissions per MWh of electricity based on emissions indices (per unit energy in the fuel) and heat rates (energy units of fuel per MWh of electricity). Fig. 20 shows the total GHG emissions caused by the electricity sector. Although public investment in energy RD&D may play a significant role in reducing GHG emissions in the long term, little short-term effects can be seen from public RD&D efforts alone. This may be explained by multiple potential reasons. First, investment in electricity generation projects is costly and have a turnover rate of decades or more, thus a lock-in process may take place where incumbent companies for old technologies (e.g. natural gas or coal plants) may try to recover the costs by different means. Second, although a significant amount of additional electricity generation from renewable sources is expected during the model run, total electricity demand is expected to rise around 50% by 2050, highlighting the need for additional generation capacity from conventional sources. Third, the development and diffusion of variable renewable energy technologies (e.g. onshore wind and solar PV) may influence the development and diffusion of conventional energy technologies (e.g. natural gas) to ensure enough flexibility on the grid. For instance, if more solar PV and onshore wind are deployed, additional natural gas generation capacity (as a flexibility source for the system) may be needed to overcome the variable aspect of renewable energy generation. Fourth, public investment in energy RD&D may have a larger influence on technologies in the early stages of the innovation process (e.g. offshore wind, solar thermal, batteries) than on those technologies that have reached the full-commercialisation stage (e.g. onshore wind and solar PV), where market-pull policy instruments may have a larger effect on technology diffusion.

4.6. Limitations and potential future research

While the 2FLC approach can improve the understanding of technological processes in energy systems, some limitations can be highlighted. First, data availability has been reported as one of the main issues when learning curves are used in energy models to inform policymaking (Castrejon-Campos et al., 2022a; Rubin et al., 2015; Samadi, 2018; Yeh and Rubin, 2012). The 2FLC approach often encompasses public RD&D expenditures only, because of data on private investment in RD&D for energy technologies are usually not publicly available. Thus, including private RD&D investment within the model to investigate how (complementary) private and public RD&D expenditures affect technology costs projections is an important task for future research.

Second, the application of learning curves for model-based energy policymaking is context-dependent and how sources of learning are

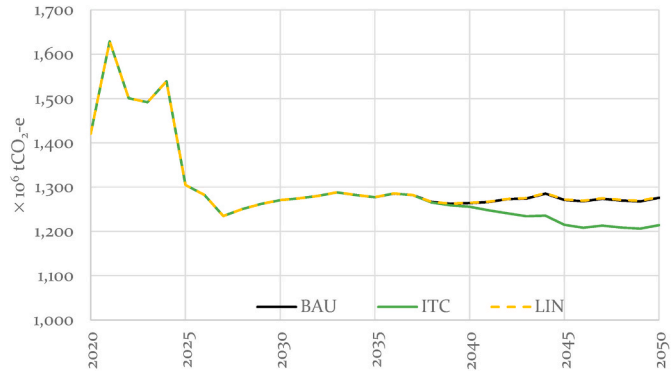


Fig. 20. Estimated GHG emission from the electricity sector in the USA from 2020 to 2050 under diverse scenarios.

explicitly defined in energy models may have significantly different policy implications (i.e. different technology costs predictions based on alternative definitions of technological learning) as previously discussed in (Castrejon-Campos et al., 2022a). Thus, analysing the role of alternative definitions of experience and knowledge stock is proposed for future research (e.g. including international spillover effects). Also, technological progress in energy systems is driven by complex dynamic interactions involving multiple factors. Apart from experience and knowledge stock, there may be other factors to include in energy models to inform policy-making decisions. Future research could be oriented to explore the potential effects of additional factors on energy systems (e.g. societal influences).

Third, in the process of knowledge development/creation and diffusion, diverse actors may influence the pace and direction of innovation processes. In this article, we have focused on government actors who influence innovation through public investment in energy RD&D. However, other actors should be included in the analysis. For instance, universities or research institutes may influence innovation processes by focusing researching efforts on specific challenges. Also, interest groups (e.g. oil & gas companies) may influence these processes through lobbying. Similarly, end-users may play a key role in diffusion of innovations through social acceptance to capture market diffusion complexity (Bettin, 2020). Although future technology progress may be estimated using quantitative methods, such as the learning curve approach, complementary qualitative analyses may help to better explain the plausible effects of technological change on energy systems.

Fourth, we have investigated the role of a technology-push policy instrument (public investment in energy RD&D), however the dynamic interactions between this and complementary market-pull policy instruments focused on energy transitions should be further analysed. A promising mixed approach (quantitative and qualitative analyses) aiming at investigating policy mixes under deep uncertainty towards clean energy transitions may be found in (Castrejon-Campos et al., 2020).

5. Conclusions and policy implications

Innovation policy focused on supporting clean energy development and diffusion plays a crucial role in reducing GHG emissions. The aim of this article was to explore the potential impacts of public investment in energy research, development, and demonstration (RD&D) on future technology cost developments by using a two-factor learning curve (2FLC) approach. We compared the 2FLC approach adopted in this investigation with a one-factor learning curve (1FLC) approach using a system dynamics model. Also, we explored the plausible long-term economic and environmental effects of diverse RD&D investment scenarios on electricity generation and GHG emissions. The focus was on onshore wind and solar photovoltaics (PV) in the United States of America (USA).

Learning rates were estimated based on empirical data by applying a 2FLC approach. Technological experience (using installed capacity as proxy) and knowledge stock (using public investment in energy RD&D as a proxy) were chosen as the main sources of learning. We found that the learning-by-deploying rates were 31.38% and 27.56%; and the learning-by-researching rates were 2.3% and 4.72% for onshore wind and solar PV, respectively. The estimated learning rates suggest that technological experience may have a significantly larger impact than knowledge stock, which is consistent with the maturity level of these renewable technologies. Following the logistic function approach described in Section 3.5, we have estimated that an additional $1322 and $819 mil. are expected to be spent in RD&D for onshore wind and solar PV respectively by 2050 (BAU scenario). Using the estimated learning rates and predicted public investment in RD&D, we explored the potential impacts of changes in public (under)investment in energy RD&D on renewable energy cost developments, electricity generation, and GHG emissions. It was found that RD&D investment may play a critical role in the speed of capital cost reductions and technology diffusion. However, little effects can be seen on market dynamics and GHG emissions from RD&D efforts alone. Also, limitations of the investigation and potential future research were presented and discussed in Section 4.6.

