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Author/s:

Rybak, A;Rybak, A;Joostberens, J;Kolev, SD

Title:

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Date:

2025-08-01

Citation:

Rybak, A., Rybak, A., Joostberens, J. & Kolev, S. D. (2025). Assessment of the Impact of Renewable Energy Sources and Clean Coal Technologies on the Stability of Energy Systems in Poland and Sweden. *Energies*, 18 (16), pp.4377-4377. <https://doi.org/10.3390/en18164377>.

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Article

Assessment of the Impact of Renewable Energy Sources and Clean Coal Technologies on the Stability of Energy Systems in Poland and Sweden

Aurelia Rybak ^{1,*}, Aleksandra Rybak ², Jarosław Joostberens ¹ and Spas D. Kolev ^{3,4,5}

¹ Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, 44-100 Gliwice, Poland; jaroslaw.joostberens@polsl.pl

² Department of Physical Chemistry and Technology of Polymers, Faculty of Chemistry, Silesian University of Technology, 44-100 Gliwice, Poland; aleksandra.rybak@polsl.pl

³ School of Chemistry, The University of Melbourne, Melbourne, VIC 3010, Australia; s.kolev@unimelb.edu.au

⁴ Department of Chemical Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia

⁵ Faculty of Chemistry and Pharmacy, Sofia University "St. Kl. Ohridski", 1 James Bourchier Blvd., 1164 Sofia, Bulgaria

* Correspondence: aurelia.rybak@polsl.pl

Abstract

Implementing the provisions related to energy transition, decarbonization, and, thus, the implementation of the Green Deal in the European Union requires increasing the share of renewable energy sources in the energy generation mix. On the one hand, this approach enables the acquisition of clean energy, but, on the other hand, it can affect the stability of energy supply to consumers in terms of the time and quantity required. Therefore, in the presented research, the authors proposed and verified the following thesis: Innovative coal technologies can play a temporary but crucial role in building the stability of the energy system by developing an operational stability index for the energy system in Poland. To this end, they determined the energy system stability index (ESSI) level, verified its variability over time, and simulated changes in the index when clean coal technology was used. The proposed method is highly universal and can be applied to any country, and the program written specifically for this research fully automates the ESSI calculation process. It is an excellent tool for facilitating decision making and enables the creation of simulations and scenarios of the impact of potential energy development strategies on its operational stability. The set of indicators developed by the authors characterizes the operational stability of the energy system according to the four-dimensional energy security paradigm. This allows for the consideration of the entire spectrum of operational and structural indicators when analysing the stability of the energy system. The developed ESSI allows for the assessment of the system's stability in a technical sense, but also its adaptability, power and energy balancing, and, ultimately, its independence.

Keywords: energy system stability index (ESSI); Hellwig method; SVR model; clean coal technologies (CCTs); renewable energy sources (RESs)



Academic Editor: Abdul-Ghani Olabi

Received: 22 July 2025

Revised: 8 August 2025

Accepted: 15 August 2025

Published: 17 August 2025

Citation: Rybak, A.; Rybak, A.; Joostberens, J.; Kolev, S.D. Assessment of the Impact of Renewable Energy Sources and Clean Coal Technologies on the Stability of Energy Systems in Poland and Sweden. *Energies* **2025**, *18*, 4377. <https://doi.org/10.3390/en18164377>

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1. Introduction

The energy transition is forcing major changes in the energy systems of European Union member states. Since fossil fuels are expected to completely disappear from energy mixes by 2050, they will have to be replaced by alternative energy sources [1,2]. Currently, renewable energy sources (RESs), particularly solar and wind energy, are perceived as

such a substitute [3,4]. They have many advantages that will cause their share in the energy generation structure of European Union (EU) countries to increase in the coming years [5]. Above all, generating energy using RESs does not generate greenhouse gas emissions, which is assumed to be crucial in the fight against climate change [6]. However, the amount of energy generated by using RESs depends on the time of day, year, and weather conditions. This means variability in generation, the risk of power shortages or surpluses, and the need for power reserves and regulatory sources [7]. Stable operation of energy systems in the coming years, as demonstrated by the examples of Spain and Portugal in April 2025, will require the use of buffers to stabilize them. One such solution is energy storage. It will be able to accumulate excess energy generated during periods of high production and then return it to the system when demand increases. Storage facilities would reduce production variability and emergency reserves. However, the share of storage facilities in the national energy systems in the EU is negligible. Germany leads in this regard, holding almost 50% of grid-scale battery energy storage systems (BESSs) in Europe (excluding the UK) in 2024 [8]. In Poland, the battery infrastructure is still being built. The strong geographic dispersion of renewable energy sources increases the load on the transmission grid and creates challenges in ensuring the system's operational stability. Reducing the number of synchronous energy sources, such as coal-fired power plants, and simultaneously increasing the importance of nonsynchronous sources, such as photovoltaics and wind farms, could lead to an imbalance in the stability of the energy system by disrupting the inertia and frequency of generated electricity [9].

According to the classic definition of stable power system operation, stability is understood as the system's ability to maintain voltage–frequency balance despite disruptions [10]. However, with the growing importance of renewable energy sources, the importance of new indicators that describe the operational stability of the power system is increasing, such as the energy balance, the variability of renewable energy generation, the ability of renewable energy sources to meet peak demand, and the available power margin. Therefore, it is necessary to develop an indicator that would be more useful in the context of stable power system operation, where renewable energy sources are gaining increasing importance. Another way to provide a buffer to stabilize the system is to use regulated energy sources, such as fossil fuels, the combustion of which is currently unacceptable in the EU. Therefore, in this sense, solutions enabling the use of coal while ensuring the elimination of harmful emissions are important. Clean coal technologies (CCTs) are one such remedy. To increase operational flexibility, a hybrid transition system model equipped with a smart grid can be implemented. Modern coal-fired units could act as a peak or emergency power reserve in such a case. Thus, CCTs and a smart grid would provide system resilience (like rotating masses or synchronization), operational resilience, and logical resilience. Since the literature on energy system stability has so far focused on the technical aspects of energy system stability (very often on single indicators and probabilistic models), there is a noticeable lack of practical decision-making tools that decisionmakers could use to quickly assess system stability, compare scenarios, refer to an adopted benchmark, or monitor a selected system. The potential impact of clean coal technologies in this context in Poland has also not been studied.

This article presents a solution for determining an energy system stability indicator that integrates multiple operational dimensions, allowing for the provision of a comprehensive perspective on energy system stability. The analysis was carried out for Poland, as a typical representative of countries with a significant share of fossil fuels in their energy generation mix. Poland was assessed against the backdrop of Sweden, a benchmark in energy transition and the use of renewable energy. The indicator was constructed for the two years of 2018 and 2024. This allowed us to verify the dynamically growing contribution

of RESs to system stability in Poland during this period on the one hand, and to consider the potential role of clean coal technologies in ensuring energy system stability on the other. The authors integrated multiple operational dimensions of the system and presented them as a single clear indicator using a taxonomic approach [11]. The set of variables comprising the indicator was selected to indirectly represent the system's technical stability while also allowing for the inclusion of the impact of RESs and CCTs. It considers, among other factors, how the system balances power, its reserve capacity, and how renewable energy sources meet peak demand. Renewable energy is not seen as a disruption here [12,13], but rather as an operational factor. The multidimensionality of the measure was ensured by a set of variables used to determine the indicator, selecting them according to the 4A paradigm [14] characteristic of determining energy security indicators.

