



Pictures of power play: Visual language and analysis of Victorian electricity

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ABSTRACT

Australia's electricity system is undergoing a transition, with each jurisdiction contributing to this shift. Despite progress, about 70% of Victoria's electricity is still generated from brown coal, underscoring the importance of understanding its historical development to inform future transitions. This article presents the Socio-Technical Layout (STL) framework as a graphical tool to map, diagnose, and analyse key elements of socio-technical systems, including technologies, actors, markets and energy-money flows. Applying the STL to Victoria's electricity system uncovers three development phases: emerging, public, and private; and reveals that: (i) complexity — traditionally linked to scale — depends on the lenses (technological, organisational) and viewpoint (household, system operator); and (ii) transformative actors institutionalised socio-technical solutions aligned with societal values and needs. This approach also carries implications for transition agendas. As an explanatory framework with diagnostic capabilities, STLs provide a common language to enhance participatory processes. Stakeholders can use STLs to identify areas ripe for change, test and evaluate potential modifications from different viewpoints, and identify what is needed to support them (new markets, actors). STLs can be formalised into computer models, bridging qualitative and quantitative research. STLs should be complementary to narratives and other transition frameworks, given their representational limitations.

1. Introduction

The energy transition is no longer an aspiration but is well underway. A major concern now is ensuring that it unfolds swiftly, justly, and at a reasonable economic cost. This situation presents a significant governance and analytical challenge, particularly in integrating technological innovations like Distributed energy resources (DER) (a.k.a Consumer energy resources (CER)), into existing systems. New market structures and institutional arrangements would be needed to accommodate a diverse range of stakeholders, with households (and aggregators) increasingly acting as electricity generators through technologies such as rooftop solar, batteries, and electric vehicles.

Current National plans and agendas reflect these governance and analytical challenges. The European Green New Deal (European Commission, 2023a) underscores the need for internal energy markets to facilitate the integration of renewable and flexible assets (European Commission, 2023b). Similarly, the UK's target of a 78% emissions reduction by 2035 highlights the need for initial policy support while new markets mature and they alone drive the Net Zero transition (Climate Change Committee, 2022, 2024). Closer to this article's home,

Australia's Net Zero Plans (Department of Climate Change, Energy, the Environment and Water, 2023; International Energy Agency, 2023) have made the need for enhanced capacity investments in generation and transmission infrastructure and regulatory support for CER apparent (Australian Energy Market Commission, 2023; Department of Climate Change, Energy, the Environment and Water, 2024; Clean Energy Council, 2024).

Agendas and roadmaps typically outline objectives and outcomes to be achieved by different workstreams, each supported by a designated task force, timeline, and dependencies. Workstream participants could benefit from a shared understanding of the current socio-technical configuration and its development, which would enable them to accurately diagnose the current system state, path dependencies, lock-ins and opportunities, as well as consider the implications of interventions, drawing on lessons learned from the past.

Sustainability Transitions research provides various frameworks for understanding system change, including the Multi-Level Perspective (MLP) (Rip and Kemp, 1998; Geels, 2002), Multi-Phase Model (MPM) (Rotmans et al., 2001), Transition Management (TM) (Rotmans

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List of Acronyms

AEMO	Australia Energy Market Operator
ASX	Australian Securities Exchange
DER	Distributed energy resources
CER	Consumer energy resources
COAG	Council of Australian Governments
ETM	Exchange Traded Market
GWh	Gigawatt hour
MCC	Melbourne City Council
MESCo	Melbourne Electricity Supply Company
MW	Megawatt
NEM	National Electricity Market
OTC	Over the counter
PPA	Power purchase agreement
PV	Photovoltaic
RET	Renewable Energy Target
SECV	State Electricity Commission of Victoria
SPM	Service provision module
STL	Socio-technical layout

et al., 2001; Loorbach, 2010), Strategic Niche Management (SNM), and Technological Innovation Systems (TIS). These frameworks are valuable analytical tools, but there is room to improve their ability to do detailed system diagnosis, with a tool that can be consistently applied across different periods to capture the dynamic interdependencies of its socio-technical components. Most traditional frameworks cannot be used for detailed mapping exercises that explicitly link actors, assets, dependencies, and flows (e.g. energy–money), and are difficult to operationalise in cross-scale analysis, and formalised into computer simulation models. Also, some of these frameworks tend to focus on a single technology or have a narrow scope, overlooking existing infrastructure or institutions.

Building on research in transitions and complexity, this article proposes and tests the Socio-technical Layout (STL) framework. The STL enables a detailed diagnosis of the system's state (including technical, organisational, governance, and institutional aspects) at any given time. The STL is a diagrammatic approach to mapping the socio-technical interplay within energy systems, focusing on both the 'hardware' of technology and infrastructure and the 'software' of markets, regulations, and stakeholders. Considering the institutional (rules of the game) and governance (how governing happens) arrangements that drive their operations, such as the energy–social contract considerations linking money and electron flows. By examining different configurations across time, we can deepen our understanding of how complex systems, such as energy systems, adapt to and influence change.

This detailed diagnostic STL framework with multi-scalar modularity (i.e. SPM) and granularity (actor–asset relationships, arenas, and actor interactions) improves analytical detail and facilitates their formalisation into computer models. Thus, the STL framework can complement established ones — grounding abstract middle-range theories in the specific socio-technical architecture of the system — enhancing the analytical capacity of traditional transition analysis practices.

Following a stepped approach (Section 4) and based on original research from primary sources, this article applies the STL to the history and development of electricity provision in Victoria, Australia, from its inception to the near present. In doing so, we aim to illustrate that using STLs one can diagnose the system state and augment a traditional historical narrative to the point that it readily permits technical and policy analysis and design.

Thus, this article presents the first comprehensive, diachronic analysis of this history in socio-technical terms. The history is given — as is

customary in Transition studies — in the form of a rich narrative. We use STLs to analyse the development of the system, pausing at various years to take a 'snapshot'. By comparing snapshots of the system, we can capture regimes — long periods during which STL snapshots remain largely unchanged, and track the trajectories of change. Consequently, innovation in STLs is captured by the 'delta' in the layout's snapshots across time, encompassing any changes in assets, actors, or governing logics (such as regulations, tariffs, or market access).

We demonstrate how STLs assist in analysing a system over time, capturing how the evolution of electricity has identifiable phases of relative stability: *emerging*, *public* and *private*, between which the technological infrastructure and the organisational, institutional and governance arrangements change profoundly, confirming findings about socio-technical regimes in transitions studies using the MLP and MPM frameworks. Thus, the primary contribution of this work is to provide a diagnostic tool that combines the descriptive insights of established theories with the practical orientation of newer methods, directly aiding decision-making, guiding national roadmaps, and informing the development of strategies and computer models.

Moreover, using the STLs revealed the following:

- The STLs further unravel the uneven trajectories of the system in terms of complexity and scale, depending on the *lens* (technological, organisational) and *viewpoint* (household, manager, politician, engineer) of analysis. Sometimes, technological and, at other times, institutional and organisational developments lead to changes in the system's complexity.
- A detailed, diachronic mapping of the socio-technical system using historical data allows us to identify, as key drivers of change, the societal values and needs framed by transformative actors. This aligns with current theories in transition studies regarding the roles of actors (de Haan and Rotmans, 2018) and societal values and needs (de Haan et al., 2014).

These findings have important implications for transition agendas. The STL provides a cohesive framework for integrating diverse workstreams, enabling actors to examine interventions from multiple perspectives. It supports the exploration of how proposed changes align with societal needs and values, while also offering a means to visualise future system configurations. This is particularly valuable at the local scale — such as the SPM (described later) — where emerging technologies like DERs (and CERs) introduce new layers of technical and social complexity.

The STL's diagnostic capabilities help identify where there is 'room for change' and the actors, markets, and institutions required to support these changes effectively. These capabilities can also be used to test where misalignments or tensions among actors might arise if infrastructure configurations are challenged. Its elements also assist in clarifying responsibilities, recognising overlaps among workstream objectives, and assessing the feasibility of interventions.

Empirically, we contribute a detailed and in-depth historical case study of the Victorian electricity system, drawing on valuable analyses of its evolution. While these previous studies did not specifically adopt a socio-technical perspective, they offered significant insights that inform the narrative of this article. Some studies have summarised the overall system's history and future outlook (CIGRE, 1996), while others have focused on a particular period such as the restructuring years (Aghdam, 2006, 2011) of Australian energy systems. Additionally, some research has highlighted both the achievements and challenges faced by the Victorian system (SECV, 1949; Edwards and Connolly, 1969; Pierce, 2010), as well as the impacts of industrial reforms (Evans, 2001).

Academically, we contribute to the fields of sustainability transitions and complexity as STLs build on and enhance the existing toolkit for Sustainability Transitions practitioners (Section 2), but can also be used by professionals from broader disciplines, enabling engineers,

financiers, managers, entrepreneurs, historians, sociologists, and modellers to thoroughly examine the system under analysis. Similarly, we expect some of these contributions to generalise to similar cases of electricity system configurations or be applicable to diagnoses and analyses of other service provision systems in other geographies, guiding computer models, roadmaps and national agendas.

The article is organised as follows. Section 2 situates the work within the literature of transitions and complexity. 3 offers a brief overview of the STL framework. Section 4 describes the methods, data collection, sources, and the mapping methodology used to analyse the system's evolution. Section 5 details the historical narrative, organised by periods that describe the socio-technical context, historical detail, and a snapshot of the system's STL. Section 6 presents the findings from the historical narrative and discusses the limitations and opportunities. Section 7 presents the conclusions and outlines future work.

2. Background

Sustainability transitions research has been shaped by several foundational frameworks that have advanced our understanding of socio-technical change, stakeholder roles, and governance strategies. Among the most influential is the Multi-Level Perspective (MLP), which conceptualises transitions as interactions between niche innovations, established regimes, and broader landscape pressures (Rip and Kemp, 1998; Kemp et al., 1998; Geels, 2002). Transition Management (TM) complements this by emphasising participatory governance and the co-design of transition pathways (Rotmans et al., 2001; Loorbach, 2010). Technological Innovation Systems (TIS) focus on the functions and dynamics of emerging technologies within innovation ecosystems (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Bergek et al., 2008), while Strategic Niche Management (SNM) highlights the importance of experimentation and protective spaces for nurturing new practices (Schot and Geels, 2011; Raven et al., 2012). The Multi-Phase Model (MPM) adds a temporal dimension by framing transitions as a sequence of phases — pre-development, take-off, acceleration, and stabilisation — each with distinct characteristics and dynamics (Rotmans et al., 2001).

Together, these frameworks offer a wealth of useful conceptual tools for analysing transitions. However, they share a common shortcoming: they describe transformation processes in broad terms but lack detailed means to assess the state of socio-technical systems in detail, with a tool that can be consistently applied across different periods to capture the dynamic interdependencies of its socio-technical components. The absence of clearly defined diagnostic components also hampers their integration into computational models, which in turn limits their practical usefulness for decision-making, setting agendas, scenario analysis, and creating actionable national roadmaps.

In response to these limitations, newer approaches have emerged to enhance operational relevance. The Transitions Typology (TT) proposed by Strambach and Pfaltzsch (2020) builds on the MLP by distinguishing between different change pathways — such as transformation, substitution, or reconfiguration — enabling policymakers to anticipate likely trajectories. The Transition Model Canvas (TMC) provides a structured and visual approach for identifying drivers, barriers, and leverage points, thereby making complex systems more accessible to decision-makers (van Rijnsoever and Leendertse, 2020). Participatory Systems Mapping (PSM) further strengthens inclusivity by involving stakeholders directly in mapping socio-technical dynamics and surfacing diverse perspectives (Sedlacko et al., 2014). While these approaches improve the communicative and participatory dimensions of transitions research, they still lack a comprehensive and systematic method to link technical assets with actor relations and value flows. This limits their ability to diagnose system states across different contexts in a consistent and comparable manner.

The STL framework aims to address this analytical and methodological gap by offering a structured approach to map technical assets,

actors, arenas, relations, and energy–money flows as interconnected elements of a socio-technical system. Building on traditional frameworks while enhancing diagnostic capabilities, the STL retains the MLP's focus on multi-level interactions but disaggregates broad concepts, such as regimes and niches, into their constituent elements. It incorporates TM's emphasis on governance arenas and the MPM's phased view of temporal change, presenting these in a spatially and materially explicit diagnostic format, enhancing MPM phases — pre-development, take-off, breakthrough, and stabilisation — by offering an analytical view of a system's transition pathway that captures diverse perspectives and socio-technical elements. STL also leverages the communicative strengths of TMC and PSM, extends TT's pathway sensitivity, while adding the ability to diagnose system states.

Understanding complexity and scale is also essential in transitions research, though these concepts are interpreted differently across disciplines. The Large Technical Systems (LTS) literature suggests that complexity tends to increase with scale, but can be managed through innovation (Hughes, 1987). In fields such as complexity science, evolutionary economics, network science, and ecological systems, complexity increases with scale, driven by distinct mechanisms. Scale may refer to geographical spread, the number of actors, market adoption, or the number of components and their interconnections. Complexity, meanwhile, emerges from interactions among system components — such as physical assets, firms, governments, network nodes, actors, or species and their environments. This article uses the STL for a closer examination of the relationship between scale and complexity (findings are discussed in Section 6).

3. STL framework

The STL framework represents socio-technical systems, with equal focus on social and technical aspects (Rojas and de Haan, 2019; Rojas Arevalo, 2022). STLs can describe service provision systems across various scales. While well-suited for resource flow systems, such as water, energy, food, and waste, it is less applicable to systems like health and education. We use electricity systems in this article to describe the STL framework.