Based on this analysis, some policy implications can be highlighted.

(1) This article explored the potential economic and environmental benefits of public investment in energy RD&D. We have assumed no constraints to budget allocation for energy RD&D. However, public RD&D investment in energy technologies are restricted by several factors (e.g. financing constraints, finding an optimal RD&D resource allocation, market organisation, lack of information). Technology-oriented innovation policies may pose a danger in crowding out other relevant initiatives (e.g. investment in other promising technologies or market-pull policies). This is, other policy instruments may get less resources because of the nature of public limited resources. Although these limitations, energy RD&D has been recognised as a key policy tool for clean energy transitions in a cost-effective way by reducing technical issues, improving technology performance, and supporting technology niche markets.
(2) The behaviour of innovation and diffusion of emerging energy technologies may be different from previous technologies or from other regions because of structural changes within the electricity system (e.g. different actors, different market dynamics, different institutions, infrastructure needs). Model-based investment decisions may vary significantly based on the stakeholder's definition of technological progress. It has been found that incorporating learning through RD&D may accelerate or slow down the speed of costs reductions and technology diffusion compared to scenarios employing a one-factor learning curve approach. Integrating public investment in energy RD&D adds a technology-push policy variable to the model and reduces somehow the problem of omitted variable bias.
(3) We found that public investment in energy RD&D alone may have little impact on GHG emissions (only evident in the long term). This finding highlights the importance of complementing technology-push mechanisms with market-pull policies throughout the innovation process. After the basic principles of a technology are proven (e.g. through demonstration plants) and market formation take place (i.e. early technology diffusion), complementary efforts are needed to drive the cost (and price) down to a competitive level and foster technology deployment.
(4) There is no simple policy instrument for reducing GHG emissions. The best approach would be to adopt a policy mix (i.e. diverse policy instruments) that reinforces policy strategies for tackling emissions. If they are designed properly, they could minimise the cost of transitioning to a low-carbon economy. Thus, the investigation of the potential effects of diverse policy mixes on clean energy transitions is suggested as a future research.

Data availability

The data that support the findings of this article are available in Mendeley Data at https://doi.org/10.17632/82nfwvcgdz.2 (Castrejon-Campos et al., 2022b).

CRediT authorship contribution statement

Omar Castrejon-Campos: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Lu Aye:** Validation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Felix Kin Peng Hui:** Supervision, Writing – review & editing. **Paulo Vaz-Serra:**

Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Sensitivity analysis with respect to alternative time lags and periods of analysis to estimate learning rates for onshore wind and solar PV in the USA

Table A1
Sensitivity analysis with respect to alternative time lags and periods of analysis for onshore wind. Selected values used in this investigation have been highlighted. Reasoning on the selection of these values is provided in Section 3.

Time lag	Period	lbd[a] rate (%)	lbr[b] rate (%)	R-squared (-)	RMSE[c] ($ kW^{-1})
2	2008-2020	18.65	11.81	-0.19	334.31
	2009-2020	32.81	-10.20	0.87	110.52
	2010-2020	33.00	-3.74	0.93	73.18
3	2008-2020	12.11	29.74	0.39	239.28
	2009-2020	29.17	2.81	0.84	124.62
	2010-2020	31.38	2.30	0.91	85.02
4	2008-2020	13.19	29.31	0.40	237.10
	2009-2020	25.64	13.42	0.90	95.22
	2010-2020	28.42	10.44	0.93	74.26
5	2008-2020	13.60	29.06	0.40	237.32
	2009-2020	25.82	13.09	0.91	91.25
	2010-2020	28.75	9.33	0.95	63.93

[a] lbd = learning-by-deploying.
[b] lbr = learning-by-researching.
[c] RMSE = Root Mean Square Error.

Table A2
Sensitivity analysis with respect to alternative time lags and periods of analysis for solar PV. Selected values used in this investigation have been highlighted. Reasoning on the selection of these values is provided in Section 3.

Time lag	Period	lbd[a] rate (%)	lbr[b] rate (%)	R-squared (-)	RMSE[c] ($ kW^{-1})
2	2008-2020	29.79	-66.11	0.97	195.68
	2009-2020	30.29	-60.57	0.98	126.25
	2010-2020	29.64	-67.69	0.99	76.61
3	2008-2020	31.73	-67.83	0.86	424.89
	2009-2020	32.93	-62.54	0.98	153.52
	2010-2020	33.19	-59.79	0.93	218.98
4	2008-2020	31.82	-48.11	0.75	559.35
	2009-2020	34.36	-57.08	0.88	346.03
	2010-2020	35.84	-57.20	0.82	352.05
5	2008-2020	27.56	4.72	0.81	484.44
	2009-2020	31.50	-13.67	0.86	384.88
	2010-2020	35.18	-31.46	0.65	484.80

[a] lbd = learning-by-deploying.
[b] lbr = learning-by-researching.
[c] RMSE = Root Mean Square Error.

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Appendix E Publication related to Chapter 5

Co-author authorisation form

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All co-authors must complete this form. By signing below co-authors agree to material from the listed publication being included in the graduate researcher's thesis and that the graduate researcher contributed greater than 50% of the content of the publication and is the "primary author" ie. the graduate researcher was responsible primarily for the planning, execution and preparation of the work for publication.

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A. PUBLICATION DETAILS *(to be completed by the graduate researcher)*

Full title	Robust policy mixes for clean energy transitions in developing countries: An exploratory analysis for Mexico
Authors	Omar Castrejon-Campos Lu Aye Felix Kin Peng Hui Paulo Vaz-Serra
Graduate researcher's contribution (%)	65
Status	☐ Published ☐ Accepted and In-press ☒ In progress
Journal or book name	Nature Energy
Volume/page numbers (if published)	Date accepted/ published (if relevant)

B. CO-AUTHOR'S DECLARATION *(to be completed by the collaborator)*

I authorise the inclusion of material from this publication in the graduate researcher's thesis and certify that:

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- the graduate researcher contributed greater than 50% of the content of the publication and is the "primary author" ie. the graduate researcher was responsible primarily for the planning, execution and preparation of the work for publication.