The proposed methodology implemented a hybrid approach, which used artificial intelligence-based forecasts, indicators describing the state of the energy system in Poland and Sweden, and multidimensional comparative analysis to determine the ESSI index. The methodology used included the following elements:

- (I) Estimation of the share of RESs in the energy mix. The SVR machine learning method was used, with automatic parameter optimization, model error analysis, and residual analysis.
- (II) Estimation of a set of indicators characterizing the stability of the energy system. Each indicator was determined separately, identifying its impact on the state of the energy system. It was determined whether this impact was positive or negative, which was crucial in the next step.
- (III) Construction of a coherent indicator encompassing all the indicators estimated in Step (II) using the Hellwig method. At this stage, work began with normalizing and standardizing the data. Next, the method required determining the weights of the individual indicators calculated in Step (II). Information entropy was used for this purpose. The Hellwig method allowed for the determination of a benchmark, i.e., the best values of the analyzed features, in order to determine the distance of objects (countries) from this benchmark. These values allowed for the determination of the final ESSI index value—the closer to the benchmark, the higher the index value is.

In summary, the objective of the investigation was to verify the following proposed thesis: Innovative coal technologies can play a temporary but crucial role in building the stability of the energy system based on RES. The thesis was verified by developing an indicator of the operational stability of the energy system in Poland, based not on simulations or local indicators but on actual system data nationwide. For this purpose, a simulation of the impact of RESs and CCTs on this indicator was carried out.

2. Literature Review

Typically, in the literature, indicators used to describe power system stability are divided into three categories, namely frequency stability, transient stability [15], and voltage stability [16]. These indicate whether the system will operate synchronously after a sudden disturbance, so they measure the system's physical resistance to disturbances. Particular attention has been paid to technical stability, which can be understood as the ability of a power system to maintain a state of dynamic equilibrium and synchronization after a disturbance. Many examples of voltage stability indicators can be found in the literature, and they are further divided into two categories, i.e., line voltage stability indices and bus voltage stability indices [17–19]. The most commonly used technical stability indicators include the voltage stability load index (VLSI), critical clearing time [20], rotor angle deviation [21], rate of change in frequency [22], frequency nadir [23], L-index [24], and voltage collapse margin [25]. There are also interesting examples of the construction of

resilient systems to restore the operation of an integrated energy and transport network after potential failures [26]. Stability in the sense of sustainable development of power systems has also been studied using resource, environmental, social, and economic factors. On their basis, measures were determined, which were then used to estimate a synthetic measure of energy system stability using the multicriteria aggregation method [27].

Operational stability is analyzed less frequently. This can be understood as ensuring reliable operation, access to infrastructure and energy when needed, the ability to balance supply and demand, and ensuring resilience to disruptions. In this case, the focus is on real-time system continuity. Instead of measuring physical resilience to disruptions, it assesses how well the system handles power balance, renewable energy share, responses to renewable energy variability, and congestion management. Operational data, which are not typical measures of technical stability but are related to it, are provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) [28]. These include, among others, actual operational data, such as electricity generation, power balance, energy trading, and energy transmission. These indicators have also been analyzed in the literature, such as the cost of congestion management [29], outages [27,30], balancing [31], total load [32], energy production variability coefficient [33], and generation margin [34].

The authors decided to develop an indicator that would encompass stability assessment while considering generation variability and the availability of balancing reserves and addressing the need to stabilize the operation of uncontrollable energy sources. In this case, the authors mainly considered such indicators as annual generation, volume imbalance, cross-border physical flows, actual load, unavailability in the transmission grid, and cost of congestion management [35]. In the presented research, the set of indicators was selected to reflect the current state of the system, i.e., the growing role of RESs. Although the classic approach to technical system analysis is common, as described in the literature, the authors concluded that system stability should be considered in a broader context, as is the case with energy security. Therefore, the factors were classified into four dimensions, namely accessibility, availability, acceptability, and affordability (4A) [36]. The evolution of the definition of energy security was required by changes in the political and economic environments of countries around the world [37]. Over time, energy security analysis has focused not only on supply but also on energy costs, climate change, and environmental protection [38–40]. Therefore, in the research presented, the authors, following the example of the energy security indicator, considered system stability indicators that can be assigned to categories analogous to 4A, focusing on the role of RESs and CCTs in the energy system. A set of indicators was selected so that each category was represented by at least one indicator.

- I. Availability—related to power resources and generation resources:
 - Generation margin
 - Load factor
 - Outages ratio
 - Activated balancing energy
 - Accepted balancing energy
 - Coverage of peak demand by RESs and coal
- II. Accessibility—real access to power for consumers:
 - Cross-border physical flow
 - Power import
 - Power export
 - Net position
 - Import dependency
 - Single-supplier dependency ratio

- III. Affordability—are consumers willing to accept energy prices?
Congestion cost ratio
- IV. Acceptability—is the method of power distribution and production socially acceptable?
Power volatility ratio
Import volatility ratio

Some indicators could be classified into multiple categories but were divided uniquely. This set allows for a comprehensive diagnosis of energy system stability, not only indicating whether the system's capacity is available but also enabling a more transparent analysis of the system's resilience and assessing the impact of potential crises, which is important in the context of energy transformation.

Despite the clarity of the selected set of indicators and the ease of interpreting each individually, analyzing them all simultaneously is a difficult task for decisionmakers. Therefore, it was necessary to develop a synthetic measure to assess the stability of the power system. Examples of such indicators can be found in the literature. A method was proposed to build a composite indicator with four subindices, including the integral of acceleration, speed deviation, and generator rotor angle using the PCA method [41]. A transient stability indicator was also developed, combining indicators, such as the rotor angle and the dot products of the system variables. LSM regression and summing indices by equal weights were used [42]. Measures that can be used in real time were also developed, based on contingency screening to reduce the computational burden of building dynamic security regions [43].

The authors proposed a solution based on the Hellwig method. It offers numerous advantages, such as easy interpretation of results and the ability to establish benchmarks and create rankings for countries. The method also allows the analysis to incorporate both stimulating and destimulating features. It is suitable for use with both large data sets and small numbers of observations [44]. The methods and tools used in the study are described in the next section.

3. Methods

The tools described below were used according to the proposed methodology described in the Introduction.

3.1. SVR Model

Initially, the basic assumption of the growing contribution of RESs to Poland's energy system was confirmed by building the support vector regression (SVR) model [45,46]. This model allowed forecasting of the amount of energy production from RESs until 2030. It is a regression variant of the SVM support vector machine model [47]. It allows modeling of nonlinear time series dependencies and is resistant to overfitting [48]. The regression equation is described by the following formula [49,50]:

$$z(a, w) = (w \cdot \rho(a) + c) \quad (1)$$

which is intended to minimize the following Equation (2) [51]:

$$Q(f) = C \frac{1}{N} L_e(b, z(a, w)) + \frac{1}{2} \|W^2\| \quad (2)$$

where

w —vector weights;

N —number of observations;

a —vector of real independent variables and b ;

L_e —epsilon-insensitive loss;
 C —constant, which determines the trade-off curve between the smoothing model and the experimental risk;
 $\rho(a)$ —feature function.

$$L_e(b, z(a, w)) = \begin{cases} 0 & \text{if } |b - z(a, w)| \leq e \\ |b - z(a, w)| - e & \text{otherwise} \end{cases} \quad (3)$$

The model was verified using the mean absolute percentage error (MAPE) [52]. Model residuals were tested for autocorrelation and normality of distribution using the Ljung–Box and Shapiro–Wilk tests [53,54].

3.2. Energy System Stability Index (ESSI)

A set of indicators was constructed that served as input data for determining the ESSI. The set of characteristics used in the analysis consisted of the indicators and formulas described in the subsequent subsections.

3.2.1. Balancing Index

The index was calculated in four variants. Both indices were created in the form of an up (U) version, when the amount of generated energy or power should be increased, and a down (D) version, when the amount of generated energy or power should be reduced. The closer the index to 1, the more stable the system is. The index acts as a stimulant. Equations (4) and (5) are as follows:

$$AVBE = 1 - \frac{AvR}{TL \cdot t} \quad (4)$$

$$APBE = 1 - \frac{ApR}{TL} \quad (5)$$

where

AvR —activated reserve, MWh;

ApR —accepted offers, MW;

TL —total load, MW;

t —time, h, 8760 h for a year.