Regardless of the system design — centralised, distributed, decentralised, or a combination of these — an energy system will have *generation assets* — any physical asset used to convert primary energy to electrical power, *network assets* — grids and related assets used to manage power quality and deliver electricity, *storage assets* — batteries, molten salt, and gravitational (pumped hydro) to store energy. Additionally, there are *consumption assets*, which are anything connected to the electricity system that requires energy to operate, i.e. a load. Consumption assets can be aggregated for analysis purposes. For instance, household appliances can be aggregated into 'dwellings' and dwellings into consumption sectors, such as residential.

The electricity system can be considered a black box from the end-user perspective. The end-user pays the bill for the service and gets the electricity to meet energy needs and wants (e.g. warmth, comfort, entertainment, and safety) through an *interface* — i.e. wall outlet. The end-user may remain unaware of how the system behind the interface is implemented. The group of physical assets of the energy system in 'boxes' are called Service Provision Modules (SPMs) in this framework. These recursive structures represent the primary physical assets of the system and contain the broad classes of generation, network, storage, interfaces, and consumption assets (Rojas and de Haan, 2019).

These physical assets and infrastructures provide balancing services — producing, conditioning and transporting electrical power, ensuring supply always meets demand. Thanks to their modular and nested properties allowing for the reconfiguration of their main components, by changing the demand aggregation and supply assets, the SPM can represent different system configurations (off-grid, micro-grids), scales of analysis (individual household, neighbourhood, State, National) and help define system boundaries.

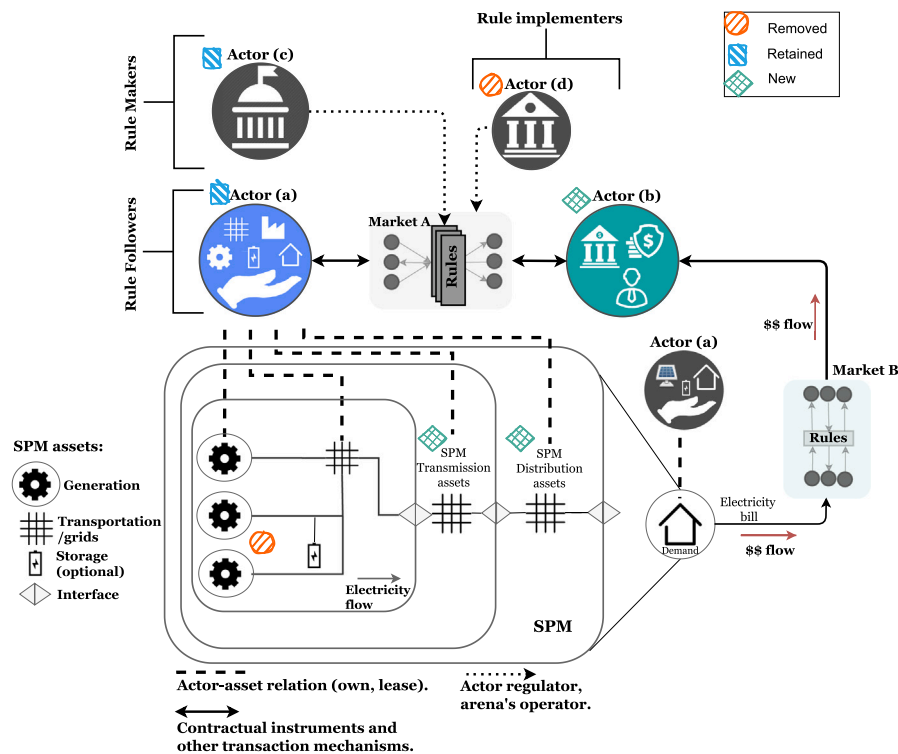


Fig. 1. Generic STL with main components: physical assets in the SPM, networks of societal entities, relationships and markets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Besides the technicalities of energy balancing, social entities engage in strategic, financial, and other transactions to turn electricity production into provision. Physical assets, infrastructures, societal entities, and institutions combined were designed to connect energy production with energy use to meet societal needs (de Haan et al., 2014).

The socio-technical literature commonly refers to social entities as *actors* (Weber, 2003; Geels, 2004; Holtz and Chappin, 2019; Markard et al., 2012). Here, ‘actor’ and ‘organisation’ are used interchangeably and can be individuals, groups, or organisations. In the STL, actors can have relationships with other organisations or assets, classified as actor–actor or actor–asset relationships. Importantly, actors can own, manage, lease, and use assets. Actors can enter into contractual agreements, such as in an energy-only or financial markets. However, they can also establish strategic relationships to position themselves in the market, adjust their business objectives, and respond to landscape changes. For instance, they can change their name and rebrand, merge with or acquire other actors, or consolidate different operations through subsidiaries. Actors are more diverse than assets and can be classified into various categories, including: households, retailers, market operators, and regulators. Depending on their power and agency, these can be categorised into broader groups of *rule makers*, *rule implementers*, and *rule followers*. One actor can be part of one of these broader categories and can be influential in another category.

Another important class of entities needed are those that provide an arena that regulates social interactions (Beckert, 2009), i.e. markets. A centralised wholesale spot market, such as an energy-only market, is an example of an arena where a system operator manages the physical supply and demand balance and sets the energy price according to the arena’s rules. The wholesale spot market in Fig. 2, market A ‘box’, shows how actors (small circles in the box) engage in transactions framed by regulations and standards (inner rectangular box). Market A from Fig. 2 represents market rules where participants do not necessarily know their counterparts (arrows point in different directions among actors). In some markets, such as ‘B’, rules permit actors to know whom they transact with. An example of a market ‘B’ could be a

retail electricity market, where a household could choose the electricity retailer and pay the electricity bill directly.

The visual representation from Fig. 1 is an example of a generic STL composed of SPMs, organisations, markets, and relationships. The SPM illustrated the electricity flow from generation to consumption and the monetary flow via its societal dimension — i.e., from energy consumers through markets and actors. It represents the modular, recursive and networked nature of the system. In the STL, the assets connected to actors are owned, leased, and exploited up to where one or several actors provide an *interface*. These actors engage in contracts and transactions to pay for the electricity services they provide to one another. In other words, each SPM is associated with a network of actors, and the STL adheres to specific institutional, economic, and governance structures. Table 1 summarises the main STL elements and can guide their construction.

Fig. 1 illustrates how colour coding and icons can be used to highlight differences and facilitate the comparison between STLs. In this case, dark orange circles mark removed items (such as decommissioned assets, actors ceasing operations, or name changes); blue squares highlight retained items (assets in the same condition or expanded, and existing actors incorporated into the electricity sector); and green rhombuses indicate new items (SPM assets, actors, and markets).

The STL’s unique analytical contribution is its capacity to make the structural, institutional, governance, and actor-based configurations of a socio-technical system both visible and formalisable. Depending on the analysis objective, the generic STL can be utilised to gain insights from various lenses and viewpoints, allowing analysts or researchers to decide which actors and arenas to include or exclude. The STL represents how the system *responds* to its context. Consequently, the socio-technical context (including socio-economic conditions, political discourse, and landscape pressures) is crucial for its development. The next Section 4 explains how STLs are constructed and employed to analyse innovation trajectories and regimes.

Table 1
Main elements of the Socio-Technical Layout (STL) framework.

STL element	Description
Service Provision Module (SPM)	Modular “boxes” of technical assets enabling service delivery. They can be scaled or nested (household, micro-grid, national system). Main asset classes: • Generation: convert primary energy into electricity. • Network: grids delivering power and maintaining quality. • Storage: assets storing energy for balancing and flexibility. • Consumption: loads using electricity, which can be aggregated. • Interface: points where service changes hands (outlets, meters).
Actors	Individuals or organisations (e.g., households, firms, regulators). They can own, manage, or use assets and be grouped as <i>rule makers</i> , <i>implementers</i> , or <i>followers</i> .
Actor–asset relations	Links showing actors’ control, use, or benefit from physical assets (e.g., ownership, leasing, operation).
Actor–actor relations	Social and strategic interactions among actors (e.g., financial contracts, mergers and acquisitions).
Arenas	Institutional spaces where interactions are governed (e.g., spot, OTC, and retail markets, community schemes).
Flows	Movement of <i>energy</i> , <i>money</i> across the system, linking technical and social dimensions.

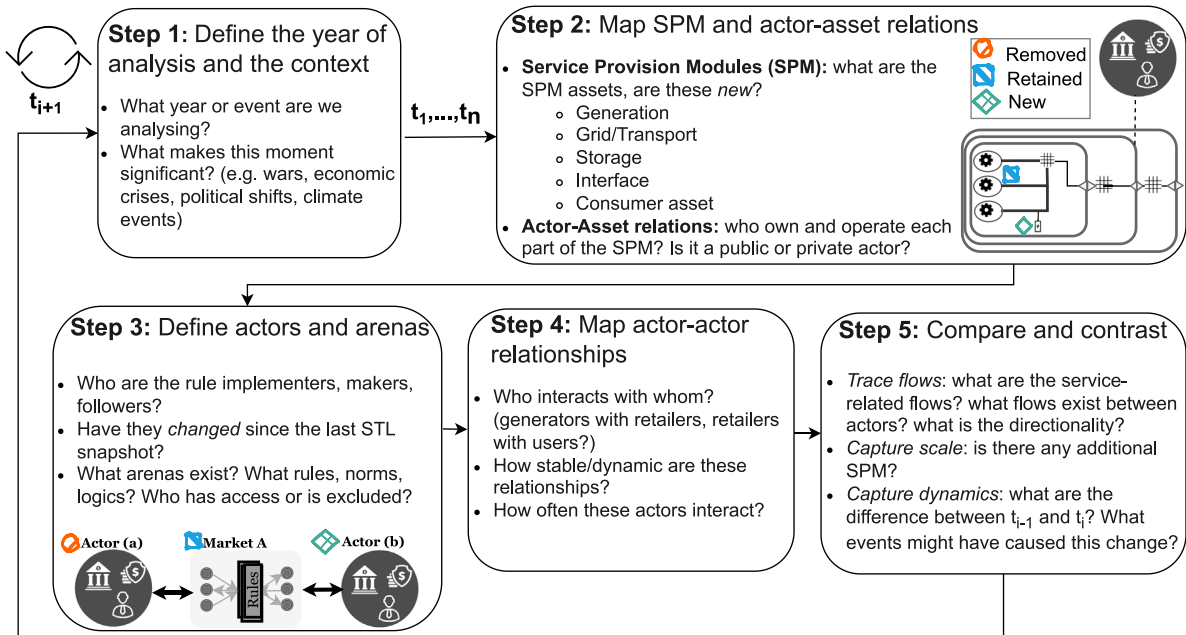


Fig. 2. STL Step by step guide for STL construction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Methods: Data collection and STL mapping

The STL elements outlined in Section 3 (summarised in Table 1) guided the data collection effort to describe Victoria’s electricity system history. The data collected physically from the state’s public archives located in Melbourne,¹ was digitised to facilitate processing. Data was also collected from online sources including the State of Victoria and National Parliament archives, newspapers, companies’ websites, and professional and academic publications.

Fig. 2 illustrates the methodology employed to construct each STL, which involves distinct steps, data and guiding questions. First, the analyst should establish the temporal boundary, t_1 , or the year for analysis, that will determine the socio-technical context. Step 2 is to start mapping the electricity system’s SPMs (all physical assets) and SPM levels, which helps determine the system’s boundaries. Given that this step helps identify the physical assets, it is possible to define the actor–asset relations — i.e., who owns, operates, and manages each part of the SPM asset. Step 3 is to define the arenas and institutions, as well as actor types (rule makers, implementers, and followers). Step 4 involves defining the actor–actor relationships. Step 5 is to compare and contrast the STL, paying particular attention to any notable differences

between the energy and financial flows, whether there was a system expansion (another SPM level), and whether there are significant changes in the actors, new arenas, or regulations. Colour coding and labelling, as described in Section 3 can be used to highlight changes in Steps 2 to 4, easing the qualitative comparison between STLs in Step 5.

The systematic mapping of STLs chronologically to these sources was conducted using a free diagram software tool² with templates for each element, pausing at different points in time to capture potential responses with the STL, particularly after influential events, regulations or institutional changes. Therefore, The STLs are temporally indexed. After each STL snapshot analysis, the process can be repeated to represent the system at the next time step t_{i+1} .

If, after analysing consecutive snapshots, there were long, relatively stable periods — though not static — we classified them as ‘regimes’ in line with the usage in the socio-technical transitions literature (Geels, 2002; Geels and Schot, 2007), representing the dominant institutional logic behind the strong alignment of practices and technologies over long periods (Loorbach, 2010; Strambach and Pflictsch, 2020). While innovations can be captured by the ‘delta’ in the snapshots across time, showing structural modifications to the system layout, affecting physical infrastructure, governance, market roles, and rules, and making it

¹ Public Records Office Victoria <https://prov.vic.gov.au/>.

² <https://www.drawio.com/>.