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Lu Aye		

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Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Felix Kin Peng Hui		18 March 2022

Co-author authorisation form

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Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Paulo Vaz-Serra		18 March 2022

Robust policy mixes for clean energy transitions in developing countries: An exploratory analysis for Mexico

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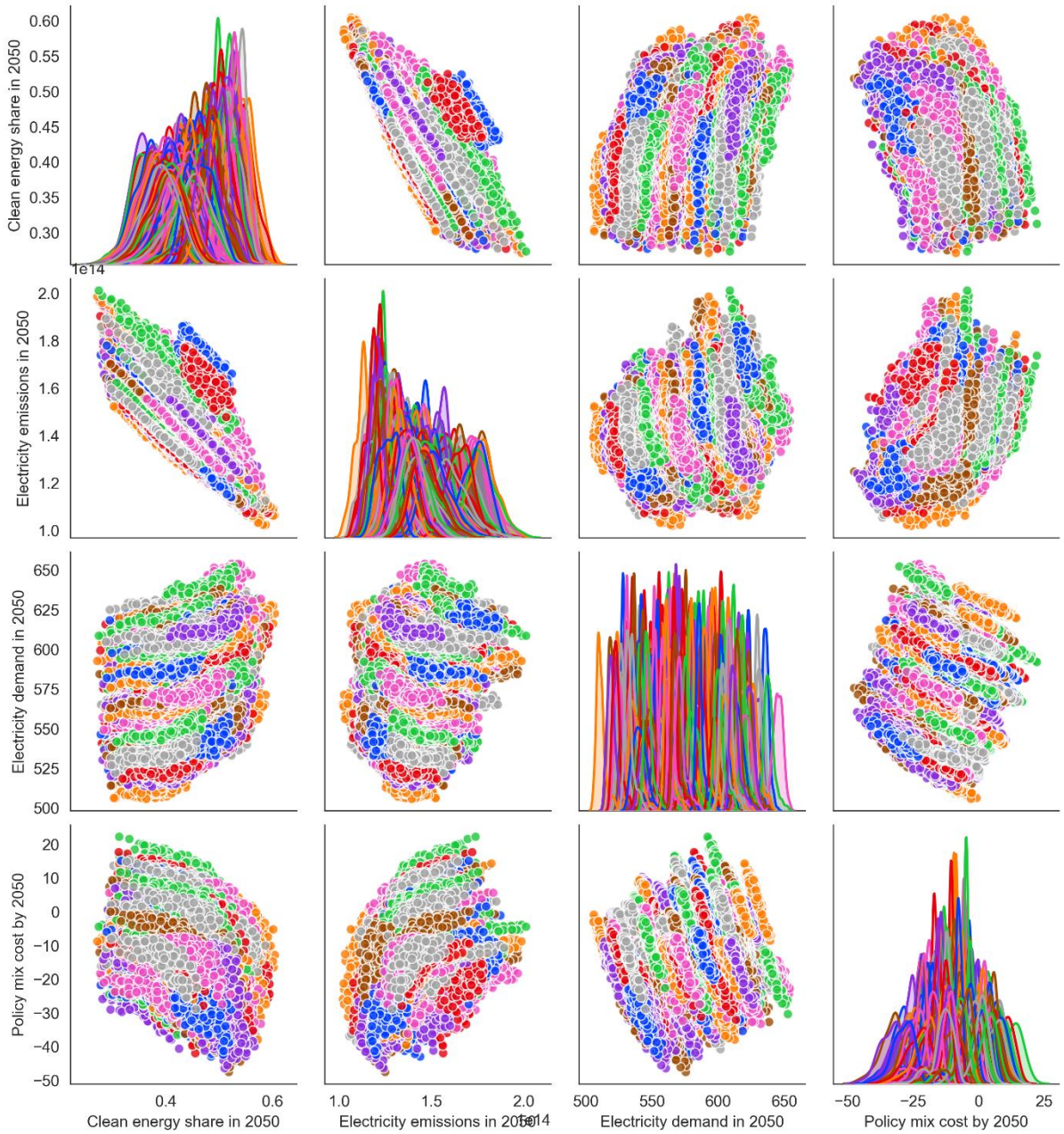
*Corresponding author. Email address: lua@unimelb.edu.au (Lu Aye). Tel: +61 3 8344 6879