Activated balancing energy ($AVBE$) is the energy actually activated to balance the system. The closer the $AVBEU$ value to 1, the less intervention was required; the system did not require reserves. An $AVBEU$ value close to 0 indicates that the system relies primarily on reserves. An $AVBED$ value close to 1 indicates that the system does not have to reduce production, while a value close to 0 indicates that the system has to frequently curtail energy production.

Accepted balancing energy ($APBE$) refers to the planned reserves and show the expected system instability. An $APBEU$ value close to 1 means that the system does not expect a power deficit and demand can be met without operator intervention, while an $APBEU$ value close to 0 indicates that the system has low self-sufficiency. An $APBED$ value close to 1 means that the system must rarely reduce power, while a value close to 0 means that the intervention to curtail production must be frequent.

3.2.2. Congestion Cost Ratio (CCR)

CCR (Equation (6)) is an economic measure of the stability and efficiency of the power system. It determines the cost of congestion management per unit of energy consumed. If the indicator is low, that is, below 0.1 EUR/MWh, the system can be considered efficient,

and the costs of congestion management are low. This indicator serves as a destimulant. Equation (6) is as follows:

$$CCR = \frac{\sum TCCM}{TL} \quad (6)$$

where

$TCCM$ —total cost of congestion management, EUR.

3.2.3. Load Factor (LF)

LF (Equation (7)) indicates how much maximum power was used in a given year. This value determines how efficiently energy sources operate; the higher the index value, the lower the risk of power shortages is. This indicator acts as a stimulant. Equation (7) is as follows:

$$LF = \frac{\sum EP}{L_{max} \cdot t} \quad (7)$$

where

EP —total energy production, MWh;

L_{max} —maximum load, MW.

3.2.4. Outages Ratio (OR)

OR (Equation (8)) is a measure of unavailability of system capacity. It determines how much of the installed capacity is unavailable due to failures, maintenance, or technical limitations. This indicator serves as a destimulant. Equation (8) is as follows:

$$OR = \frac{\sum IC - \sum AC}{\sum IC} \quad (8)$$

where

IC —installed capacity, MW;

AC —available capacity, MW.

3.2.5. Power Volatility Ratio (PVR)

The PVR index (Equation (9)) for a given source indicates how often the power produced by this source changes. The higher the value, the greater the volatility of the source. The PVR index was determined for individual energy sources, such as coal, solar, wind, nuclear, and hydropower. This is particularly important in the context of renewable energy sources. The index serves as a destimulant. Equation (9) is as follows:

$$PVR = \frac{\sigma_{AG}}{\overline{AG}} \quad (9)$$

where

σ_{AG} —standard deviation of actual generation per production type, MW;

\overline{AG} —average actual generation per production type, MW.

3.2.6. Generation Margin (GM)

This indicator (Equation (10)) shows how much reserve-generating capacity the system has in relation to actual demand. The higher the value of this indicator, the safer the system is, as it has reserves that can cover peak demand, as well as demand during outages. Therefore, it serves as a stimulant. Its value should be at least 10% for the system to be considered stable. The indicator was determined for individual energy sources, such as coal, solar, wind, nuclear, and hydropower. Equation (10) is as follows:

$$GM = \frac{\sum AGC - PL}{PL} \quad (10)$$

where

AGC —power actually available in the system, MW;
 PL —peak load, maximum power demand, MW.

3.2.7. Covering Peak Demand with Energy from a Selected Source (PD)

This indicator (Equation (11)) determines whether renewable energy sources and coal can deliver adequate power during peak demand. It indicates the extent to which the system can rely on renewable energy sources and coal during critical periods. The higher the index value, the greater the potential for renewable energy or coal to relieve the system during peak stress. The index was calculated based on peak hours in Poland, i.e., from 5 p.m. to 8 p.m., as follows:

$$PD = \frac{\sum AGRES}{\sum AG} \quad (11)$$

where

$AGRES$ —RESs (or coal) actual generation, MW.

The indicators mentioned and their values may be partially influenced by imports, for example, in terms of the activation of domestic reserves (impacting energy up-balancing). The analysis of imports, exports and the relationships between them provides information on strategic and operational stability.

3.2.8. Power Import (PI)

PI (Equation (12)) represents the sum of power imported from neighboring countries. In the case of Poland, these are mainly Germany, Ukraine, Slovakia, Sweden, Lithuania, and the Czech Republic, while in the case of Sweden, these are Finland, Denmark, Germany, Lithuania, Norway, and Poland. The indicator serves as a destimulant. Equation (12) is as follows:

$$PI = \sum PIC \quad (12)$$

where

PIC —power imported from each country, MW.

3.2.9. Power Export (PE)

PE (Equation (13)) represents the sum of power transmitted to neighboring countries. This variable was treated as a stimulant, indicating that the capacity exceeds domestic needs. This can serve as a reserve capacity, a source of system competitiveness at the time of sale, and an indication of the system's flexibility, which allows the country to support its neighbors when needed.

$$PE = \sum PEC \quad (13)$$

where:

PEC —power exported to each country, MW.

3.2.10. Import Dependency (ID)

This indicator (Equation (14)) shows whether the system meets demand from its own resources, i.e., the degree of operational self-sufficiency. This variable was treated as a destimulant. Equation (14) is as follows:

$$ID = \frac{PI}{TL} \quad (14)$$

3.2.11. Net Position (NP)

NP (Equation (15)) represents the difference between imports and exports of electricity. If its value is less than 0, it indicates that the country is a net exporter of electricity. Otherwise, the country is a net importer of electricity, as in the following Equation (15):

$$NP = PI - PE \quad (15)$$

In the context of energy system stability and energy security, this variable was treated as a destimulant. An increase in the variable's value indicates a growing dependence on imported power, which may indicate a shortage of domestic power in the system.

3.2.12. Import Volatility Ratio (IVR)

The indicator determines the percentage by which power imports change over time, as in the following Equation (16):

$$IVR = \frac{\sigma_I}{\overline{AI}} \quad (16)$$

where

σ_I —standard deviation of the power import, MW,

\overline{AI} —average import in a given year, MW.

A low index value (below 1) indicates stable and predictable import usage. High volatility can make the system vulnerable to external disturbances. The indicator serves as a destimulant.

3.2.13. Single-Supplier Dependency Ratio (SSI)

This indicator (Equation (17)) measures the degree to which a country is dependent on power imports from a single supplier. The closer its value is to 1, the greater the risk of supply disruptions in the event of incidents, such as technical or political ones, indicating low supply diversification. The indicator serves as a destimulant, as in the following Equation (17):

$$SSI = \sum \frac{PIC_{max}}{PI} \quad (17)$$

The results of each indicator were used as input data for multi-criteria analysis conducted using the Hellwig method.

3.3. Hellwig's Method

A taxonomic method was used to construct a single synthetic measure of the energy system stability index. The Hellwig method enables the classification of a set of features and the detection of emerging patterns and regularities [55,56]. It is important to classify the set of features in terms of their impact on the analyzed phenomenon, in this case the ESSI. This impact can be positive for stimulants, negative for destimulants, or neutral. To correctly determine the index, it was necessary to standardize the variables, i.e., transform the destimulants into stimulants, which was carried out using the max-minus method using the following equation [57]:

$$x_{ij}' = x_{imax} - x_{ij} \quad (18)$$

where

x_{ij}' —destimulant value converted into stimulant;

x_{imax} —maximum value of the feature among all objects i .

It was also necessary to transform each of the features into a dimensionless form, i.e., to standardize them, as follows [58]:

$$z_{ij} = \frac{x_{ij} - \bar{x}_j'}{S_j} \quad (19)$$

where

S_j —standard deviation for the j -th variable;

z_{ij} —standardized values of the j -th variable;

\bar{x}_j' —arithmetic mean of the j -th variable.

The weights of the individual variables were estimated using Shannon's entropy [59,60]. The weight was determined by the information given variable carries. For each variable j , the entropy E_i was calculated according to the following formula:

$$E_i = - \sum_{j=1}^n p_{ij} \cdot \ln(p_{ij}) \quad (20)$$

where

p_{ij} —normalized value of the variable.