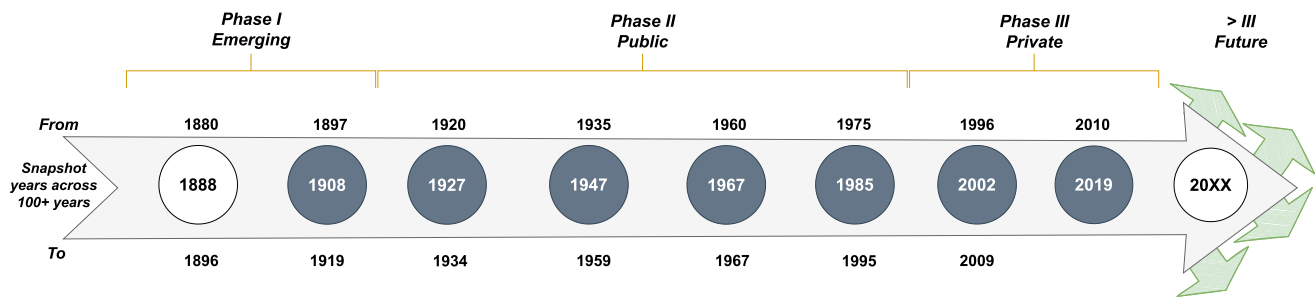


Fig. 3. Timeline of Victoria's 100+ years of electricity sector development, highlighting the three main phases and the snapshot years in circles. The STLs in this article are for all the snapshot years in dark grey.

possible to trace innovation trajectories (e.g., how novel technologies expand and new market structures form).

The STL definition greatly facilitated this mapping and diagnostic exercise, which was validated among the authors and experts during informal sessions. Still, it might have also constrained empirical evidence to the framework, risking missing other dimensions of the system's evolution — for instance, by embedding some of the key inputs of the system, like coal and jobs, within the layout, and by excluding from the system boundary the role of technology manufacturers and providers (lamps, wind turbines, transformers). The authors aimed to capture some of the dimensions by contextualising the case under analysis within its geographic and socio-economic factors, and regarded the STL to sufficiently address the scope of the research: analysing the socio-technical evolution of systems for service provision, considering the institutional, governance, and organisational arrangements driving their operations, such as the energy–social contract considerations linking money and electron flows. Nevertheless, even though the STL might constrain the elements of inclusion, an analyst can be as exhaustive as needed, broadening the STL's elements or zooming into dimensions to capture what is suitable for their research aim.

The data collection, mapping of the STL snapshots at different years (Fig. 3) and historical narrative revealed three phases. The *emerging regime* (the 1880s to 1919) at the beginning of the electricity sector in Victoria. Strong regulation enacted in 1919 for a uniform and public system marked the beginning of the *public regime* (1920–1994) with the establishment of the State Electricity Commission of Victoria (SECV). The public regime ended in 1994 when the SECV and the electricity system underwent disaggregation of its supply chain, corporatisation and privatisation. The narrative marks 1995 as the beginning of the *private regime*, which is the current system's phase.

5. Socio-technical evolution of Victorian electricity

This section describes, in each subsection, the narrative (summarised from Rojas Arevalo, 2022, p. 65–115) of the period preceding each snapshot year in Fig. 3, followed by the STL snapshot (drawn) and its description, including the context and main elements. Readers interested in the application of the STL can proceed directly to the STL analysis immediately after the historical narrative.

5.1. Beginnings (1888–1908)

Historical narrative — Entrepreneurship, political climate, early institutional interventions and first legislation

Australia's electricity sector began in the late 1800s, mirroring developments in other Western nations. Early innovations included battery-powered telegraphs and the illumination of public spaces with arc lights — such as the fifty-cell battery setup for the Duke of Edinburgh's visit to Melbourne in 1867. However, gas lighting prevailed due to technological limitations. Pioneers in Victoria, like R.E. Joseph, introduced small lighting plants for public displays in 1878 (Randall,

1937; CIGRE, 1996) and eventually established the Victorian Electric Light Company Ltd (SECV, 1892–1969), which later evolved into the Australian Electric Company Limited (AEC) (Randall, 1937).

By the 1880s, the AEC was illuminating public buildings, such as the Athenaeum Theatre, with incandescent electric lamps generated at Russell Place, as well as the Tivoli Theatre and the Victoria Hotel's public rooms with arc lights (Pierce, 2010). It had also agreed with the Melbourne City Council (MCC) to light the Eastern Market. In 1883, the Australian Electric Light, Power & Storage Company (AELPSC) started competing with the AEC and signed an agreement with the MCC to light Elizabeth Street. This company showcased an extensive electric lighting installation featuring 1000 arc lights and 2000 Swan incandescent lights at the Melbourne Centennial International Exhibition. Still, the company was acquired in 1891 by Brush Electrical Co., a British-owned company. Another company, the Union Electric Company (UEC), also entered into lighting contracts with the MCC to light street intersections with arc lights. By 1887, electric lighting had reached landmarks such as Melbourne's Public Library and Parliament House.

The MCC became the first municipality actively engaged in local electrification, initially driven by the Town Clerk's discontent with the gas regime's poor performance and high costs, which was fuelled by critical press (Pierce, 2010). Additionally, other private companies contracted by the MCC successfully demonstrated technological innovations, providing confidence in the electricity provision business. Simultaneously, the MCC began work on its first powerhouse in 1892 (Edwards and Connolly, 1969), fully operational in the central district by March 7, 1894.

Electricity systems initially relied on direct current (DC) dynamos, which suffered from high network losses, limiting the AEC's ability to supply distant energy users from Russell Place. The introduction of the Ganz transformer in the late 1880s revolutionised electricity distribution, reducing voltage drops and replacing numerous small generating systems that started 'cluttering the city' (Cannon, 1975, p. 111). Innovator Alcock was among the first to implement single-phase alternating current (AC) at a large Burnley St., Richmond station.

This period of entrepreneurship gave rise to the first cliques of actors that would influence the sector's development. It also represented a period of dynamic organisational changes. UEC's engineer, J. Arnot, was appointed the first City Electrical Engineer of the MCC's Electrical Supply Department (MCCESD). The AEC was re-registered in 1899 as the Electric Lighting and Traction Company of Australia, with F.W. Clements at the lead, assisted by Herbert Reah Harper — both named Electricity Commissioners during the public regime.

In the regulatory landscape of 1888, private entrepreneurs needed permission from the Victorian Parliament to provide electrical services. Commonly, private electricity providers engaged with municipalities, and municipalities recovered the costs (mainly from lighting services) from residents through council rates.

The late 19th century brought a significant shift, driven by technological progress, political debates — mainly about the Federal Constitution — and the 1890 economic depression. Each of the six colonies

developed its own electricity laws, with private companies leading the way in Victoria, South Australia, and Tasmania, while Western Australia, Queensland, and New South Wales preferred municipal control.

Following the economic depression, Alcock Electric Light and Motive Power Company Limited absorbed the remaining private firms, while the MCC, shielding its citizens from the bankruptcy of private firms, began supplying electricity for private use by 1895 (Cannon, 1975), and building a robust network of dynamos and cables.

A rivalry emerged between Alcock and the MCC, with Alcock facing opposition in Parliament when attempting to legislate and protect its interests (Randall, 1937). International firms also entered the fray, lobbying for regulation. These legislative and actors' pressure attempts ultimately culminated in the *Electric Light & Power Act 1896* (Randall, 1937), formalised electricity supply through 15 permit rules. Also, the Act granted local authorities 42-year orders, while private entities were limited to 30 years. Public safety measures included mandates for underground mains in populated areas, which explains the prevalence of underground power lines in Melbourne's city centre, while overhead lines are found in the surrounding suburbs and regions.

The 1896 Act triggered a wave of investment reminiscent of the gold rush (SECV, 1949, p. 15) and a significant increase in municipal-private partnerships (Hagelthorn, 1915). The drivers of each organisational change are difficult to predict, but actors reacted to regulatory clashes and financial difficulties.³ Despite a 1904 agreement on service standards, supply remained fragmented in current types, phases, and pricing. Private firms targeted industrial users with special rates, while households faced block pricing. In response, the MCC adjusted its flat tariffs to retain customers (Randall, 1937), illustrating the sector's evolving and competitive nature.

We stop to capture the STL in 1908 and how the system responded more than a decade after the economic depression and the enactment of the first Electricity Act.

Snapshot of socio-technical system by 1908

Context and STL. *Victorian electricity starts from scratch. It is a novel technology, initially competing with gas for street lighting. The context is entrepreneurial, with little or no regulation, while the MCC gradually becomes a central player in all relevant arenas.*

SPM Assets: Bottom of Fig. 4. **Generation** — General Electric dynamos (local SPM level in blue); the Russell Place plant (AEC), Burnley Street station (Alcock), and Spencer Street station (MCC) (green rhombus) (Edwards and Connolly, 1969) added an additional SPM level. **Network** — underground mains and street cables in central Melbourne and overhead lines in surrounding suburbs. **Storage** — was minimal. **Interface** — Arc and incandescent lamps in public buildings and streets. **Consumption** — Public institutions (e.g., the Athenaeum, Tivoli Theatre, and Parliament House), residential, and industrial assets.

Actors: *Rule makers:* Victorian Parliament (blue square in STL); *Rule implementers:* Governor-in-Council and Postmaster-General retained from previous years. An Electric Inspector added after the first legislation; *Rule followers* Entrepreneurs (also undertakers after first legislation) R.E. Joseph, AEC, AELPSC, UEC, MCC, MCCESD, Alcock's company, Brush Electrical Co.

³ For example, the Tramways Act of 1890 and the Electricity Act of 1896 had conflicting requirements, creating a regulatory clash. The Electric Light and Traction Co. of Australia took advantage of the situation and applied for new orders, even in locations where other electric companies were already operating, despite their main business being in the transport sector.

Actor-Asset Relations: MCC managed its generation and distribution systems; Alcock and AEC operated their respective stations; Brush Electrical Co. owned and operated AELPSC assets.

Actor-Actor Relations: Contractual relationships between MCC and private firms (AEC, AELPSC, UEC), and acquisitions such as Brush Electrical Co.'s takeover of AELPSC (Hagelthorn, 1915). The SECV opens electricity supply branches in various regions and begins acquiring existing municipal and private utilities.

Arenas: Electricity provision was initially unregulated, later shaped by the *Electric Light & Power Act 1896* and the *Tramways Act 1890*. Rules in arenas, such as tariffs, were set by undertakers, with MCC recovering costs via council rates (market in Fig. 4) and adjusting flat tariffs to remain competitive. Private firms offered block pricing and industrial discounts (Randall, 1937).

Energy-Money Flows: Electricity was generated and distributed near demand centres — energy flows from left to right in the SPM. Consumers paid providers according to local rules — money flows from the consumer to the MCC. If the service was managed by private operators under MCC's area, the MCC acted as an intermediary. The sector saw financial instability and consolidation after the 1890 depression, and investment growth after the 1896 Act (SECV, 1949, p. 15).

5.2. Emergence of public regime (1908–1927)

Historical narrative — Victoria's fuel insecurity and the need for energy independence

In the early 1900s, Victoria's electricity sector was constrained by its reliance on imported black coal from New South Wales (NSW), which, along with diesel and gas, powered key sectors like manufacturing and rail. Frequent coal strikes in NSW exposed the vulnerability of this dependency, prompting Victoria to seek energy independence. Although brown coal deposits in the Latrobe Valley were discovered as early as 1873, serious exploitation did not begin until 1892. However, early efforts, such as those by the Great Morwell Coal Mining Company, were short-lived due to competition from NSW coal and a disastrous bushfire that led to its closure in 1899. The discovery of black coal in Wonthaggi in 1909 marked a renewed push for local fuel sources (Edwards and Connolly, 1969).

The push for brown coal for electricity generation intensified after a 1911 Royal Commission recommended electrifying the railway industry. Small private electricity companies struggled with costs (Hagelthorn, 1915), prompting the state to retain control of rail electrification. Under Premier William A. Watt, the government established the Brown Coal Advisory Committee in 1917 (ANU, 2019), leading to the formation of the SECV in 1918.⁴

Amid a 1919 industrial crisis caused by shipping strikes (SECV, 1949, p. 25), with Sir John Monash at the helm, the SECV appointed Thomas Ranken Lyle, George Swinburne, and Archibald McKinstry, with a mission to “free Victoria from the bonds of imported fuel” (Edwards and Connolly, 1969). They began exploring the State for power plant installations and opened electricity supply branches in various regions to initiate the expansionary work.

Long-term planning and sustained institutional support allowed the SECV to adapt its operations to meet societal energy needs. The SECV earned authority to manage the electricity supply chain — influencing

⁴ Watt's socialist government grappled with whether to privatise or maintain the rail electricity supply as a public asset, ultimately deciding to keep it public. Edwards and Connolly (1969) argue that this was a good decision since no private company could have withstood the tremendous socio-economic effort of developing the state's electricity system in an economy as small as Victoria's.