Supplementary information

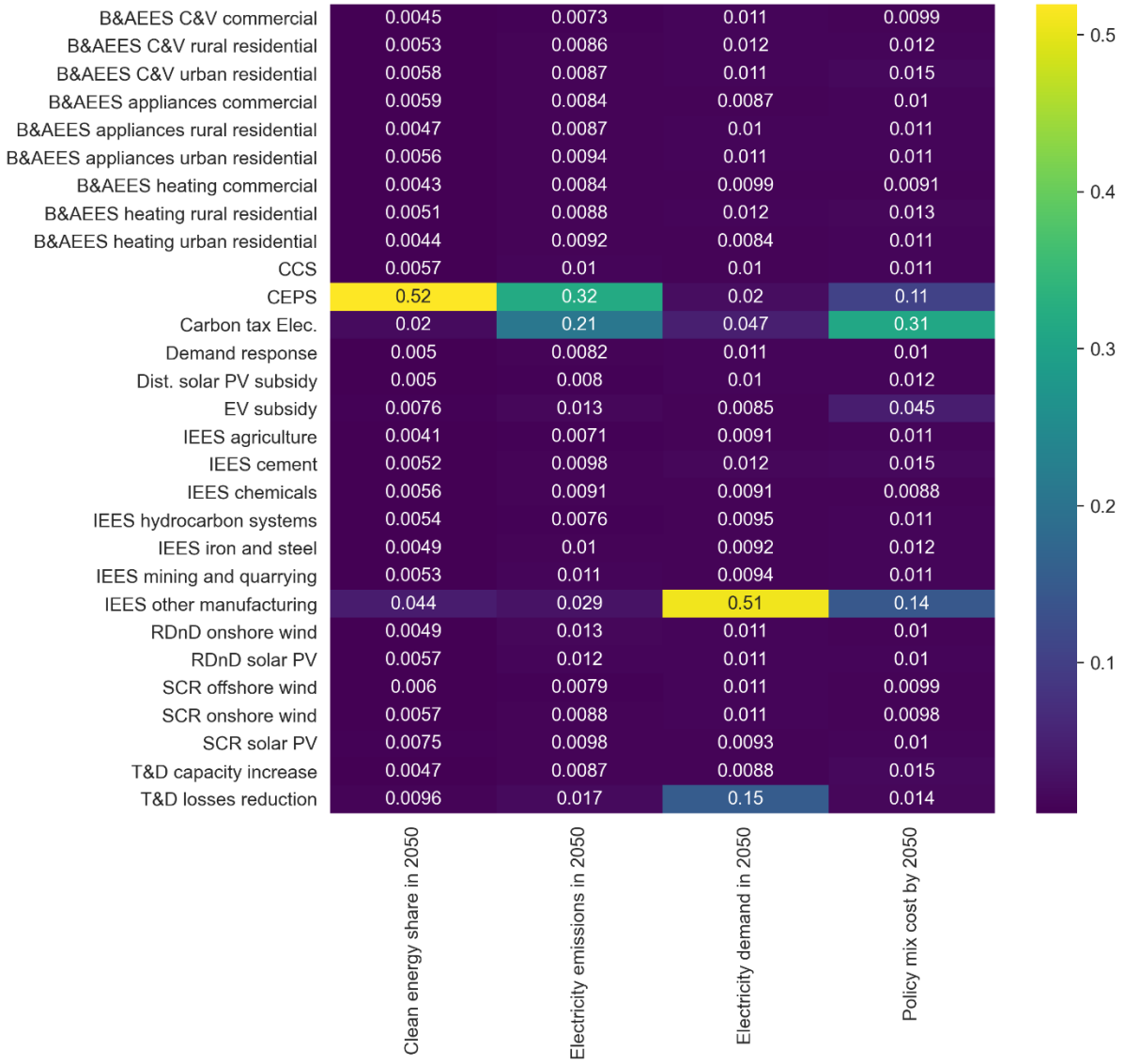
Supplementary Table 1. Policy characterisation of the most robust policy alternative under open exploration.

Policy instrument	Value	Units
CEPS	48.77	% of electricity generation
SCR solar PV	38.63	% reduction in soft costs
SCR onshore wind	28.07	% reduction in soft costs
SCR offshore wind	30.02	% reduction in soft costs
T&D capacity increase	19.31	% increase in transmission capacity
T&D losses reduction	31.76	% of losses avoided
Dist. solar PV subsidy	8.44	% of PV system cost
RD&D onshore wind	0.60	Million USD
RD&D solar PV	1.88	Million USD
Carbon tax Elec.	94.39	$/metric ton CO2e

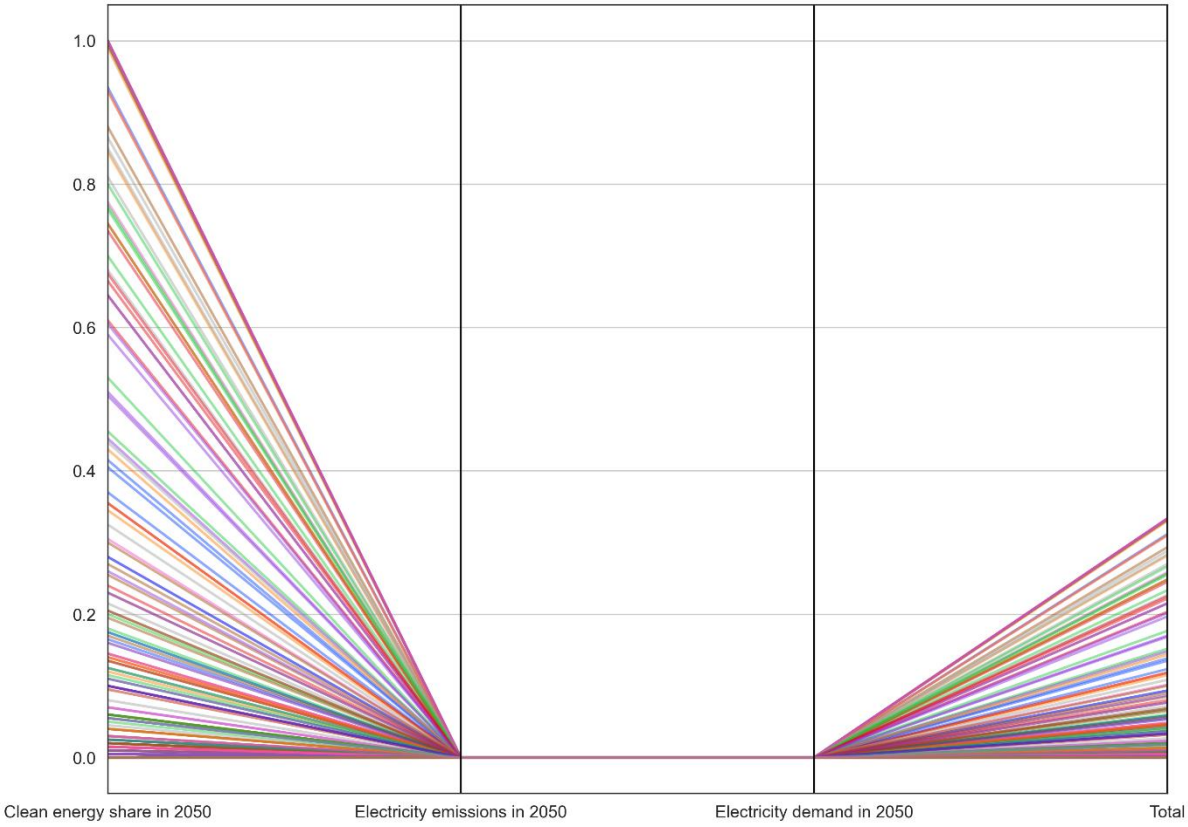
Policy instrument	Value	Units
CCS	10.24	% of CO2 captured
IEES mining and quarrying	22.41	% reduction in energy use
IEES cement	23.93	% reduction in energy use
IEES iron and steel	29.70	% reduction in energy use
IEES chemicals	30.00	% reduction in energy use
IEES hydrocarbon systems	22.05	% reduction in energy use
IEES agriculture	27.42	% reduction in energy use
IEES other manufacturing	16.17	% reduction in energy use
B&AEES heating urban residential	36.14	% reduction in energy use
B&AEES heating rural residential	29.88	% reduction in energy use
B&AEES heating commercial	26.93	% reduction in energy use
B&AEES C&V urban residential	4.64	% reduction in energy use
B&AEES C&V rural residential	15.17	% reduction in energy use
B&AEES C&V commercial	30.39	% reduction in energy use
B&AEES appliances urban residential	37.29	% reduction in energy use
B&AEES appliances rural residential	32.35	% reduction in energy use
B&AEES appliances commercial	8.60	% reduction in energy use
Demand response	40.82	% of potential achieved
EV subsidy	0.38	% of vehicle cost