Weights [61] were determined using the following formula:

$$w_j = \frac{1 - E_i}{\sum_{i=1}^m 1 - E_i} \quad (21)$$

If the data are highly diversified, the weight is high; if they are uniform, the weight will be low.

This modification allowed us to obtain objective weights, taking into account the informativeness of the feature rating, and balance the obtained rating.

In the next step, the pattern P_0 and the distance of each object point from this pattern (d_i) were determined, as in the following Equation [62]:

$$d_i = \sqrt{\sum_{j=1}^n w_j (z_{ij} - z_{0j})^2} \quad (22)$$

where

w_j —weight of the j -th variable;

$z_{0j} = \max\{z_{ij}\}$ —model object.

Then, a standard (d_0) was applied, which ensured that the meter value could only take values in the range of 0–100%, as in the following Equation (23):

$$d_0 = \bar{d} + 2 * S_d \quad (23)$$

where

d_0 —standard;

\bar{d} —arithmetic mean of the variable d_i ;

S_d —a standard deviation.

The synthetic measure of the stability of the energy system was determined according to the following equation [63]:

$$ESSI = 1 - \frac{d_i}{d_0} \quad (24)$$

4. Results

The research began with the creation of a model for the production of electricity from renewable sources in Poland. This made it possible to initially verify the validity of the research conducted. It was assumed that the growing share of renewable energy in the Polish energy system would impact the stability of the system. Using the SVR machine learning model, a forecast of renewable energy production until 2030 was generated. For this purpose, a Java program was written using the Weka library. It utilizes the SVR regression algorithm (SMOREG with an RBF (radial basis function) kernel). For each time series variable, the program builds a set of values consisting of the year and the previous period. The program automatically optimizes the model's C parameter using cross-validation. Finally, the model is trained on the full dataset. Model accuracy was assessed using the MAPE error [64]. The error value was 3%, indicating that it can be considered highly reliable. Furthermore, using the Shapiro–Wilk ($p = 0.2$) and Liung–Box ($p = 0.89$) tests, it was confirmed that the residuals of the model were characterized by a normal distribution and that autocorrelation did not occur. The actual data and forecasts made using the model are presented in Figure 1.

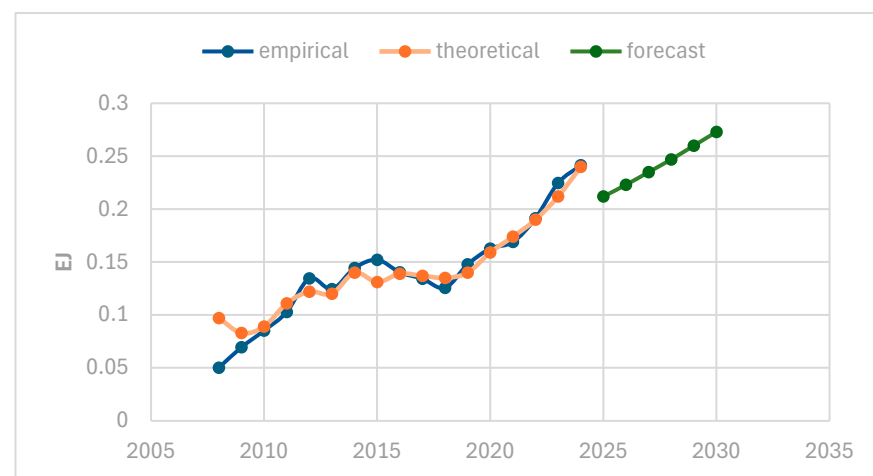


Figure 1. Total renewable energy production in Poland, actual values and forecast until 2030, source: own study.

The resulting forecast to 2030 confirmed that the share of renewable energy supplied to the Polish energy system will increase in the coming years. When comparing the years 2024 and 2030, this increase exceeds 20%. This is also consistent with the assumptions of the EU's climate policy.

After verifying the hypothesis of a growing share of renewable energy in Poland's energy mix, the authors began to determine the values of indicators characterizing the stability of the energy system, as described in the Section 3. Data for determining indicators were obtained from the ENTSO-E website. Only values characterized by the completeness of the data for the selected years and common to both countries were used. The exceptions were values related to the share of coal in the Polish energy generation structure, which are available only for Poland and were used in the simulation of the impact of CCTs on the energy system. The data were also selected to represent each of the categories distinguished by ENTSOE, namely load, generation, transmission, balancing, outages, and congestion management. In addition, they were selected to ensure that each of the 4A categories was covered by at least one indicator. A total of 28 indicators were determined, and their values are presented in Table 1. The indicators were estimated for Poland and Sweden in 2018 and 2024.

Table 1. Values of the indicators determined describing the stability of the energy system.

Number	Indicator	Poland 2018	Poland 2024	Sweden 2018	Sweden 2024
1	<i>AVBED</i>	0.998	0.999	0.999	1.000
2	<i>APBED</i>	0.970	0.988	1.000	1.000
3	<i>AVBEU</i>	0.995	0.999	0.999	1.000
4	<i>APBEU</i>	0.970	0.932	1.000	1.000
5	<i>CCR</i>	0.002	0.002	0.012	0.055
6	<i>LF</i>	0.760	0.868	1.005	1.160
7	<i>OR</i>	0.250	0.282	0.752	0.842
8	<i>PVR</i>				
	A <i>Coal</i>	0.185	0.279	-	-
	B <i>Solar</i>	0.000	1.493	0.000	1.801
	C <i>Wind</i>	0.819	0.824	0.634	0.615
	D <i>Water</i>	0.180	0.540	0.400	0.331
	E <i>Nuclear</i>	-	-	0.149	0.147
9	<i>PI</i>	13,359,495.000	12,732,722.000	12,235,076.000	5,602,504.000
10	<i>PE</i>	7,774,277.000	15,675,042.000	29,205,513.000	39,140,886.000
11	<i>NP</i>	-5,585,218.000	2,942,320.000	16,970,437.000	33,538,382.000
12	<i>ID</i>	0.078	0.030	0.089	0.042
13	<i>IVR</i>	1.121	1.823	2.409	3.168
14	<i>LF solar</i>	0.006	0.008	0.011	0.010
15	<i>LF wind</i>	0.001	0.017	0.001	0.003
16	<i>GM</i>				
	A <i>total</i>	0.501	1.316	0.678	1.315
	B <i>Solar</i>	-0.991	-0.446	0.009	0.011
	C <i>Wind</i>	-0.785	-0.637	-0.729	-0.222
	D <i>Coal</i>	0.064	0.0004	-	-
	E <i>Water</i>	-0.983	-0.988	-0.308	-0.241
	F <i>Nuclear</i>	-	-	-0.627	-0.679
17	<i>SSI</i>	0.400	0.870	0.670	0.400
18	<i>PDRES</i>	0.085	0.280	0.510	0.665
19	<i>PDC</i>	0.840	0.530	-	-

The *AVBE* and *APBE* balancing factors for Poland and Sweden in 2018 and 2024 are close to 1. This may indicate that the Polish and Swedish power systems did not require significant interventions in terms of capacity curtailment or reserve activation and were characterized by sufficient capacity and energy levels. Poland slightly improved its indicators in 2024. The *CCR* indicator remained unchanged in Poland, but in Sweden it more than quadrupled. Poland is characterized by very low congestion management costs, indicating system efficiency. Sweden may experience greater transmission or traffic management problems. The load factor (*LF*) in Poland increased by 13% and in Sweden by 15%. This indicates greater utilization of available capacity, while in Sweden, an *LF* value above 1 indicates the possibility of exporting surplus power. The outage rate (*OR*) deteriorated slightly in Poland, while in Sweden the deterioration was more significant at 12%. Increasing unavailability may indicate more frequent outages or maintenance, which can be typical of aging infrastructure.