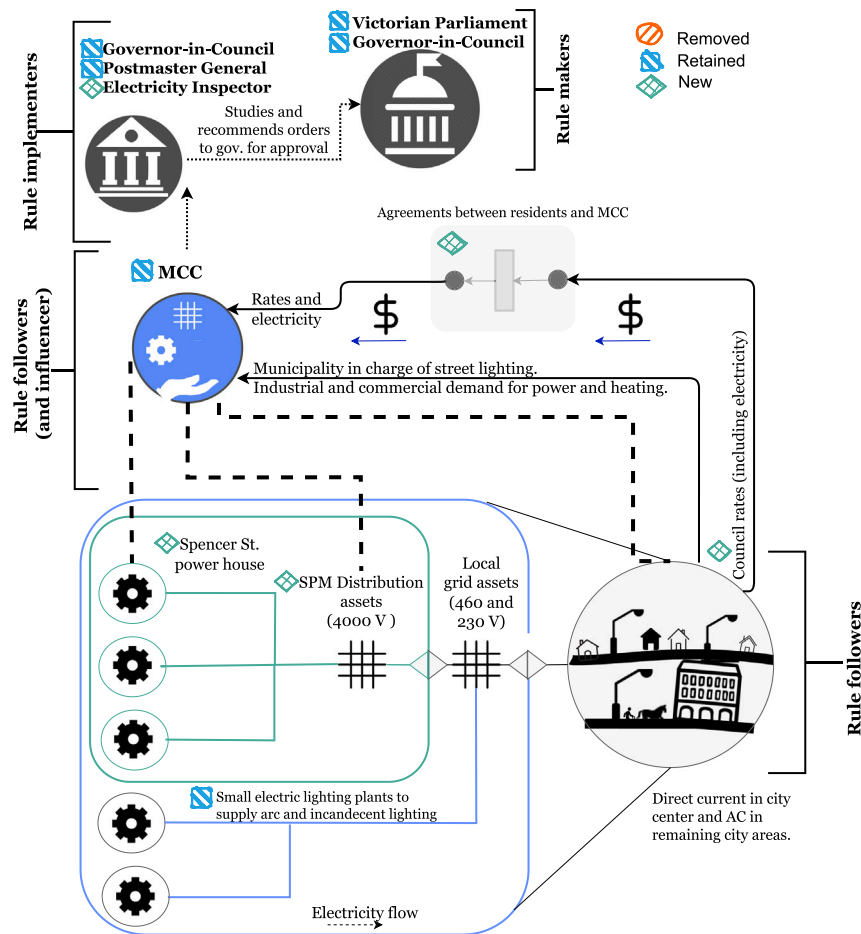


Fig. 4. STL circa 1908. New SPM level with added centralised power plants and distribution networks (green rhombus). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rulemaking, in addition to rule implementer. It recommended new orders and took over existing operations while maintaining accountability to Parliament (Edwards and Connolly, 1969). Its governance ensured independence, shielding the Minister from conflicts of interest.

In its early years, the SECV established diverse supply schemes for rural and metropolitan areas. It expanded in 1922 by acquiring the electricity supply portion of the North Melbourne Electric Tramways and Lighting Company. They commissioned new-generation units and laid the groundwork for significant infrastructure projects to extract brown coal in the Latrobe Valley, notably leading to the creation of the town of Yallourn — a term derived from the Indigenous people's language, referring to the brown fire.

The SECV harnessed German technical expertise to experiment with brown coal of 68% moisture. Efficient combustion of this high-water-content fuel was challenging, prompting the deployment of transmission towers to mitigate supply shortages during the construction of the Yallourn power plant. After various design iterations and tests, Yallourn began operations in June 1924. A half-briquette factory was also established in 1925, creating domestic briquettes for heating and solid fuel stoves, although these accounted for only 3% of the state's fuel consumption (SECV, 1925).

In 1920, the SECV explored hydroelectric power from the Kiewa River but focused on brown coal power due to high capital costs (SECV, 1949). Although the Sugarloaf–Rubicon hydroelectric project gained Parliamentary approval in 1922, it was not operating until 1927–28.

In addition to technical innovations in industrial processes and energy use, such as producing oil and petrol from the hydrogenation of coal and curing tobacco leaves with electric heating, the SECV looked

internationally for best practices and identified a significant gap in electricity demand compared to the USA, Canada, and the UK. To stimulate energy use, they invested in 'demand development', in which they promoted electrical appliances for domestic (vacuum cleaners, toasters, washing machines), commercial (fish fryers, vegetable boilers, and refrigerators), and rural applications (feed mills, poultry food grinders, portable farm motors, and dairy water heaters) (SECV, 1968).

In January 1925, the SECV introduced a 'two-part' tariff, akin to telephone billing, which included a fixed service charge and a variable usage charge (SECV, 1925). They also established showrooms in 1926 to facilitate consumer access to various electrical appliances at comfortable tariffs, boosting consumption.

The SECV targeted productivity enhancements through specialised machinery for users, including automatic refrigeration and electric incubation for poultry. In rural areas lacking electricity, groups would jointly commit to cover 20% of the capital costs for power, establishing a network of early adopters encouraging broader electricity usage among businesses like buttery factories and poultry farms. This led to a vertically integrated monopoly controlling the entire electricity supply chain in Victoria (Abbott, 2006).

We stop in 1927 to examine how the STL responded to the Royal Commission's recommendations, and the establishment of the SECV seeking fuel independence.

Snapshot of socio-technical system by 1927

Context and STL. This period sees expansion and consolidation of the early Victorian electricity system under the auspices of the newly founded

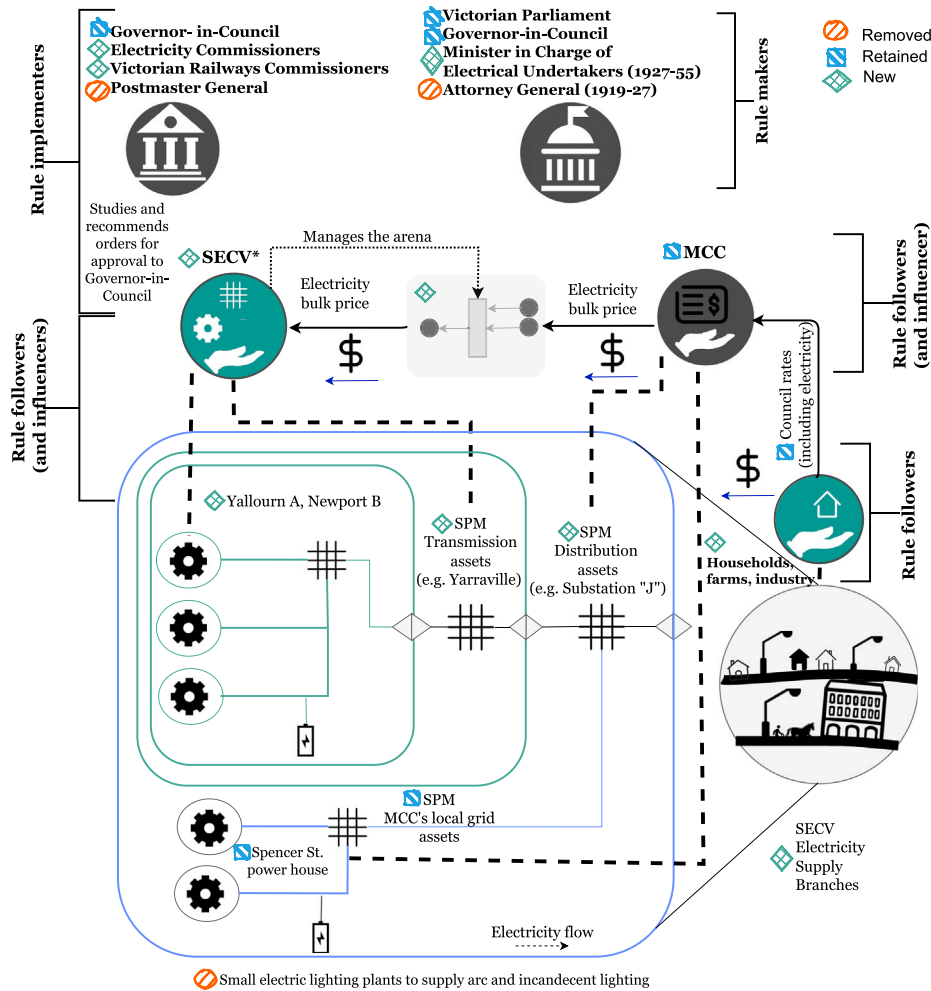


Fig. 5. STL circa 1927. *Some infrastructure was managed by the Victorian Railways Commission, which sold its production to other municipalities and industries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

SECV. The context is one of growing electricity demand and aspiration for Victorian fuel independence, while the state has limited fuel availability.

SPM Assets: The bottom of Fig. 5 shows the SPM by 1927, which includes more areas of supply beyond Melbourne City and close suburbs, to regional areas. **Generation** — Small electric generators (e.g. dynamos) for arc and incandescent lighting largely disappeared (red circle). Largest power stations in Newport B and Yallourn A (green rhombus and new SPM level). Smaller units in Preston, Sunshine, and Belmont. Briquette factory (established in 1925). **Storage** — was limited, though briquettes served as a form of solid fuel. **Network Distribution** — Several DC (230 V) and single and 3-phase AC (230–400 V) systems. Transmission — 22 kV lines between substations, e.g., Newport — Yarraville, Maffra to Bairnsdale, Thomastown and Maindample, and 132 kV lines between Yallourn and Yarraville (green rhombus). **Interface** Buildings (residential, commercial, industrial, farms). **(Consumption)** Space heating with briquettes and the expansion of electrical appliances to metropolitan, rural, and industrial sectors were enabled by demand development initiatives and the establishment of appliance showrooms. Rural users contributed 20% of capital costs for electrification, creating a network of early adopters and expanding the customer base.

Actors: Actors and organisations began to shrink while rule-makers and implementers settled. **Rule makers:** Mostly unchanged, but

the creation of the Minister in Charge of Electrical Undertakers (green rhombus) responsible for the SECV after the Attorney General ceased its role in 1927 (red circle); **Rule implementers:** Governor-in-Council continue approving new 'orders' (blue square), the new actors (green rhombus) include the Electricity Commissioners (F.W. Clements, Herbert Reah Harper, Sir John Monash) representing the SECV (and rule-making influencer), as well as the Victorian Railways Commissioners. The Postmaster General ceased operations in the electricity sector (red circle). **Rule followers:** All electricity undertakers. Details about actors can be found in Rojas Arevalo (2022, p. 65–115), but a few examples include the Electric Supply Company of Victoria Ltd. (Ballarat and Bendigo), Boort Co-operative Butter and Ice Company (Boort), Martin O'Donohue (Garfield), Marong Shire (Kangaroo Flat), Kerang Shire (Koondrook), Melbourne Electricity Supply Company (MESCo), MCC, North Melbourne Electric Tramways Co. The SECV enters the layout (green rhombus), and starts supplying most regional areas and Melbourne's eastern metropolitan areas. It established electricity supply branches (green rhombus) in various Victorian regions.

Actor–asset relations: Diverse and constantly changing business models, including the mix of private companies and local councils owning and operating assets meeting their local demand — e.g. MESCo owned and operated area (Collingwood, South

Melbourne, Richmond, Camberwell, St. Kilda, Oakleigh and Mentone). While other councils with official mandates to supply electricity outsourced all or part of the service. The SECV owned and operated open-cut mines, power stations, transmission networks, and administrative systems.

Actor–Actor Relations: A municipality's financial capacity determined their engagement in the provision of electricity. One business model was to engage with private actors (individuals, or companies) or other municipalities and acting as a retailer mediating between residents and electricity providers. Some, like the MCC, engaged with the SECV to buy electricity in bulk. Generally, consumers purchased electricity from the municipality, a private operator, or the SECV (via electricity supply branches). The SECV collaborated with rural communities (who co-financed grid extensions) and engaged with international experts (e.g., German engineers for brown coal combustion). It acquired companies, such as the North Melbourne Electric Tramways and Lighting Company in 1922.

Arenas: SECV implemented the two-part (service and usage) domestic tariff since 1927. The bulk pricing arrangements between SECV and MESCo on the one hand, and Municipal and private electric providers on the other, as well as some areas of overlap between SECV and MESCo. SECV and MESCo would charge their consumers directly, and Municipalities would pass these rates to consumers via council rates. Energy was delivered from increasingly centralised power plants, and consumers paid the local utility provider for electricity.

Energy–Money Flows: Fuel insecurity due to NSW coal strikes and shipping disruptions (1919) (SECV, 1949, p. 25) drove investment in local brown coal from the Victorian Government. Electricity flows from centralised power stations to urban and regional areas, with money flowing directly from consumers to the SECV, their local municipality, and from the municipality to the SECV or another private undertaker. Consumers also purchased briquettes for heating and appliances at the SECV's showrooms.

5.3. Consolidation of public regime and war (1927–1947)

Historical narrative — Private undertakers' final days, WWII and postwar periods

By 1934, the SECV had taken decisive steps to consolidate Victoria's electricity sector by acquiring the MESCo and the Electric Supply Company of Victoria Ltd, effectively eliminating private undertakers. While some metropolitan and rural municipal corporations (Bendoc and Bonang (SECV, 1934)) continued to operate as bulk purchasers from the SECV,⁵ while it maintained dominant control over generation and distribution. However, retail operations remained partially decentralised; for example, the SECV managed distribution at the MCC's Spencer Street plant from 1941, while the MCC retained retail responsibilities (SECV, 1949, p.90).

As World War II loomed, the SECV took proactive measures to prepare, increasing stocks of essential items and training personnel for air-raid service (Edwards and Connolly, 1969). However, war efforts led to fuel shortages and the diversion of resources, challenging their operations. Rationing measures affected all states and limited consumption growth, compelling the SECV to implement demand management techniques, such as restricting new hot-water system installations and

rotating the operation of existing appliances. Remarkably, despite these hardships, the SECV achieved a reduction in electricity costs, which fell more than 70% from 1913 to 1944, even as the cost of living soared by 85% (SECV, 1944).

Post-war Victoria faced industrial unrest and continued fuel shortages, culminating in 1947 when the SECV could not meet electricity demand for the first time (SECV, 1947). Labour strikes and resource constraints exacerbated supply issues. Nevertheless, electricity demand surged: from 1919 to the 1940s, consumer numbers grew by 450%, population by 45%. Electricity generation skyrocketed by 1900% per capita and 2800% in total (Edwards and Connolly, 1969). The war also catalysed local manufacturing, with the SECV producing its own machinery. A 1947 Royal Commission recommended separating generation from distribution and retail, but the SECV retained full control. Let us pause in 1947 to capture the STL after the war.