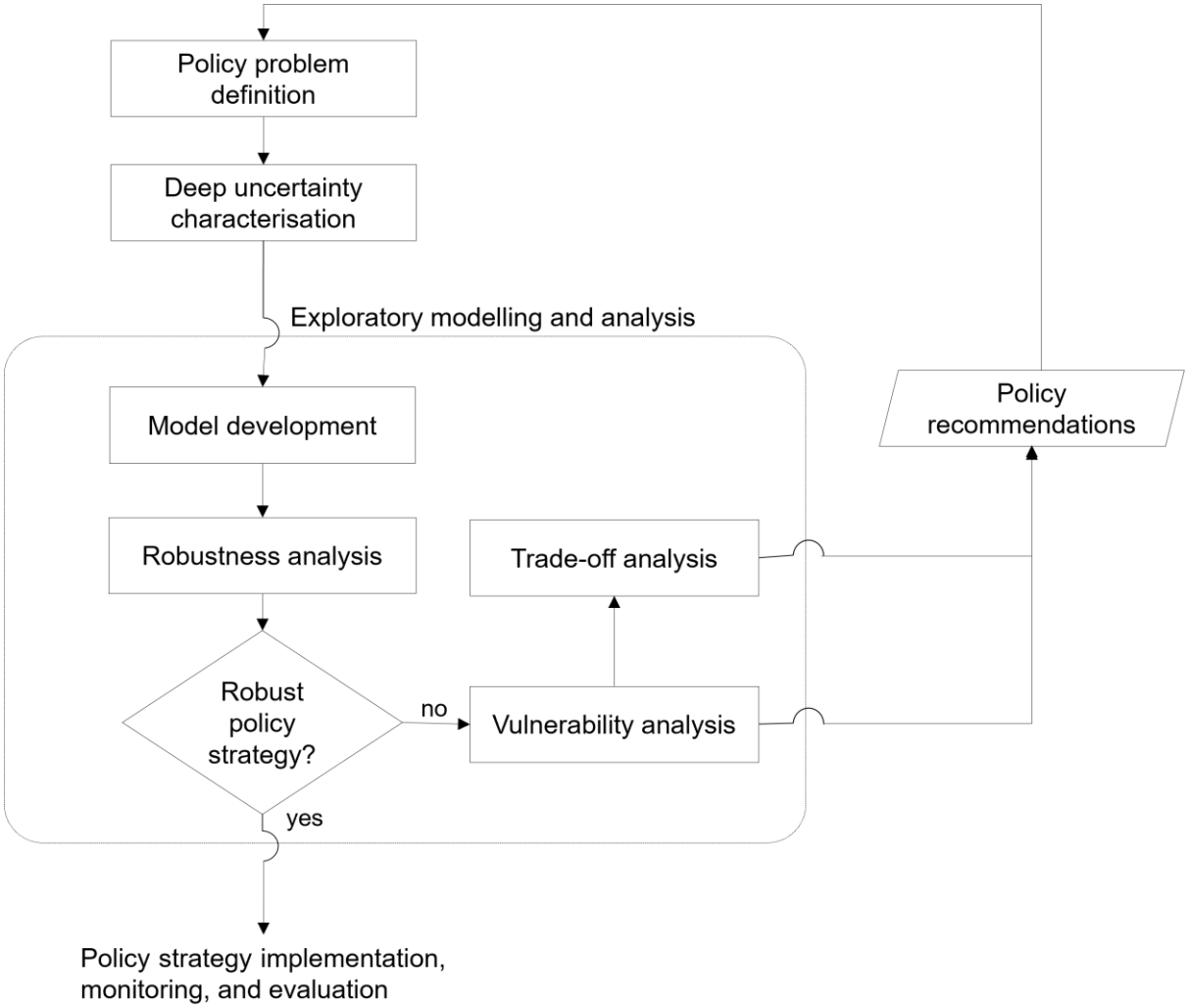
Supplementary Fig. 1. Performance of policy alternatives with respect to policy objectives for 2050 following a directed search approach.