The power volatility ratio (*PVR*) determined for Poland indicates a decline in the stability of coal-based power. This is due to its decreasing role in the mix. In both Poland and Sweden, the volatility index for solar energy indicates that it is a highly unstable source, dependent on changing weather conditions. In this case, the use of reserves and energy storage is required. Wind energy is also an unpredictable energy source, but the index is up to half as low as that of solar energy. The most stable renewable energy source is

hydropower, but the *PVR* index for Poland has also deteriorated. The most stable energy source is nuclear energy, which is still absent in Poland's energy mix.

Poland's *PI* decreased by approximately 5%. Poland reduced its dependence on imports, while in Sweden imports fell twofold. This improved the stability and independence of energy systems and may indicate improved energy efficiency.

Poland's power exports indicator (*PE*) doubled, while Sweden's increased by 30%. This confirms the growing position of both countries as energy exporters. It is also indicated by the *NP* index. Poland achieved independence and an export advantage, while Sweden strengthened its position. However, it should be noted that 2018 was a record year for Poland's power imports. Both countries reduced their dependence on power imports, Poland by 60% and Sweden by 50%.

Interpreting the *PI* and *PE* indices alone without a broader context can lead to misleading results, as the system can only import energy during peak periods and export it for most of the day. Therefore, two additional factors were determined.

The Import Volatility Ratio (*IVR*) showed that, although imports decreased, they became less predictable and subject to fluctuations. This suggests that Poland relies on imports during peak periods. It also indicates a lack of flexible domestic sources capable of supporting the system in the short term. In Sweden, this indicator has also increased as imports are used in crisis situations or when energy from neighboring countries is at favorable prices.

The coefficient of variation of renewable energy imports in Poland indicates better capacity utilization. In Sweden, the indicator is stable, with a slight deterioration in the case of solar energy.

The aggregate *GM* indicates a significant increase in the stability of the system in terms of surplus capacity. This means that the entire system has sufficient capacity to meet peak demand, but individual sources cannot be relied on at critical moments. In 2018, the *GM* for coal in Poland was 6%, which means that this source was able to meet all the power demand with a small margin. However, in 2024, the indicator is still positive, but the margin is close to 0. For other energy sources, the indicator is below 0.

The single-supplier dependency ratio (*SSI*) has increased in Poland, meaning that it has become more dependent on power imports from Germany. Sweden, on the other hand, has improved its diversification of supply. The coverage of the peak power demand from renewable energy sources (*PDRESs*) indicates an improvement in both countries. In Poland, it is still low compared to Sweden, as RESs are not yet sufficiently reliable during peak hours. The value of this ratio determined for coal in Poland indicates that Poland is increasingly relying less on coal during critical hours.

As can be seen, interpreting individual indicators is possible but time-consuming, and combining individual results into a single coherent assessment is practically impossible. Therefore, it was necessary to use a method that combined all of these variables into a single synthetic measure. The Hellwig method was used for this purpose. Data were entered into the ESSI 1.0 program, which was written specifically for the research presented. It allowed the assessment of the entities, namely Poland and Sweden, in 2018 and 2024, based on multiple indicators (rows in Table 2), considering the nature and importance of these indicators.

Table 2. Indicators used in the analysis and their weight.

C	Indicator	Libra
1	<i>AVBED</i>	0.037
2	<i>APBED</i>	0.048
3	<i>AVBEU</i>	0.047
4	<i>APBEU</i>	0.048
5	<i>CCR</i>	0.058
6	<i>LF</i>	0.034
7	<i>OR</i>	0.047
8	<i>PVR solar</i>	0.048
9	<i>PVR wind</i>	0.054
10	<i>PVR water</i>	0.031
11	<i>PI</i>	0.041
12	<i>PE</i>	0.035
13	<i>NP</i>	0.037
14	<i>ID</i>	0.040
15	<i>IVR</i>	0.033
16	<i>LF solar</i>	0.036
17	<i>LF wind</i>	0.049
18	<i>GM total</i>	0.047
19	<i>GM solar</i>	0.047
20	<i>GM wind</i>	0.036
21	<i>GM water</i>	0.057
22	<i>SSI</i>	0.046
23	<i>PDRES</i>	0.035

Only variables for which data were available for both countries and years were entered into the program. Therefore, indicators designated solely for coal and nuclear energy were eliminated. First, the indicators were standardized to unify the nature of the variables. Then, they were normalized, eliminating differences in features, their units, and scales. This ensured the objective determination of the synthetic indicator. The entropy was also calculated and used for deriving the weights of the individual indicators. These weights are usually adopted based on expert opinion. The procedure using entropy resulted in objective weights, free of the influence of subjective assessments by individual experts. The high entropy of a variable meant that it carried little discriminating information, so it received a low weight. The lower the entropy, the less random the data were, and the higher the weight was. For each feature, the best case (maximum value) was determined. Then, the distances of each value from the designated pattern were determined. Finally, the program calculated the value of the ESSI. The program algorithm is presented in Figure 2.

Table 2 presents the weights assigned by the program to each of the indicators used in the analysis. The highest weights were assigned to the *CCR* indicator and the *PVR wind* indicator. The lowest weights were assigned to the *PVR water* and *IVR* indicators.

The value of the synthetic ESSI assessment measure for each of the objects determined by the program is presented in Table 3.

Table 3. The value of the ESSI as determined by the ESSI 1.0 program.

Object	2018	2024
Poland	0.11	0.31
Sweden	0.40	0.45

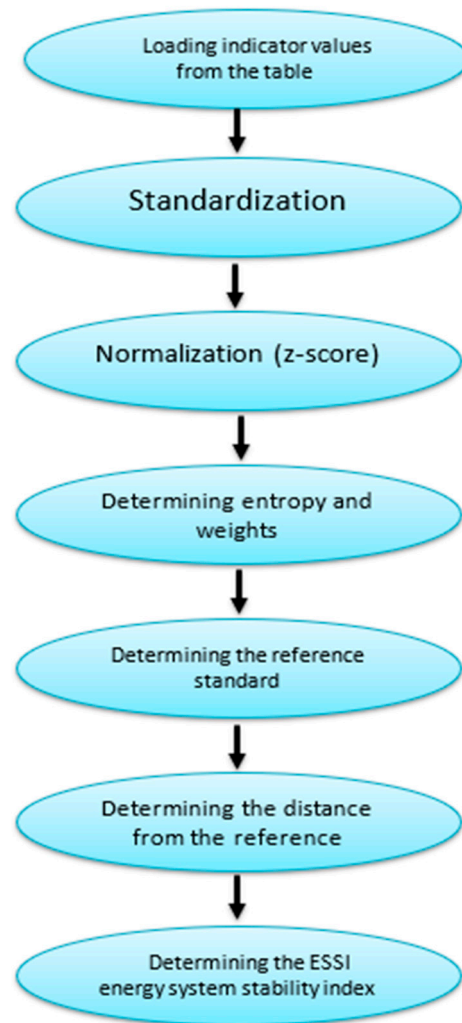


Figure 2. Algorithm of the program used to determine the ESS I; source: own study.

The highest value that the index can reach is 100%. The actual values are significantly lower. Sweden achieved the highest ESS I value in 2024, at 45%, which was a slight increase compared to 2018. The lowest value for Poland was recorded in 2018, at 11%. In 2024, this index nearly tripled for Poland, reaching 31%. A graph was also generated by the program for the ESS I components for all objects (Figure 3).

Each axis of the graph displays one of the indicators in Table 2. The further the value on an axis from the center of the graph, the lower the value of the standardized indicator is. Therefore, the shape of the grid presented in the graph represents the stability profile of the energy system of a given country (Figure 3). The smaller the area of the graph, the better the result of the synthetic assessment indicator is. Poland significantly improved the stability of the system in 2024, particularly in terms of the *LF solar*, *LF wind*, *GM*, and *PDRES* indicators. However, there was a slight deterioration of the *APBEU*, *PVR solar*, and water indicators. In the case of Sweden, on the other hand, the indicator improved the values of *GM total* and *GM wind*, single-supplier dependency ratio (*SSI*), *ID*, and *PI*. However, less favorable values were recorded for the *CCR*, *OR*, *PVR solar*, *NP*, and *IVR* components.