Snapshot of socio-technical system by 1947

Context and STL. *This period is marked by a large increase in population and even larger increases in electricity users and generation. Electricity as a public service for everyone seems to be the slogan. The war and its challenges (e.g. fuel and staff shortages) drive support for local manufacturing.*

SPM Assets: The system's snapshot in Fig. 6 retains a similar configuration to the one in 1927. The system has a consolidated, centralised, and standardised logic and infrastructure that expands in size — with new and larger generation and networks — while preserving its structure **Generation** — Increasing number of power plants. New (green rhombus) hydroelectric plants (Sugarloaf, Rubicon and Kiewa). Existing power plants, such as the Spencer Street power plant (managed by the SECV from 1941), and the expansion of generation capacity post-war, despite fuel shortages and industrial unrest (SECV, 1947). **Network (Transmission and Distribution):** — New terminal stations and substations (green rhombus) transporting electricity to a wider area of Victoria. Growing distribution networks in addition to the existing ones. **Storage** — not explicitly mentioned, but wartime stockpiling of essential materials and in-house manufacturing of machinery suggest limited strategic storage capacity of fuel (Edwards and Connolly, 1969). **Interface** — residential, industrial, commercial, farms, and other infrastructure managed by municipalities and SECV. **Consumption** — motors, machines, household appliances. Wartime restrictions on hot-water systems and rotation on appliance use.

Actors: — *Rule maker:* Largely unchanged. *Rule implementer* Unchanged and very limited mention of the SECV's commissioners (red circle) and a more prominent role of the Statutory Company as a whole. *Rule followers:* All consumers, which grew by 450% from 1919 to the 1940s, with electricity generation increasing by 2800% (Edwards and Connolly, 1969).

Actor–Asset Relations: The SECV continue ownership of infrastructure. It coordinated with municipal corporations for bulk supply and integrated rural and metropolitan networks, while increasing its ownership and system operations. MCC's continued retail operations at Spencer Street.

Actor–Actor Relations: The SECV continued recommending new entrants to the Governor-in-Council, acquiring private undertakers and coordinated with municipal corporations for bulk supply. It managed distribution while municipalities handled retail.

Arenas: — Electricity provision was regulated under SECV oversight, with limited municipal participation. Despite wartime challenges, electricity prices continue to fall, and the customer base continues to grow. Most municipalities buy bulk electricity for SECV on behalf of their constituents.

⁵ Historical annual reports list these corporations as 'municipal undertakers purchasing bulk supply from SECV'. The list includes the City of Melbourne, Boxhill, Brunswick, Coburg, Footscray, Heidelberg, Northcote, Port Melbourne, Preston, and Williamstown (e.g. Appendices from SECV's annual fifteenth annual report SECV, 1934).

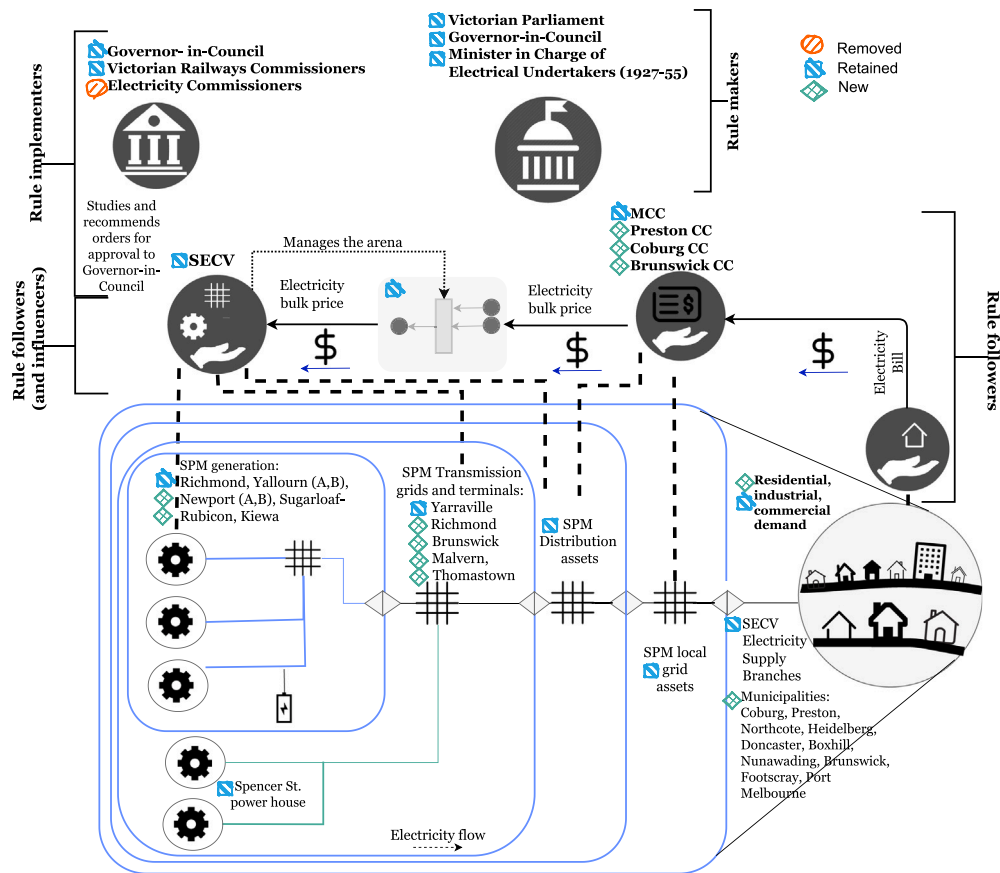


Fig. 6. STL circa 1947. Notable expansion of infrastructure (green rhombus) within the same centralised system logic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Energy–Money Flows: Energy is increasingly being supplied from centralised power stations. SECV supported local manufacturing to maintain supply. Money flows from consumers to either one municipality or directly to the SECV.

5.4. Public electricity for all (1947–1967)

Historical narrative — Continuing the expansionary objectives and reliability challenges

In 1949, the Federal Parliament enacted the *Snowy Mountains Hydroelectric Power Act* to manage river systems across eastern states, including NSW and Victoria, primarily for agriculture and hydroelectricity. This legislation led to the establishment of the Snowy Mountains Hydroelectric Authority and initiated construction in the same year. Simultaneously, the SECV expanded its portfolio by acquiring the Metropolitan Gas Company and Brighton Gas Company in 1951 in addition to expanding existing power plants and constructing new ones, including a 10.53 Megawatt (MW) plant in Shepparton in 1951 and a 4.88 MW plant in Warrnambool in 1953, while increasing hydroelectric capacity in Eildon and West Kiewa. By the early 1960s, SECV's electricity generation reached around 1.5 GW across coal, diesel, and hydroelectric sources.

More than two decades after World War II, the SECV claimed to have achieved fuel independence, even supplying electricity to towns in NSW. It pursued system-wide electrification by building capacity reserves and extending transmission infrastructure to prevent blackouts (Edwards and Connolly, 1969). This period marked a shift towards large-scale, centralised generation, with significant increases in unit capacity — from 12.5 MW (Yallourn's first unit) to over 120 MW by the 1960s–70s. Electricity sales rose dramatically from 800 MWh in 1940 to 8000 MWh by 1965 (SECV, 1965, p. 4).

By the mid-1960s, the state's electrification was nearly complete, with independent plants contributing only 0.4% of total supply (SECV, 1965). A few municipalities in metropolitan Melbourne — 'The last eleven', kept operating as utilities acting on behalf of their local users. In 1965, the SECV introduced standardised tariffs to ensure equitable pricing across regions, followed by a transition to decimal currency in 1966. In 1967, domestic tariffs were revised to reflect actual consumption rather than fixed charges per room. Special rates were also introduced for charities, hospitals, and senior citizens' clubs (SECV, 1964, p.18), reflecting a shift towards socially responsive energy policy and reinforcing the SECV's role as a centralised public utility.

We pause in 1967 to capture the system's response to the significant investments made over the two decades after the last snapshot.

Snapshot of socio-technical system by 1967

Context and STL. *This is an era of achievement and expansion. By the end of this period, most people in Victoria have electricity, and most of them get it from the SECV. Fuel independence is achieved. But in most senses, there is a continuation of existing developments rather than structural change. The focus is now on reliability.*

SPM Assets: — No structural changes and same system's logic—centralised, long-distance grids. New and expanded portfolio post-1949, including assets from the Metropolitan Gas Company and Brighton Gas Company in 1951. **Generation** — New plants (green rhombus) in Shepparton (10.53 MW, 1951) and Warrnambool (4.88 MW, 1953), and increasing hydroelectric capacity in Eildon, West Kiewa, and Snowy (Murray and Tumut). Existing (blue square) power plants remained in place (Yallourn A,B, Morwell, Newport, Richmond, Geelong, Ballarat,

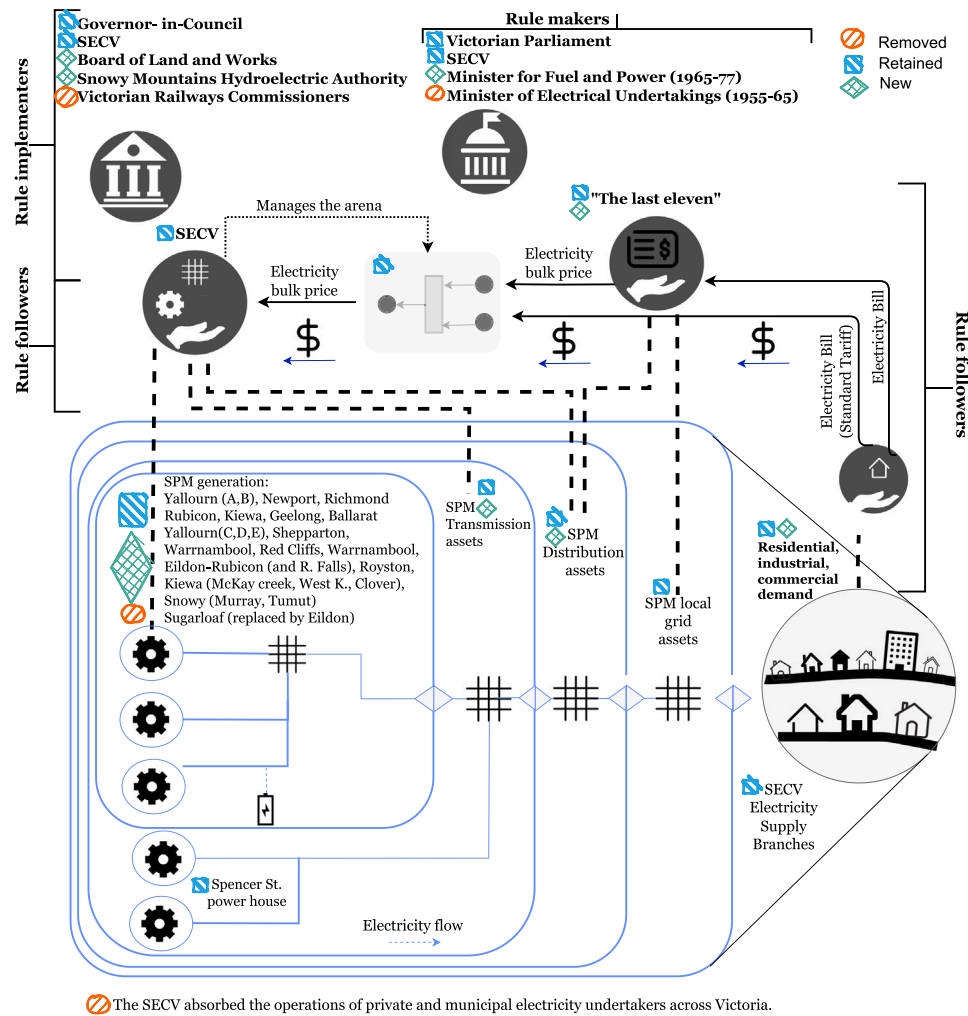


Fig. 7. STL circa 1967. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Spencer Street), and some expanded in Yallourn (C, D, E). Sugarloaf was removed (red circle) and replaced by Eildon. By the early 1960s, total generation capacity reached approximately 1.5 GW across coal, diesel, and hydro sources. **Network** — The SECV extended transmission infrastructure to connect every town in Victoria, aiming to eliminate blackouts and build capacity reserves (Edwards and Connolly, 1969). The system included expanded grids, transformers, and capacitor banks. **Storage** — Hydroelectric schemes and capacity reserves. **Interface** — Electricity was delivered through public systems, with metering infrastructure evolving in tandem with tariff reforms. By the 1960s, most consumers were connected to SECV's public supply. **Consumption** — Residential, industrial, commercial, related appliances, machines and equipment. Consumer connections grew significantly with sales increasing from 800 MWh in 1940 to 8000 MWh by 1965 (SECV, 1965, p. 4).

Actors: — Mostly unchanged but for the ceased operations of the Victorian Railways Commissioners (red circle) and the creation or name change of a few actors (green rhombus). **Rule makers:** The Victorian Parliament and the Minister of Electrical Undertakings; **Rule implementers:** the SECV, the Governor-in-council, the Minister for Fuel and Power, the Snowy Mountains Hydroelectric Authority, and the Board of Land and Works; **Rule followers:** 'The last eleven', Regional communities, industrial, residential, commercial users, and independent generators.

Actor–asset relations: The SECV owns most of the generation, distribution and transmission assets. A few municipalities own and operate assets, but mostly act as utilities in their areas, as the SECV managed most of the system's SPMs. Independent plants contributed only 0.4% of supply by the mid-1960s (SECV, 1965).