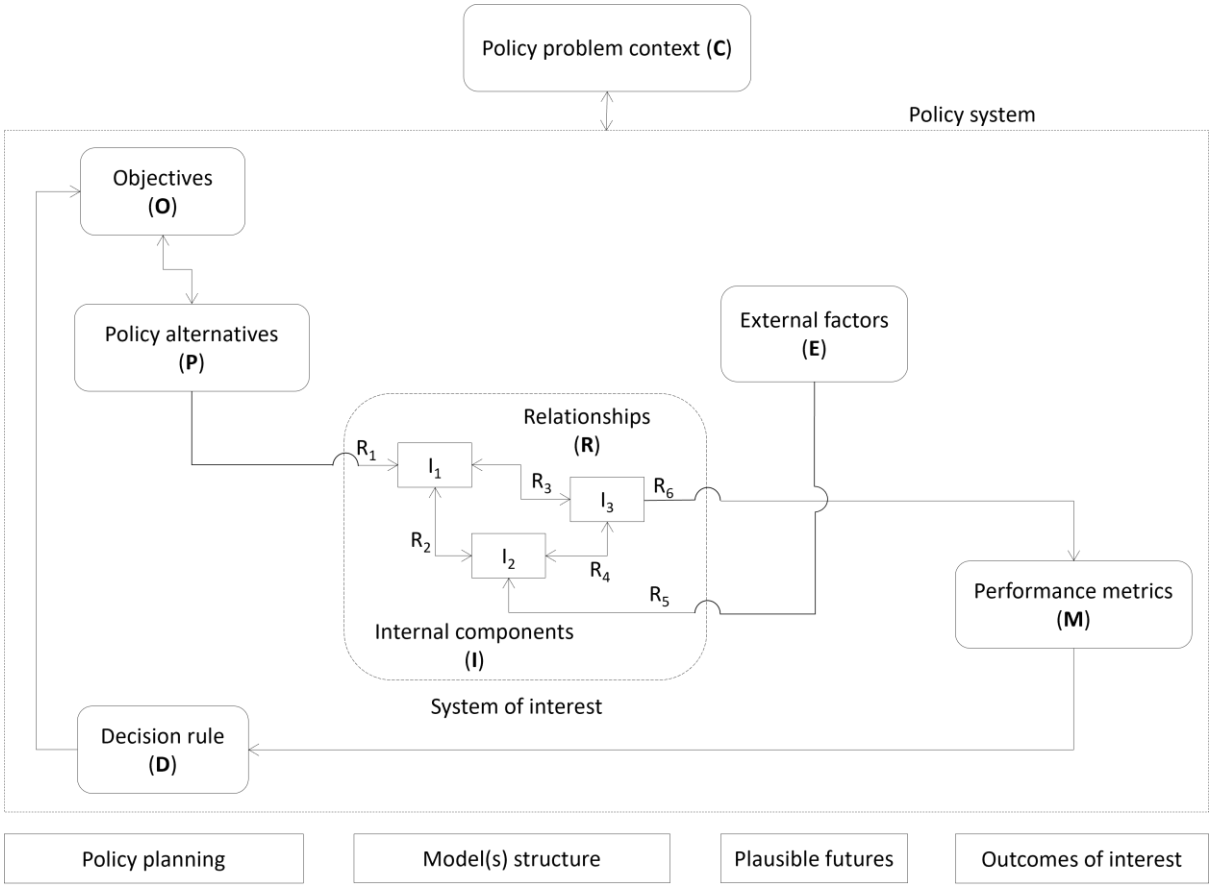
Supplementary Fig. 2. Feature scoring for 2050 policy objectives following a directed search approach. (*B&AEES* = buildings and appliances energy efficiency standards, *C&V* = cooling and ventilation, *CCS* = carbon capture and storage, *CEPS* = clean energy portfolio standard, *PV* = photovoltaics, *EV* = electric vehicle, *IEES* = industry energy efficiency standards, *RDnD* = research, development, and demonstration, *SCR* = soft cost reductions, *T&D* = transmission and distribution).



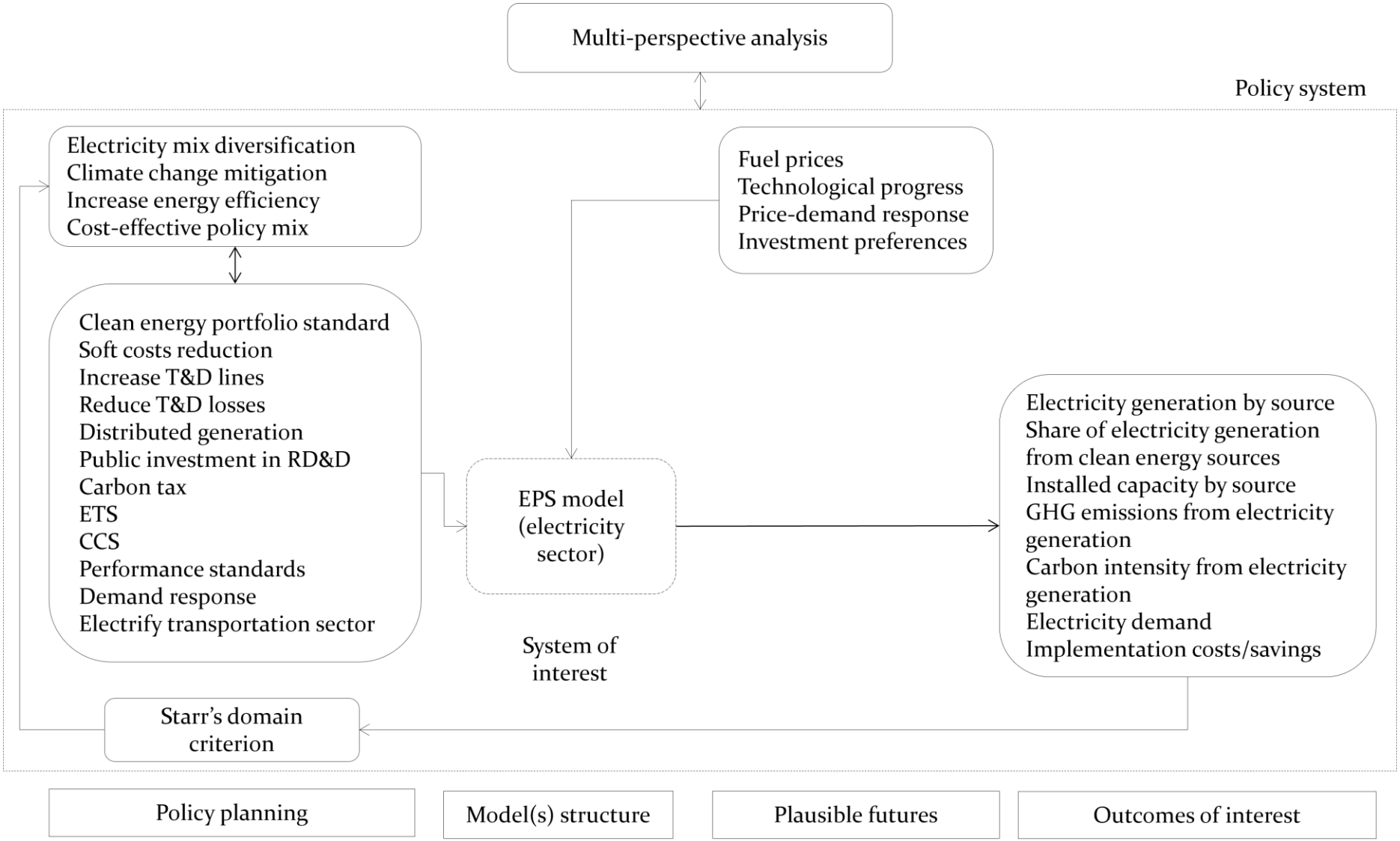
Supplementary Fig. 3. Robustness analysis of different policy alternatives with respect to 2050 policy objectives following a directed search approach.