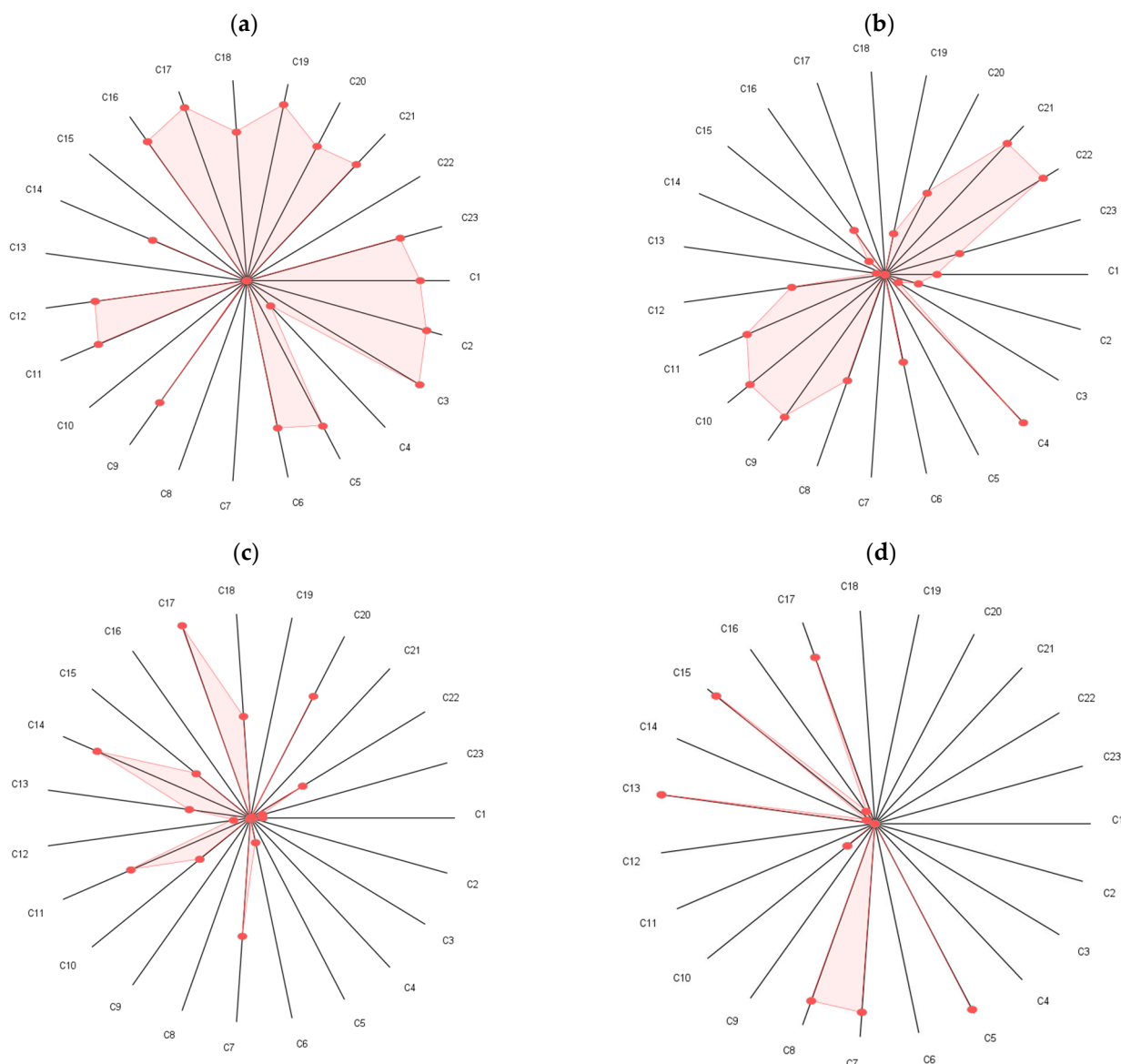


Figure 3. Radar charts generated by the program for the ESSI components for all objects in (a) 2018 and (b) 2024 in Poland, and (c) 2018 and (d) 2024 in Sweden.

The next stage of the study examined the potential impact of clean coal technologies on the ESSI. To this end, coal-specific indicators were added to the set (Table 1) and indicators related to renewable energy were removed. Due to the lack of coal data for Sweden, the analysis was conducted solely for Poland. In this case, the value of the ESSI for 2018 was 0.27, while for 2024, it was 0.13.

The decline in the index in 2024 (Figure 4) was primarily due to balancing accepted rate up, *CCR*, *OR*, *PVR Coal*, *PI*, *GM Total*, *GM Coal*, *SSI*, and *PD* for coal. The areas where the system improved its stability included balancing activation rate down, balancing accepted rate down, and balancing activation rate up.

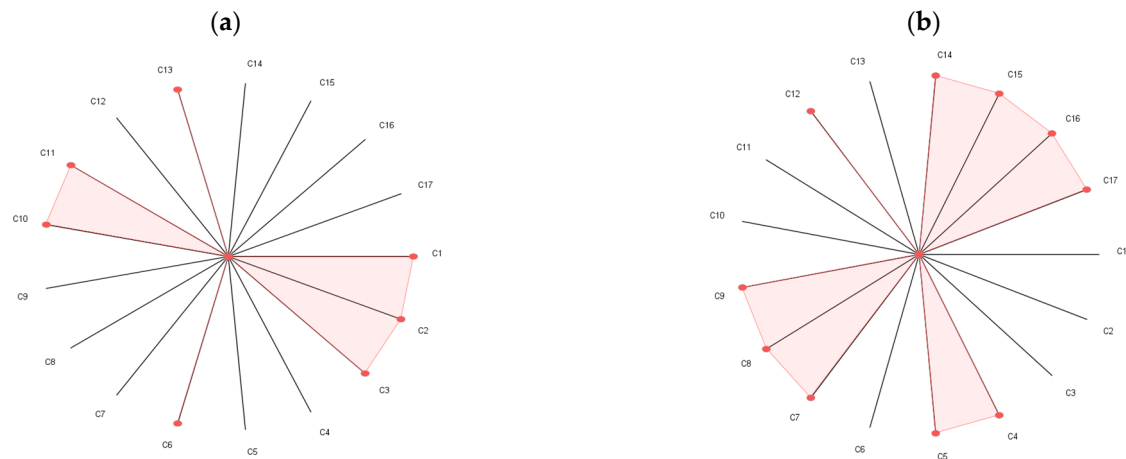


Figure 4. Radar charts generated by the program for the objects of the ESS components chosen in (a) 2018 and (b) 2024 in Poland.

5. Discussion

The aim of the analysis carried out was to examine the impact of the growing share of renewable energy sources on the stability of the energy system. Typically, indicators used in the literature that describe system stability are limited to the technical and physical parameters of the grid. The goal of this approach was to comprehensively describe the stability of the energy system, similar to the 4A category used in energy security studies. This approach also enabled analysis over a longer time horizon, rather than the usual focus on short-term network parameters. The proposed approach also allowed comparisons not only of a given country's energy system over time but also with other systems and countries at different levels of development. The results of the research presented clearly indicate that the share of renewable energy in Poland's energy mix will systematically increase, as confirmed by the forecast made using the SVR model until 2030. This prediction is highly probable, with a MAPE error of 3%.

The Hellwig method, which has rarely been used to assess energy system stability, was applied to determine a synthetic assessment metric. Analysis conducted for Poland and the benchmark country, Sweden, showed that Poland significantly lags behind the established benchmark in terms of energy stability. In 2018, the ESS index was four times lower than that in Sweden in the same year. A significant change was observed in 2024, as it increased threefold. However, the index value is still lower than that in Sweden. Sweden has an energy system based on the only stable renewable energy source, i.e., hydropower, and stable nuclear energy. This has a positive impact on various indicators, such as *PVR*, *GM*, *LF*, *SSI*, *ID*, *PI*, *AVBE*, and *APBE*, whose values indicate system maturity, limiting the number of necessary interventions due to balancing and the use of reserves. Poland is making visible progress in energy transformation and system independence, but the success of this endeavor will depend on the implementation of energy storage and technologies that enable the management of variability of the energy system.