Actor–Actor Relations: — No major changes. The SECV coordinated with federal initiatives (e.g., Snowy Mountains Authority), serviced towns in neighbouring NSW, and managed regional stakeholders. It absorbed most independent operations, standardised tariffs, and managed equitable access. Most consumers contracted electricity services with the SECV, unless they lived in the 'The last eleven' municipalities.

Arenas: — No major changes. 'The last eleven' municipalities in charge of retailing electricity to their areas but buying bulk from the SECV, which managed the main arena and coordinated the balancing process and the transactions with other end-users. By 1965, SECV standardised tariffs across regions, transitioned to decimal currency (1966), and revised domestic pricing models (1967), including special rates for charities, hospitals, and senior citizens (SECV, 1964, p.18).

Energy–Money Flows: — No major changes. Electricity flows from centralised power plants to energy consumer's premises, with tariffs and contracts between consumers and the SECV, and municipalities bulk-buying from the SECV.

5.5. Peak public (1967–1985)

Historical narrative — Aging infrastructure, financial and political pressures

By the 1970s, the SECV had achieved near-total electrification, serving over one million consumers (SECV, 1931–1979, p. 1.4).

Brown coal accounted for 90% of electricity generation, with hydro and gas making up the remainder. Infrastructure modernisation was a priority, exemplified by the completion of the Hazelwood power station in 1971, featuring eight 200 MW units. That same year, the SECV began exporting briquette coal to Japan. The completion of the Snowy Hydro Scheme in 1974 added seven power stations and 100 Gigawatt hour (GWh) of surplus electricity, enabling service to over 1.15 million users.

In the early 1980s, the SECV supplied electricity across Victoria's 228,000 square kilometres, with 21,891 employees and nearly 6.5 GW of generating capacity. It served 1.343 million direct users and 276,200 indirect users via remaining municipal retailers. Despite expansion adding a new 240 MW unit at Jeerlang, winter capacity constraints emerged (SECV, 1980), prompting an increase in Snowy Hydro entitlements from 100 to 550 GWh. Strikes led to significant operational disruptions, notably employees halting coal supplies at Morwell to Hazelwood, resulting in restrictions and direct load shedding in 1981.

New units installed at Yallourn W (West) and Newport D to improve reliability, and domestic supply charges were abolished in 1982 to encourage conservation (SECV, 1982). However, ageing infrastructure led to plant closures, including Richmond (1980), Spencer Street (1982), Newport (A, B and C between 1979 and 1981), and Yallourn (A, B and C between 1968 and 1984).

Efforts to interconnect southeastern states, stalled in the 1970s, resumed with the 1980 “Electricity Generation and Sharing of Power Resources” inquiry (SECV, 1980, p.45) to determine the potential sharing of electrical power among states using the surplus of a state to offload more expensive generation in another part of the interconnected network. By the decade's end, only the Snowy Hydro Scheme linked Victoria to NSW, with the Heywood interconnector to South Australia commissioned in 1990.

During the 1980s, the SECV struggled financially but focused on expanding its generation capacity rather than reducing debt. The government authorised the construction of Loy Yang A (four 500 MW units) and B (two 500 MW units) despite high-interest rates (Evans, 2001) and the need to contribute to social programs (Abbott, 2006). Economic pressures and government demands with a “no new debt” policy forced the SECV to downsize and sell assets by the decade's end. The Australian public sector began accusing every public corporation of lacking efficiency and hindering productivity growth. These accusations were more pronounced after the 1970s oil crisis and continued into the 1980s, regardless of the type of political ideology.

We pause in the middle of the 1980s to capture with the STL the system's response to financial and political pressures at different geographical levels.

Snapshot of socio-technical system by 1985

Context and STL. *Statewide electrification essentially completed and the SECV firmly at the helm. Capacity limits are now being reached occasionally, specially in winter and driven by increased demand and ageing infrastructure. Financial difficulties, combined with economic and political pressures, seem to be harbingers of change.*

SPM Assets: — No changes in system centralised logic. **Generation** — Older plants decommissioned (red circle), including Geelong B, Richmond, Spencer Street, Newport (A,b,c) and Yallourn (A,b, C). Lost capacity replaced by newer power plants with larger capacity (green rhombus), including Hazelwood (operating from 1971 with eight 200 MW units), Yallourn W, Jeerlang A, Newport D, Anglesea, Loy Yang A. Other power plants maintained operations (blue square) or completed their projects, such as the

Snowy Mountain Hydro scheme (1974), which featured seven power stations, 16 dams, 80 km of aqueducts, and 145 km of tunnels. **Network** — The SECV expanded its transmission and distribution networks to serve over 1.343 million direct users and 276,200 indirect users. **Storage** — Increased Snowy Hydro entitlements (from 100 to 550 GWh). **Interface** — no changes. **Consumption** — Electricity demand surged, with 10.6% growth in 1988 alone, driven by industrial users like Portland's smelter.

Actors: — Essentially unchanged. *Rule makers:* The Minister for Industry, Technology, and Resources (green rhombus), replaced the Minister for Minerals and Energy (red circle), and became responsible for the SECV from 1985 to 1992. *Rule implementers* Mostly maintained (blue square). *Rule followers:* Similar to previous configurations (blue squares).

Actor-asset relations: The SECV owns and operates virtually the entire SPM in Victoria. Shared operations of the Snowy Hydro scheme with NSW and the Commonwealth Government.

Arenas: — No changes.

Energy-money flows: — No changes.

5.6. Twilight of the public, dawn of the private regime (1985–2002)

Historical narrative — Restructuring years

In the wake of the 1988 Climate Conference, the Victorian government and the SECV committed to a 20% reduction in greenhouse gas emissions by 2005. A 1989 discussion paper outlined strategies such as energy efficiency, cogeneration, and renewable energy to meet this goal (SECV, 1989b,a). The SECV initiated a 3-year Demand Management program in 1990, culminating in the 1992 ‘Focus For The Future’ conference. Key initiatives targeted business lighting, industrial efficiency, commercial air-conditioning, and public education (SECV, 1993).⁶ Social equity was also addressed through the Equal Employment Opportunity Unit, with initiatives to increase the participation, improve salaries, and provide training of women and indigenous employees across all departments.

Efforts for energy conservation were offset by the surge in electricity demand, which rose 10.6% in 1988 — largely due to industrial consumption (Portland smelter), prompting the commissioning of Loy Yang A units that increased output by 8% between 1984 and 1988. In the early 1990s, the SECV adopted its first corporate strategy, introducing KPIs and reducing staff from 21,000 to 14,925 by 1992. Electricity sales peaked at over 30,000 GWh, serving 1.6 million users (SECV, 1989a). The organisation shifted towards a more commercial and performance-driven model, eliminating cross-subsidies (Evans, 2001). Yet, scholars argued that the SECV's full potential remained unrealised.

Nationally, the Commonwealth embraced cooperative federalism to streamline electricity governance (Hughes, 2012). The Industry Commission's 1990 review led to broader economic reforms, including the National Competition Policy and the formation of the National Grid Management Council (NGMC), tasked with promoting open grid access and future planning (McConnell, 2012). The Hilmer Review (1992) and the Council of Australian Governments (COAG) laid the groundwork for regulatory and market reforms.

Victoria's Electricity Act 1993 restructured the SECV into three entities, and the Office of the Regulator-General was established in 1994 (Hughes, 2012). The Victorian Power Exchange launched a wholesale market, enabling competitive electricity trading (Siemon, 1995). Corporatisation involved vertical and horizontal disaggregation (Abbott, 2006). Generation Victoria was split into five companies:

⁶ Savings: business lighting (13 GWh), industrial efficiency (59.7 GWh), and commercial air-conditioning upgrades (13.9 GWh) (SECV, 1993).

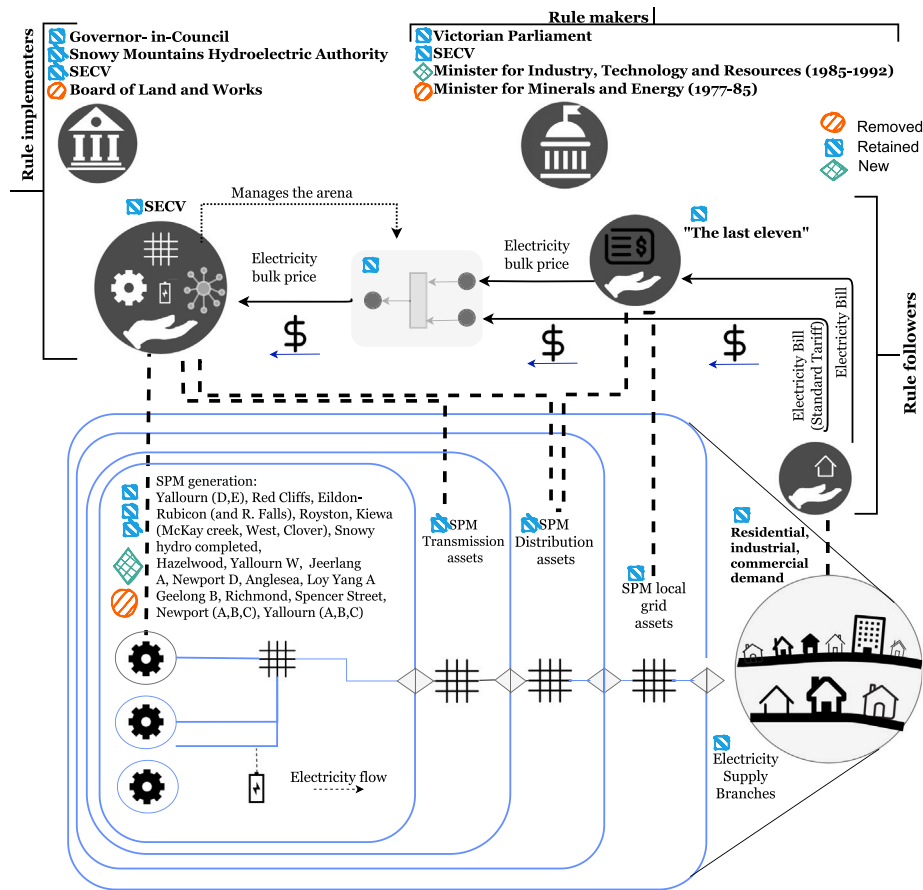


Fig. 8. STL circa 1985. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ecogen Energy Ltd, Hazelwood Power Corporation, Yallourn Energy Ltd, Loy Yang Power Ltd (two new units with a combined capacity of 953 MW in Loy Yang B entered service in 1993 and 1996), and Southern Hydro Ltd. Powernet Victoria owned transmission assets, while five regional distribution and retail companies operated: Eastern Energy, Solaris Power, Citipower, United Energy, and Powercor Australia.

The National Electricity Law (NEL), enacted through the National Electricity Act 1996, established governance frameworks for the National Electricity Market (NEM). It included the National Electricity Code (NEC), which defined market rules and objectives (NEO), and transferred NGMC duties to the National Electricity Market Management Company (NEMMCO) (McConnell, 2012). Victoria officially joined the NEM in 1998, alongside Queensland, NSW, SA, and ACT (Tasmania joined in 2005). The market was structured with competitive generation and retailing, and monopoly transmission and distribution (Abbott, 2006). Even though the systems were physically interconnected, each Australian state and territory took different paths towards developing its electricity system, as they had been accustomed to from the sector's early days.

Despite structural reforms and market liberalisation, tensions persisted between environmental goals and industrial growth. The early 2000s saw legislative efforts to reconcile these tensions. Environmental concerns were addressed through the Renewable Energy (Electricity) Act 2000, which introduced the Renewable Energy Target (RET), including the Large-scale Renewable Energy Target (LRET) and the Small-scale Renewable Energy Target (SRET). These schemes incentivised renewable energy investment via tradable certificates for large generation and small technologies — LGCs and STCs, respectively — marking a shift towards ecological sustainability.

Moreover, the Financial Services Reform Act (2001) established a unified regulatory framework for financial services providers, such

the Australian Securities Exchange (ASX) and the Sydney Futures Exchange. The reform brought electricity futures (and other derivatives) into a single framework aiming at improving disclosure, conduct standards, single authorisation and licensing, consumer protection and market integrity. These financial markets operated alongside the wholesale electricity market, while retail, commercial Over the counter (OTC), and spot markets remained under separate regulations.

Lastly, the Corporations Act 2001 became the foundation of Australian corporate law, regulating registration (Australian Company Number (ACN) or Business Number (ABN)), operations, and responsibilities of businesses, improving transparency in the electricity sector.

Let us pause in the early 2000s to capture how the STL responded to the many regulatory and governance changes.

Snapshot of socio-technical system by 2002

Context and STL. *New political winds are blowing, and corporatisation and privatisation fill the air. Environmental and climate concerns arise. Despite successfully adapting, the SECV now appears to be a dinosaur, with many willing to assist in its extinction.*

SPM Assets: — No change. Only capacity expansion in power plants, like in Loy Yang A and B.