Supplementary Fig. 4. Integrated method for energy policy analysis towards clean energy transitions. Source: Adapted from [1].



Supplementary Fig. 5. Policy problem definition using the COPRIEMD framework. Source: Adapted from [1].



Supplementary Fig. 6. Integration of key elements using the COPRIEMD framework. Source: elaborated with information from [2,3].

Supplementary Note 1. Narrative literature review process for identification of deep uncertain factors within electricity systems.

To identify and characterise relevant deep uncertain factors within electricity systems, a narrative literature review process (with search criteria, explicit parameters, and a sample) was conducted in this study. The literature search process was initially developed in July 2021 and updated in January 2022. To facilitate replicability, the process followed a series of steps (i.e. research design) to identify, screen, and select relevant documents for analysis as described in this section. The flow of information through the narrative review process is depicted in Supplementary Fig. 7 (based on the four-step flow diagram within the PRISMA statement [4]). A total of 69 main uncertainties were identified from the literature review process (see Supplementary Table 2) and they were classified in four main categoeries (see Supplementary Table 3).

Step 1. Identification of sources.

Dimensions (https://www.dimensions.ai/) was the database chosen to locate and select relevant studies for the purpose of the analysis. At first, a search was conducted on Dimensions using a combination of English-language keywords included in "Title and abstract" only. Also, the publication type was limited to "Article" only. The preliminary search resulted in 75 publications using the following string: ("uncertain" OR "uncertainty") AND ("electricity" OR "power") AND ("model" OR "modeling" OR "modelling") AND "exploratory".

Step 2. Title/abstract screening.

A preliminary screening process of these 75 documents was conducted on the criteria of title and abstract (if available) to verify their relevance to the review. From these, 59 records were excluded due to three main reasons: (1) the studies were out of scope (i.e. covering particular topics such as minimising the energy cost for wind turbines on high-altitude sites by applying a chaos-opposition-enhanced slime mould algorithm; broader topics such as coordinated wide-area damping control using deep neural networks and reinforcement learning; or topics from other disciplines such as neuroscience, bioinformatics, clinical chemistry, oncology, health care, hospitality, education, and marketing); (2) no apparent relevance was found (e.g. analysis of imperfect temporal information in geographical information systems for exploratory spatio-temporal analysis); (3) and did not match the research aim (i.e. to identify and characterise deep uncertainties in electricity systems).

Step 3. Full-text screening and eligibility.

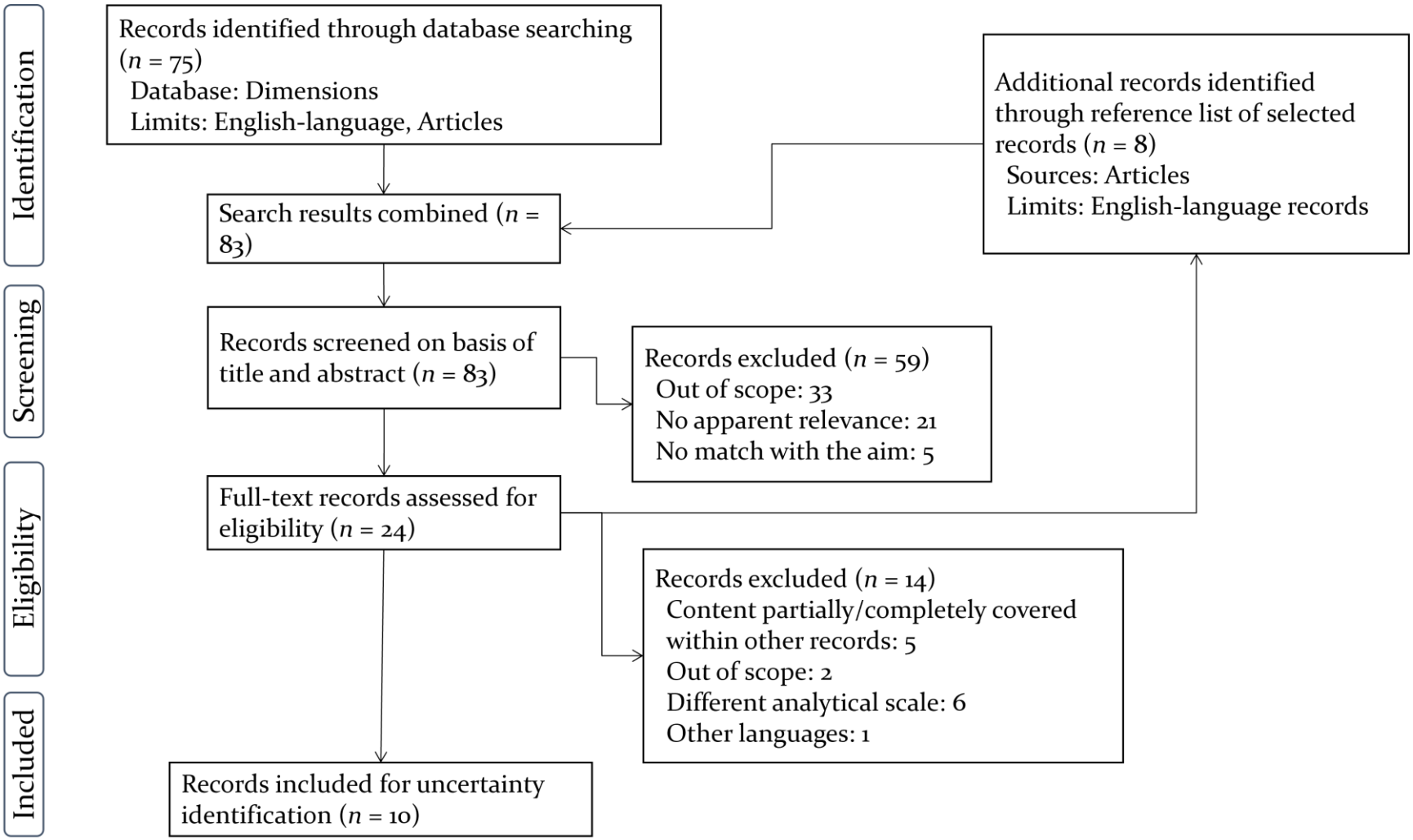
During this step we reviewed 16 documents. They were filtered based on their relevance on contributing to a critical analysis on the identification and characterisation of deep uncertainties in electricity systems using an exploratory approach. A total of 11 records were excluded due to four main reasons: (1) content of the studies was partially or completely covered by other records (e.g. updated versions of articles previously presented in