Furthermore, a simulation of the ESS index was conducted for Poland to characterize the potential impact of CCTs on the stability of the Polish energy system. For this purpose, the set of indicators used to determine the energy system stability index was modified. The index was calculated for Poland by introducing variables that characterize the share of coal in the energy mix. In this case, the index in 2024 was half that in 2018. A sensitivity analysis was also performed for two scenarios, i.e., a pessimistic scenario, where coal-related factors have virtually disappeared from the index and are close to 0, and an optimistic scenario, where coal-related factors remain unchanged and are equal to those in 2018. It was observed

that for the value of the pessimistic scenario, the ESSI decreased by 40%. However, in the optimistic scenario, the index for 2024 was twice as high as the index value in 2018. This clearly indicates the stabilizing role of coal in the system, and its removal without ensuring access to flexible energy sources could worsen the system's resilience to disruptions and the overall predictability and reliability of the system. Coal technologies could have a positive stabilizing effect on the energy system, particularly considering the controllability of the energy source, the system's resilience to changes in demand, demand surges, and, consequently, operational flexibility. The main factors contributing to the decline in the ESSI index in 2024 were the increasing *PVR* and the coverage of peak demand with coal-fired energy. The value of the ESSI decreased due to the decline in the share of coal in the energy mix. Therefore, it can be concluded that CCTs in countries with a high share of coal in their energy mixes and a low share of other stable energy sources, such as nuclear energy, could play a significant role in stabilizing the energy system during the period of the energy transition. Combining CCTs and RESs would constitute a hybrid transformation strategy that would enable a smooth transition to a zero-emission energy system without the risk of destabilization. CCTs are intended to provide a countermeasure during the transition. They are not the ultimate solution but can be crucial for energy security and ensuring that citizens have access to energy when they need it and in sufficient quantities. In future studies, the authors want to take into account additional factors, such as the possibility of coordinated planning of electrical and heating infrastructure [65].

6. Conclusions

The set of indicators developed by the authors characterizes the operational stability of the energy system according to a four-dimensional energy security paradigm. This enabled the inclusion of the entire spectrum of operational and structural indicators in the analysis of energy system stability. The developed ESSI assesses the system's stability in a technical sense, but also its ability to adapt, balance power and energy, and ultimately maintain independence. The Hellwig method used enabled the determination of a synthetic ESSI measure. The method was modified by introducing Shannon's entropy, thus obtaining indicator weights, which eliminated subjective expert interpretations. The CCR received the highest weight (i.e., 0.058). This indicates the significant impact of congestion management costs on the operational stability of the power system. This emphasizes that system stability is not solely dependent on power generation and balancing. The analysis demonstrated that implementing a strategy of gradual coal phaseout and parallel development of renewable energy can be more effective than a sudden shift away from a stable energy source without preemptive structural support, such as energy storage. The use of CCTs can be a key component in transitional energy systems. The research results fully supported the thesis that CCTs can play a key role in the construction of a stable energy system based on RESs. This is particularly justified in countries, like Poland, where energy systems are not yet prepared for the dominant role of RESs. As the results obtained for Sweden demonstrate, Poland should also consider increasing the share of stable energy sources in its energy mix, which is undoubtedly hydropower. Supporting the assessment of the system with the ESSI will enable the design of safe and realistic energy transition paths. The proposed method is highly universal and can be applied in any country, and the created program fully automates the ESSI calculation process. It is an excellent tool for facilitating decision making, enabling the creation of simulations and scenarios of the impact of potential energy development strategies on the stability of its operation. This will allow the energy transition to be designed in accordance with the expectations of decisionmakers, technical conditions, infrastructure, and raw materials in a given country. The results indicate that decisionmakers should focus on developing support mechanisms for countries that must

drastically change their energy mixes. Diversification of energy sources and imports, as well as expansion of cross-border networks, is recommended. As the example of Sweden demonstrates, the participation of diverse sources, such as nuclear and hydropower, in the energy generation structure ensures long-term system stability. Therefore, it is justified to introduce renewable energy sources with energy storage, as well as CCTs, which may be a temporary solution on the path to building a zero-emission system.

Author Contributions: Conceptualization, A.R. (Aurelia Rybak), A.R. (Aleksandra Rybak), J.J. and S.D.K.; methodology, A.R. (Aurelia Rybak) and A.R. (Aleksandra Rybak); software, A.R. (Aurelia Rybak); formal analysis, A.R. (Aurelia Rybak); writing—original draft preparation, A.R. (Aurelia Rybak), A.R. (Aleksandra Rybak), S.D.K. and J.J.; validation, A.R. (Aurelia Rybak); visualization, A.R. (Aurelia Rybak); investigation, A.R. (Aurelia Rybak), A.R. (Aleksandra Rybak), S.D.K. and J.J.; funding acquisition, A.R. (Aleksandra Rybak); methodology, A.R. (Aurelia Rybak). All authors have read and agreed to the published version of the manuscript.

Funding: The work was elaborated in the framework of statutory research 06/010/BK_25. SDK is grateful for the financial support by the European Union—NextGenerationEU project, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No BG-RRP-2.004-0008.

Data Availability Statement: The data presented in these studies are available on request from the corresponding author. The data are not publicly available due to the extremely large size.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Delbeke, J.; Runge-Metzger, A.; Slingenberg, Y.; Werksman, J. The Paris Agreement. In *Towards a Climate-Neutral Europe*; Routledge: London, UK, 2019; pp. 24–45.
- European Commission. The European Green Deal. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 20 July 2025).
- Gupta, A.; Davis, M.; Kumar, A. An Integrated Assessment Framework for the Decarbonization of the Electricity Generation Sector. *Appl. Energy* **2021**, *288*, 116634. [[CrossRef](#)]
- European Union. Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources. Available online: <https://eur-lex.europa.eu/legal-content/PL/TXT/HTML/?uri=CELEX:32009L0028> (accessed on 20 July 2025).
- Schindler, D.; Behr, H.D.; Jung, C. On the Spatiotemporal Variability and Potential of Complementarity of Wind and Solar Resources. *Energy Convers. Manag.* **2020**, *218*, 113016. [[CrossRef](#)]
- Sims, R.E. Renewable Energy: A Response to Climate Change. *Sol. Energy* **2004**, *76*, 9–17. [[CrossRef](#)]
- Mayyas, A.; Chadly, A.; Amer, S.T.; Azar, E. Economics of the Li-Ion Batteries and Reversible Fuel Cells as Energy Storage Systems When Coupled with Dynamic Electricity Pricing Schemes. *Energy* **2022**, *239*, 121941. [[CrossRef](#)]
- Energy Institute. *Statistical Review of World Energy 2025*; Energy Institute: London, UK, 2025.
- Bird, L.; Lew, D.; Milligan, M.; Carlini, E.M.; Estanqueiro, A.; Flynn, D.; Gomez-Lazaro, E.; Holttinen, H.; Menemenlis, N.; Orths, A.; et al. Wind and Solar Energy Curtailment: A Review of International Experience. *Renew. Sustain. Energy Rev.* **2016**, *65*, 577–586. [[CrossRef](#)]
- Saleh, A.M.; Vokony, I.; Waseem, M.; Khan, M.A.; Al-Areqi, A. Power System Stability with High Integration of RESs and EVs: Benefits, Challenges, Tools, and Solutions. *Energy Rep.* **2025**, *13*, 2637–2663. [[CrossRef](#)]
- Roszkowska, E. A Comprehensive Exploration of Hellwig’s Taxonomic Measure of Development and Its Modifications—A Systematic Review of Algorithms and Applications. *Appl. Sci.* **2024**, *14*, 10029. [[CrossRef](#)]
- Smith, O.; Cattell, O.; Farcot, E.; O’Dea, R.D.; Hopcraft, K.I. The effect of renewable energy incorporation on power grid stability and resilience. *Sci. Adv.* **2022**, *8*, eabj6734. [[CrossRef](#)] [[PubMed](#)]
- Khadka, N.; Paudel, R.; Adhikary, B.; Bista, A.; Sharma, S.; Shrestha, A. Transient stability in renewable energy penetrated power systems: A review. In Proceedings of the RESSD 2020 International Conference on Role of Energy for Sustainable Social Development in ‘New Normal’ Era, Kathmandu, Nepal, 28–29 December 2020; pp. 28–29.
- Paravantis, J.A.; Kontoulis, N. Energy security and renewable energy: A geopolitical perspective. In *Renewable Energy-Resources, Challenges and Applications*; IntechOpen: London, UK, 2020.
- Yang, W.; Tu, C.; Xiao, F.; Yu, J. A Method to Improve Both Frequency Stability and Transient Stability of Virtual Synchronous Generators during Grid Faults. *Sustainability* **2024**, *16*, 1769. [[CrossRef](#)]
- Agora Energiewende. *System Stability in a Renewables-Based Power System*; Agora Energiewende: Berlin, Germany, 2020.