Actors: — *Rule makers:* COAG, Office of the Regulator General, Ministerial Council on Energy (MCE), while previous actors ceding influential roles (red circles); *Rule implementers:* NEMMCO. *Rule followers* all companies from the SECV's disaggregation (e.g. Generation Victoria, National Electricity, and Electricity Services Victoria), and private entities such as Ecogen Energy Ltd, Hazelwood Power Corporation, and Southern Hydro Ltd,

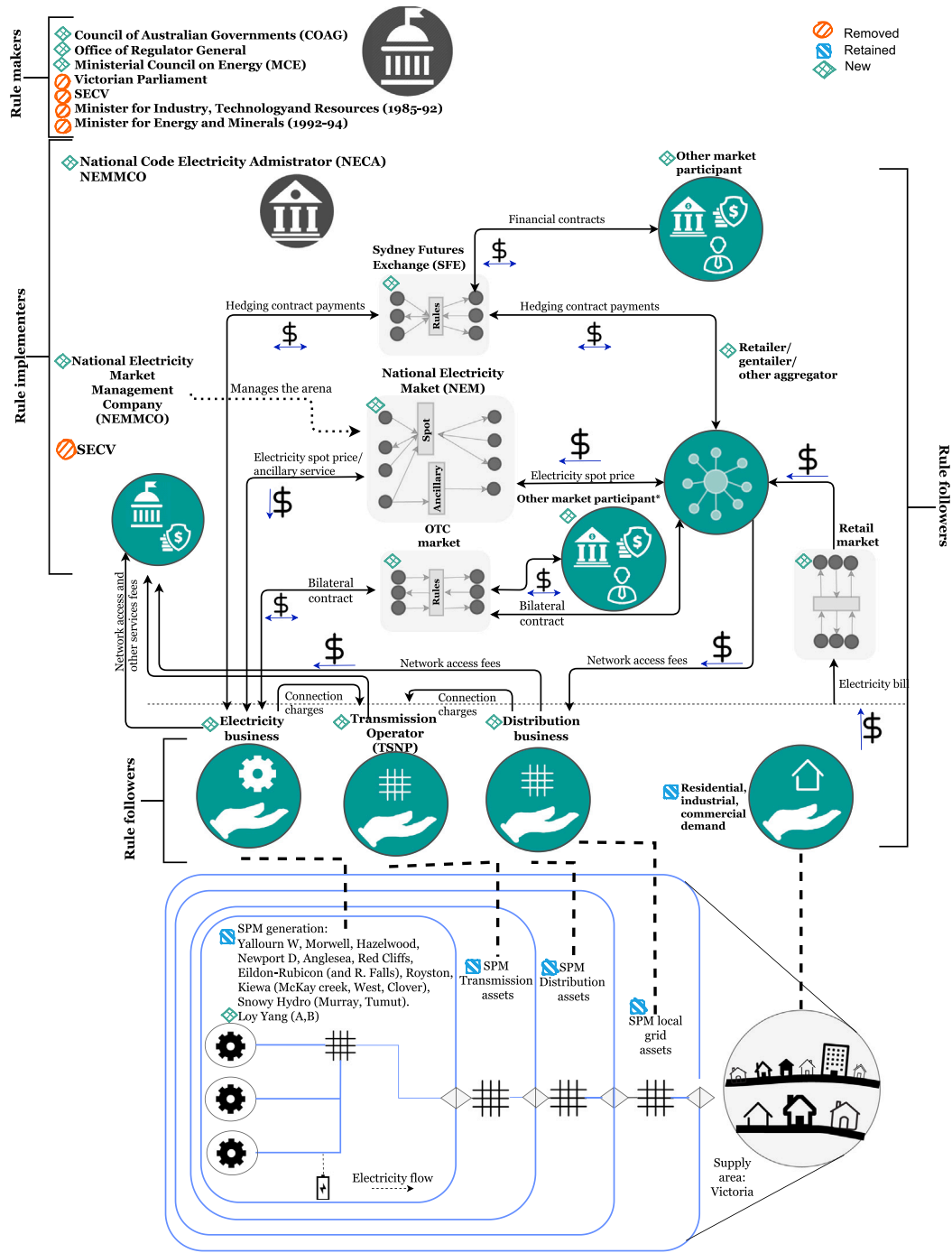


Fig. 9. STL circa 2002. Major changes in its social dimension: additional markets and actors, new roles, institutions and relationships.* These can be non-energy market participants, like brokers, banks, and speculators. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Powernet Victoria, Eastern Energy or Citipower which emerged post-corporatisation. Non-energy participants in financial markets (banks, brokers, and speculators).

Actor–asset relations: Major system ownership restructure implemented in phases of: disaggregation, corporatisation, and privatisation. Generation Victoria was divided into five companies, each owning different power plants. Powernet Victoria owned transmission assets, while five regional distribution and retail companies operated: Eastern Energy, Solaris Power, Citipower, United Energy, and Powercor Australia.

Arenas: — Major changes (main markets labelled with green rhombus). The National Electricity Law (1996) provides the framework for the NEM. The Victorian Power Exchange began operations in 1994 for the wholesale trade of electricity, connecting Victoria's market to those of Queensland, New South Wales, the Australian Capital Territory (Canberra), and South Australia. Other arenas: OTC, used for Power purchase agreement (PPA)s, which involve long-term bilateral agreements between power plant operators and other organisations for buying LGCs or environmental certificates generated by power plants. Exchange Traded Market (ETM) — Arena for trading financial products,

e.g. the Sydney Futures Exchange, regulated under the Financial Services Reform Act (2001). Finally, retail markets with retailers buying electricity on the energy market on behalf of consumers.

Energy–Money Flows: Energy flows maintained the direction of the centralised system logic. However, money flows were restructured through corporatisation and evolved from vertically integrated SECV operations to competitive generation and retailing. Money also flowed into financial markets and through instruments such as LGCs and STCs under the RET, creating new monetary incentives for renewable energy. Electricity futures trading introduced a financial layer to energy markets.

5.7. Proliferation of the private (2002–2019)

Historical narrative — Changes in generation mix and consumer's role

Following the launch of the NEM in 1998, the Energy National Cabinet Reform Committee (ENCRC) established a new governance framework comprising three market bodies: the Australian Energy Market Commission (AEMC), the Australian Energy Regulator (AER), and the Australia Energy Market Operator (AEMO). In 2009, AEMO assumed operational responsibilities from NEMMCO, becoming central to both gas and electricity market coordination. The Australian government began supporting renewable energy with the Renewable Energy Target (RET) in 2001, which aimed at sourcing 2% of electricity from renewables by 2010. This target was expanded in 2010 to source 20% of electricity from renewables by 2020. This year also marked an acceleration of household solar rooftop Photovoltaic (PV) installations. However, since 2013, the absence of a coherent national energy policy created both obstacles and opportunities for subnational actors, particularly state and local governments.

By 2019, Victoria's installed capacity reached 11.5 GW, with 40% sourced from three brown coal power plants. The generation mix included 21% gas, 20% hydro, 15% wind, 3% solar, and 1% biomass and battery storage. The annual generation totalled 50,531 GWh, comprising 72.5% from fossil fuels and 27.5% from renewables. The Victorian government's 2016 solar subsidy, combined with falling technology costs and rising electricity prices, led to over 380,000 rooftop installations (1.5 GW) by 2019.

Ownership of generation assets was concentrated among EnergyAustralia, Alinta, Origin, Snowy Hydro, and AGL, all of which were vertically integrated with retail operations. AusNet Services, partially owned by Singapore Power and the State Grid Corporation of China, became the Transmission System Network Participant (TSNP), in charge of managing the transmission network as 'natural monopoly'.

AEMO coordinated both physical and economic dispatch, working with AusNet and five regional distribution businesses — CitiPower, Jemena, Powercor, United Energy, and AusNet, each serving distinct geographic areas. Generators and distributors paid connection and network service charges to AEMO, which were then passed through to retailers, who in turn passed them on to consumers.

The energy sector operates within intertwined physical and economic arenas. AEMO manages the spot market's economic dispatch using a merit-order process, selecting cost-effective generators to meet demand. This system requires forecasting, bidding, price settlement, and dispatch scheduling.

To manage financial risk, actors employ vertical integration as a natural hedge; retailers owning generation assets offset high spot prices with the revenue from their own generation. Additionally, future contract prices in the exchange-traded market (ETM, managed by ASX) and over-the-counter (OTC) markets are influenced by spot prices, adding complexity to market dynamics.

Snapshot of socio-technical system by 2019

Context and STL. *Signs of change in the generation mix and the increasingly active role of the consumer. New arenas and regulatory changes (e.g., Corporations Act 2001) enable the participation of new actors across the supply chain.*

SPM Assets: — Large-scale infrastructure inherited from the SECV and small changes in generation mix, with: **Generation** — utility-scale renewable energy, rooftop solar PV (behind-the-meter); **Networks** — salient changes coming from the bottom up (local SPM) with solar PV exporting energy surplus to local networks. **Storage** — battery storage. **Interface** smart metering. **Consumption** Residential, commercial and industrial assets as previous STLs.

Actors: — *Rule makers:* COAG, AEMC, ESB. *Rule implementers:* AEMO, AER, ASX; *Rule followers:* AusNet, Jemena, Citipower, United Energy, Powercor, EnergyAustralia, Alinta, Origin, Snowy Hydro, and AGL. OTC market participants. Energy speculators (banks, insurance companies) in the ASX.

Actor–asset relations Ownership of generation and retail businesses (vertical integration) by EnergyAustralia, Alinta, Origin, Snowy Hydro, and AGL; regulated monopolies with private international actors owning and operating transmission (AusNet) and distribution infrastructure (5 distribution businesses).

Actor–Actor Relations: AEMO coordinates with AusNet for physical dispatch and with generators for economic dispatch. Retailers and generators often engage in vertical integration, creating natural hedges against spot price volatility. Regulatory bodies (AEMC, AER) set rules and monitor compliance. Financial actors can interact with generators and retailers through electricity futures and OTC contracts. Consumers engage with retailers.

Arenas: — Wholesale with spot market dispatch following merit-order rules, retail markets, commercial OTC (PPA) and financial OTC contracts, ETM trading futures. Planning and augmentation of the transmission system is managed by AEMO. Retail market: consumers are expected 'shop around' to find the best tariffs in the retail market.

Energy–Money Flows: Energy flows from generators through transmission and distribution networks to consumers. Money flows from consumers to retailers, who buy electricity on their behalf in the wholesale market and pay distributors for network services. Distributors pay AusNet, and AusNet pays AEMO connection charges. Generators receive payments based on spot market prices, influenced by merit-order dispatch. Generators also pay Transmission and AEMO connection charges. Financial hedging occurs via vertical integration and trading in ETM and OTC markets, with prices linked to spot market dynamics.

6. Discussion

Examining the Victorian electricity system in Section 5 using the STL effectively illustrated the system's phased socio-technical nature, aligning with other transition studies, and helped identify path dependency and lock-in, as well as misalignments or tensions among actors when infrastructure configurations are challenged.

The subsequent snapshots of the public regime revealed infrastructure saturation and stability (Figs. 6, 7, and 8). This legacy infrastructure, such as coal power plants, establishes path dependency and lock-in that constrain and influence future options, as this infrastructure persisted through most of the private regime, with notable shifts

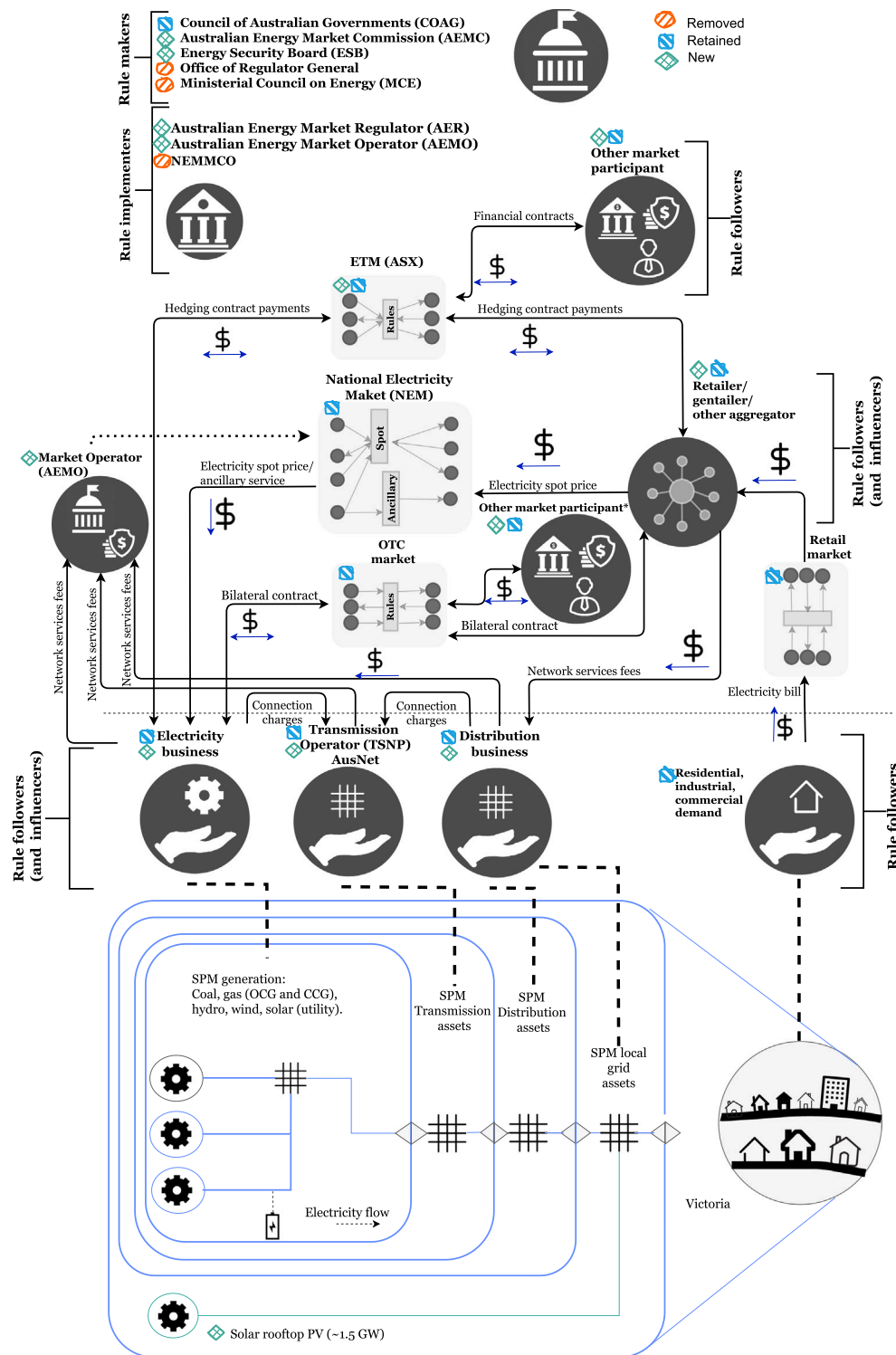


Fig. 10. STL in Victoria around 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

occurring in the STL's social composition, where most innovations took place in markets and governance frameworks.