conferences); (2) the documents were out of scope in terms of the research aim (e.g. did not follow an exploratory modelling and analysis approach); (3) analyses were conducted at specific analytical scales, other than for energy policy analysis (e.g. the exploration of different innovative business models to identify opportunities for grid operators, or the analysis of specific technologies within electric vehicles or energy storage systems); and (4) the content was in other language than English.

On the other hand, reference lists of included records were manually screened to identify additional relevant studies. A total of 8 additional studies were included to the review going through the (iterative) literature review process. After this step, the number of relevant documents was reduced to 10.

Step 4. Records included.

A total of 10 records were accordingly cited within this article to identify and characterise deep uncertainties within electricity systems using an exploratory approach.



Supplementary Fig. 7. Flow of information through the different phases of the narrative review process.

Supplementary Table 2. Identification of deep uncertainty within electricity systems based on a narrative literature review process.

Scope/Region	Main uncertainties	Total uncertainties	Total outcomes of interest	Ref.
Hypothetical investment decision for a natural-gas-fuelled power plant	Natural gas price Electricity demand Electricity price	3	1	[5]
Hypothetical electricity generation system	Economic growth Electricity intensity of economic growth Change in electricity capacity demand Annual total electricity capacity demand Decommissioning capacity technology Progress ratio	28	6	[6]
Hypothetical electric power generation sector	Initial capacities Lifetimes	Not specified	1	[7]

Scope/Region	Main uncertainties	Total uncertainties	Total outcomes of interest	Ref.
	Delay orders of lifetimes Initial decommissioned capacities Planning and construction periods Progress ratios Initial costs Economic growth Investment preference structures			
Dutch electricity generation system	Investment cost factor Operational cost factor Coal and gas price increase percentage Demand growth fraction Load slope change fraction Planning horizon of the generation companies	13	5	[8]

Scope/Region	Main uncertainties	Total uncertainties	Total outcomes of interest	Ref.
	Mean return on investment of generation companies			
Dutch electricity system	Investment costs Operational costs Demand development Decision making by the generator companies Carbon prices Year in which CCSS becomes available	13	4	[9]
European Union power sector	Economic lifetime Learning curve Economic growth Electrification rate Physical limits Preference weights	46	3	[10]

Scope/Region	Main uncertainties	Total uncertainties	Total outcomes of interest	Ref.
	Battery storage Time of nuclear ban Price-demand elasticity			
United Kingdom energy system	Investment costs - power generation Build rates – power generation Investment costs – hydrogen production Investment costs – cars Investment costs – heat pumps (HP), district heating (DH) Resource availability – biomass Resource prices Demand response Carbon prices	Not specified	2	[11]
	Potential installed capacity	24	12	[12]

Scope/Region	Main uncertainties	Total uncertainties	Total outcomes of interest	Ref.
Indian electricity sector (framed exploration)	Exogenous learning (growth rate between 2015 and 2030) due to global technological progress Endogenous learning rate due to the scale of installed capacity Capacity factor coefficient of power plants for different sources Future rate of change in FIT Future rate of change in RPO Future rate of change in AD Population growth Grid losses in transmission and distribution networks			
Ireland energy system towards 100% renewable energy	Technology costs Energy price Renewable energy potentials	15	13	[13]

Scope/Region	Main uncertainties	Total uncertainties	Total outcomes of interest	Ref.
Italian day-ahead electricity market	Investment costs Production costs Storage Phase-out coal Price subsidy policy Electricity price elasticity Economic growth Technological progress	19	3	[14]

Supplementary Table 3. Main deep uncertainty factors considered in this study.

Uncertainty in	Description
Fuel prices	The uncertainty of fuel prices (e.g. natural gas) is derived from their volatility in the financial markets. This volatility may have a direct impact in operational costs for some technologies.
Technological progress	Learning rates for selected technologies are used to determine the percentage reduction of investment costs due to learning processes.
Price-demand response	Refers to price elasticity factors for different sectors (e.g. transport, residential, industry).
Investment preference structures	Average expected return-on-investment for generation companies.

Supplementary Table 4. Deep uncertainty matrix (experiment setting for conducting EMA analysis).

See Excel file.

Supplementary note 2. Exploratory modelling and analysis (EMA) implementation.

The EMA process was implemented using Jupyter Notebook as the web-based interactive computing platform. The corresponding code is provided within two Jupyter notebooks.

See Jupyter notebooks.

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