The monopolistic structure (Figs. 6, 7, and 8), bulk pricing between the SECV and utilities, direct billing to consumers, and state-based governance of the public regime expose the tensions and misalignments inherent in this socio-technical setup, which conflicted with the goal of market liberalisation and national coordination with the eastern grid.

Thus, the initial snapshot of the private regime (Fig. 9) highlights the implications for the STL regarding these objectives, involving various market participants and arenas (spot, retail, SFE), as well as the National Electricity Market Management Company (NEMMCO). Similarly, the introduction of NECA and COAG provided support that precipitated the regime change, clearly illustrating the shift from state-based to national governance of the sector.

Therefore, the STL can indicate where there is ‘room for change’ and can be used to test where misalignments or tensions among actors might arise if infrastructure configurations are challenged.

The analysis also revealed the following two findings: (i) they depicted the uneven changes in the system’s socio-technical complexity relative to the lens and viewpoint of analysis; and (ii) it suggested that actors and institutions within the electricity system evolved, responding to the *perceived* societal values and needs as framed by transformative actors, supporting the assumptions of transition scholars regarding societal needs as key drivers (de Haan et al., 2014).

The following paragraphs discuss the findings, implications for roadmaps and agendas that aim to steer sustainability transitions, as well as methodological challenges, limitations and opportunities.

6.1. Changes in socio-technical complexity with scale

Complexity and scale are often difficult to disentangle. Despite various interventions proposed by different fields to manage complexity (such as markets or innovation), the general expectation is that complexity increases with scale. However, in the Victorian case, we observed exceptions to this rule using the STL.

During the public regime (STLs from 1927 to 1985 in Figs. 5, 6, 7, and 8), the electricity system’s scale expanded significantly — from larger power plants to widespread transmission and distribution networks, and with more people connected to the system. Interestingly, from the technical lens, complexity seemed to decrease in terms of deployment as technologies matured and were institutionalised through processes such as licensing and standardisation. From the social — i.e., organisational — lens, complexity also decreased, exemplified by the emergence of a single bureaucratic organisation (i.e., SECV), replacing numerous entrepreneurs. This organisational simplification also simplified tariff structures based on customer type (residential, commercial) and location (urban, regional), leading to an unravelling of the STL’s societal dimension.

In contrast, the private regime of the Victorian electricity system, as shown in Figs. 9 and 10, experienced a significant increase in social complexity, despite the technical SPM remaining largely unchanged. New roles, markets (wholesale, OTC, financial), and institutions emerged, expanding actor networks. The relationship between asset owners and physical infrastructure shifted from one organisation to multiple actors owning different parts of the supply chain. Additionally, new organisations like NEMMCO (then AEMO) facilitated the interconnection of the eastern grid.

In addition to an analysis from different lenses, the STL framework helped us understand how system complexity is relative to the viewpoint. For example, from the SECV viewpoint, managing such infrastructure during the public regime was highly complex. Following regulatory changes aimed at increasing retail competition, consumers faced even greater complexity — diverse tariffs, information disparities, reduced transparency, and increased difficulty in finding the best deals.

Overall, the use of STLs in Victoria’s evolution offered insights into how scale and complexity interact and how these can change over time, leading to uneven development of system scale and complexity. This enables analysts to simplify perceived complexity by applying graphical reasoning over time, using the lens (technological, organisational) and perspectives (customer, manager, politician, engineer) of interest.

6.2. Perceived societal needs drive transitions

When reviewing the structural changes in the STLs together with the accompanying narrative, a pattern emerges. The case history is dominated by the succession of two major regimes: the public regime emerging out of the diverse offerings of early entrepreneurs and the private regime that supplants it. In STL terms, these regime changes can be traced by the subsequent rise of institutions like the SECV for

the public and the NEM for the private regime. The natural question is, where did these regimes come from?

The actor framework by de Haan and Rotmans (2018) suggests a mechanism. They propose that transformative actors — by which they mean actual individuals, e.g. policymakers — interpret the needs of society (de Haan and Rotmans, 2018; de Haan et al., 2014) as they understand them and connect these with current societal values and technology. They then pursue implementing the socio-technical solutions they see through institutional entrepreneurial work. This mechanism is also supported by works like Aghdam (2006), which demonstrated how human–organisational–institutional factors influence the evolution of the system, subsequently affecting human behaviour (Aghdam, 2006).

In our case, the values precipitating the public regime were (1) independence (of interstate electricity) and (2) accessibility (electricity for all). For the private regime, the leading values were (1) affordable prices through market competition and (2) industry productivity and efficiency. The stories of the transformative actors, such as the Electricity Commissioners chaired by Sir John Monash in the public regime and actors from the then Commonwealth Government (in coordination with State actors) in the private regime, can be read in the narrative.

Two instances in a single case are inconclusive evidence of de Haan and Rotmans (2018)’ theory; this is not what we suggest. We aim to highlight that using STLs greatly assists in identifying qualitative patterns in a case study and the accompanying case data, and from there, towards testable hypotheses. At this point, we venture a conjecture: when an S-shaped curve describes an episode of transformative change, a pattern like the above underlies it, that is, transformative actors institutionalising socio-technical solutions based on prevailing societal values and needs.

6.3. Implications for sustainable electricity transition agendas

Assuming that transformative actors and institutions respond to perceived societal values and needs, the future trajectory of socio-technical systems will depend on who these actors are and what visions they advocate, which may be reflected in agendas and policy roadmaps. Whether the focus is on low-carbon transitions, net-zero economies, or energy trilemmas, these visions — shaped at national, state, or local levels — are interpreted by actors and translated into strategies, policies, and plans that ultimately influence the STL.

In this context, the STL can support the visioning process by mapping infrastructure and actor networks, fostering a shared understanding of the system’s current state, identifying areas where the system has room for change, and revealing socio-technical dependencies, misalignments, and tensions, as well as governance challenges.

For example, the current STL of Victoria highlights the increasing complexity from the integration of CERs, such as solar PV and batteries, at the local SPM level. This shift requires formalising actor–asset and actor–actor relationships, as well as clarifying roles and responsibilities across the system. Households, despite their collective generation capacity, remain excluded from direct participation in the wholesale market. Integrating CERs may require the involvement of new actors, the revision of existing roles, and adjustments to institutional arrangements and business models.

STLs enable stakeholders to evaluate these changes from various viewpoints. For instance, the wholesale market operator may face increased complexity due to limited control over distributed resources. Alternatively, complexity could be reduced if intermediaries manage these systems and coordinate with the operator. These developments raise critical questions about governance: should responsibility remain with current market operators or DNSPs, or should new markets or peer-to-peer platforms be established? By visualising these dynamics, the STL helps actors evaluate technical and economic implications for system reliability and supply security, and explore how different solutions might affect them and cascade through the broader system.

While this case study focuses on Victoria, Australia, its relevance extends beyond the state's borders. Victoria's electricity system exemplifies the centralised logic of energy sectors and the challenges of transitions — such as dependence on fossil fuels, integrating distributed resources, and coordinating diverse actors. These dynamics are not unique to Victoria and are relevant worldwide, making the STL useful for analysis, policy, and strategy in various contexts. It shows how detailed diagnostics can guide broader systemic change.

6.4. Limitations and opportunities

Without a supportive narrative or additional qualitative and quantitative methods, this diagrammatic approach has limitations. As a static one-off representation, STL will lack specific details about the causal pathways, system development, system dynamics (including feedback loops and non-linear effects), and performance (operational, greenhouse gas emissions, and electricity prices).

To address part of the challenge from a static representation, we paused at various points in time to capture snapshots guided by the historical narrative and main events. This process highlighted some of the system development and dynamics; however, only in relation to its overall changes, particularly regarding regimes and innovation trajectories, and we hypothesised externally about plausible sequences of change. This work was validated among authors and experts during informal sessions. But other qualitative methods, such as process tracing, event sequence analysis, and causal process observation, can be used to deepen the understanding of causality. Furthermore, comparative case analysis with STLs across different regions could help identify patterns and differences, thereby strengthening generalisations and contributions to theory.

Suppose there is a need to capture the system's dynamics comprehensively, including feedback loops, non-linear effects, and uncertainty. In that case, a more suitable approach is to utilise the STL as the map and the computer simulation models as the engine. Building on other transition modelling work (e.g. Jensen et al. (2015) and Chappin et al. (2011)), each element of the STL can be formalised using an object-oriented programming language (classes and objects), following other complex system modelling approaches, such as agent-based models. An example is the computer simulation model available in Rojas-Arevalo (2022),⁷ which focuses on the market dynamics of the private regime, closely replicating historical greenhouse gas emissions and spot prices. Depending on the objective of analysis and other considerations for transitions modelling outlined in Holtz et al. (2015), Köhler et al. (2018) and Moallemi and de Haan (2020), STLs can also be formalised into system dynamics or network models.

Another advantage of using computer modelling is the more accurate representation of the system's performance, depending on the analysis of interest, which translates STLs into performance impacts, such as energy prices and emissions, at finer timesteps.

Lastly, there is room to analyse embeddedness and (neo) institutional concepts with STLs, such as isomorphism, power asymmetries, and logics. However, STLs need expansion to include aspects like organisational culture and symbolic dimensions. This analysis could further map embeddedness as relational overlays on techno-economic systems, thereby enriching the understanding of relations beyond mere connections. Yet, a thorough neo-institutional analysis requires future research outside this article's scope.

7. Conclusions

This article presents an analytical and methodological approach using the STL framework to trace the historical development of Victoria's electricity system from a socio-technical perspective. It offers the first comprehensive socio-technical history of electricity provision in Victoria, highlighting its phased evolution across three regimes: emerging, public, and private. The STL supported the construction of the historical narrative, guiding data collection and analysis.

Victoria's electricity system exemplifies the centralised logic of the development of the electricity sector and the challenges of transitions that are not unique to the case — such as dependence on fossil fuels, integrating distributed resources, and coordinating diverse actors. Thus, its insights can be applicable globally.

The STL's analytical strength lies in its ability to make structural, institutional, governance, and actor-based configurations both visible and formalisable. Depending on the objective, the generic STL can be adapted to different lenses and viewpoints, allowing researchers and stakeholders to tailor the analysis and position themselves within the system. Because the STL reflects how systems respond to their socio-technical context, socio-economic and political conditions, and landscape pressures are central to its construction and interpretation.

While the STL is a static representation that lacks specific details about the system's internal dynamics, this limitation was addressed by comparing STL snapshots over time. Additionally, individual STLs alone cannot capture the impact of performance metrics such as greenhouse gas emissions and electricity prices, but this can be overcome with computer modelling and simulation (e.g. object-oriented programming to represent each STL element) with complex systems approaches like system dynamics or agent-based modelling. Moreover, a computer simulation model can enhance the understanding of the system's internal dynamics, impacts and future transition pathways.

The STL has functional limitations depending on the analysis scope. For instance, increasing the number of elements can reduce its explanatory power, and its implementation in computational models may require extensive data. Nonetheless, when combined with qualitative methods such as expert elicitation or participatory approaches, the STL remains a powerful diagnostic and explanatory tool.

Overall, the application of the STL mapped with historical data led to several important insights. It revealed how system complexity evolved unevenly over time, depending on the analytical *lens* and *viewpoint*, and demonstrated how transformative actors institutionalise socio-technical solutions in response to societal values and needs.

The STL can also be a valuable overarching framework for guiding roadmaps and national agendas, helping to uncover path dependencies and identify levers for change. For instance, the integration of CER at the local SPM level suggests a potential societal reconfiguration of the system, requiring new actors, roles, institutions, and governance arrangements. The STL offers a bridge between formal computational approaches and narrative historical methods, providing a structured way to organise and interpret complex case data.

Moreover, future STL analysis can test transformative actors and societal needs mechanisms, compare systems across different jurisdictions and sectors, and broaden its scope to include aspects such as organisational culture and symbolic dimensions, thereby further mapping embeddedness as relational overlays on techno-economic systems.

CRedit authorship contribution statement

Angela M. Rojas Arevalo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fjalar J. de Haan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Conceptualization. **Seona Candy:** Resources, Supervision, Funding acquisition. **Greg Foliente:** Supervision, Resources, Conceptualization. **Lu Aye:** Resources, Supervision, Project administration, Funding acquisition.

⁷ The repository of this model can be found in <https://github.com/gr4sp>. The Input data and simulation results are in Rojas (2021) and Rojas Arevalo (2022) respectively.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this article, the author(s) used Grammarly to improve the readability and language of the work. After using this tool/service, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Data availability

Data will be made available on request.

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