17. Rahman, T.K.A.; Jasmon, G.B. A New Technique for Voltage Stability Analysis in a Power System. In Proceedings of the 1995 International Conference on Energy Management and Power Delivery EMPD '95, Singapore, 21–23 November 1995.
18. Moghavvemi, M.; Omar, F.M. Technique for Contingency Monitoring and Voltage Collapse Prediction. *IEEE Proc. Gener. Transm. Distrib.* **1998**, *145*, 634–640. [[CrossRef](#)]
19. Valuva, C.; Chinnamuthu, S.; Khurshaid, T.; Kim, K.-C. A Comprehensive Review on the Modeling and Significance of Stability Indices in Power System Instability Problems. *Energies* **2023**, *16*, 6718. [[CrossRef](#)]
20. Wang, Y.; Ravishankar, J.; Phung, T. A Study on Critical Clearing Time (CCT) of Micro-Grids under Fault Conditions. *Renew. Energy* **2016**, *95*, 381–395. [[CrossRef](#)]
21. Vittal, E.; O'Malley, M.; Keane, A. Rotor Angle Stability with High Penetrations of Wind Generation. *IEEE Trans. Power Syst.* **2011**, *27*, 353–362. [[CrossRef](#)]
22. Phadke, A.G.; Thorp, J.S.; Adamiak, M.G. A New Measurement Technique for Tracking Voltage Phasors, Local System Frequency, and Rate of Change of Frequency. *IEEE Trans. Power Appar. Syst.* **2007**, *PAS-102*, 1025–1038. [[CrossRef](#)]
23. Chamorro, H.R.; Orjuela-Cañón, A.D.; Ganger, D.; Persson, M.; Gonzalez-Longatt, F.; Sood, V.K.; Martinez, W. Nadir Frequency Estimation in Low-Inertia Power Systems. In Proceedings of the 2020 IEEE 29th International Symposium on Industrial Electronics (ISIE), Delft, The Netherlands, 17–19 June 2020; pp. 918–922.
24. Chen, G.; Liu, L.; Song, P.; Du, Y. Chaotic Improved PSO-Based Multi-Objective Optimization for Minimization of Power Losses and L Index. *Energy Convers. Manag.* **2014**, *86*, 548–560. [[CrossRef](#)]
25. Barquin, J.; Gomez, T.; Pagola, F.L. Estimating the Loading Limit Margin Considering Voltage Collapse Areas. *IEEE Trans. Power Syst.* **1995**, *10*, 1952–1962. [[CrossRef](#)]
26. Li, Z.; Sun, H.; Xue, Y.; Li, Z.; Jin, X.; Wang, P. Resilience-Oriented Asynchronous Decentralized Restoration Considering Building and E-Bus Co-Response in Electricity-Transportation Networks. *IEEE Trans. Transp. Electrif.* **2025**. [[CrossRef](#)]
27. Gjorgiev, B.; Stankovski, A.; Wengler, J.; Sencan, S.; Sansavini, G. Availability of the European Power System Assets: What Do We Learn from Data? *Reliab. Eng. Syst. Saf.* **2025**, *258*, 110887. [[CrossRef](#)]
28. Hirth, L.; Mühlenpfordt, J.; Bulkeley, M. The ENTSO-E Transparency Platform—A Review of Europe's Most Ambitious Electricity Data Platform. *Appl. Energy* **2018**, *225*, 1054–1067. [[CrossRef](#)]
29. Ilić, M.D.; Bachovchin, K.D.; Lewis, A.S. Costs and Benefits of Transmission Congestion Management. In Proceedings of the 2011 IEEE/PES Power Systems Conference and Exposition, Phoenix, AZ, USA, 20–23 March 2011; pp. 1–7.
30. Allan, R.N. *Reliability Evaluation of Power Systems*; Springer: Berlin/Heidelberg, Germany, 2013.
31. Majchrzak, H.; Koziół, M. Analysis of Various Options for Balancing Power Systems' Peak Load. *Energies* **2021**, *14*, 513. [[CrossRef](#)]
32. Danish, M.S.S.; Senjyu, T.; Danish, S.M.S.; Sabory, N.R.; Mandal, P. A Recap of Voltage Stability Indices in the Past Three Decades. *Energies* **2019**, *12*, 1544. [[CrossRef](#)]
33. Lee, J.C.; Fields, M.J.; Lundquist, J.K. Assessing Variability of Wind Speed: Comparison and Validation of 27 Methodologies. *Wind Energy Sci.* **2018**, *3*, 845–868. [[CrossRef](#)]
34. Better Energy. Q&A: Blackout Risks and Grid Investment Needs. Available online: <https://betterenergy.org/blog/qa-blackout-risks-underscore-resilience-reliability-investment-needs-for-us-power-grid/> (accessed on 20 July 2025).
35. ENTSO-E Transparency Platform Dashboard. Available online: <https://transparency.entsoe.eu/dashboard/show> (accessed on 20 July 2025).
36. Asia Pacific Energy Research Center (APEREC). *A Quest for Energy Security in the 21st Century*; APEREC: Tokyo, Japan, 2007.
37. Lubell, H. Security of Supply and Energy Policy in Western Europe. *World Politics* **1961**, *13*, 400–422. [[CrossRef](#)]
38. Deese, D.A. Energy: Economics, Politics, and Security. *Int. Secur.* **1979**, *4*, 140. [[CrossRef](#)]
39. IEA Energy Security; Energy Technology Systems Analysis Programme: Paris, France, 2014. Available online: <http://www.iea.org/topics/energy-security/> (accessed on 20 July 2025).
40. World Energy Council. *Energy for Tomorrow's World—Acting Now*; WEC: London, UK, 2000.
41. Ye, X.; Milanovic, J.V. Composite Index for Comprehensive Assessment of Power System Transient Stability. *IEEE Trans. Power Syst.* **2021**, *37*, 2847–2857. [[CrossRef](#)]
42. Jadid, S.; Jalilzadeh, S. Effective Transient Stability Assessment Based on Composite Indices. *Int. J. Electr. Power Energy Syst.* **2005**, *27*, 525–532.
43. Simões, T.A.; Borges, C.L.; Mitra, J. Use of Performance Indices for Contingency Screening. *IET Gener. Transm. Distrib.* **2020**, *14*, 3896–3904. [[CrossRef](#)]
44. Roszkowska, E.; Filipowicz-Chomko, M. Measuring Sustainable Development Using an Extended Hellwig Method. *Soc. Indic. Res.* **2021**, *153*, 299–322. [[CrossRef](#)]
45. Ho, C.H.; Lin, C.J. Large-Scale Linear Support Vector Regression. *J. Mach. Learn. Res.* **2012**, *13*, 3323–3348.
46. Liu, Y.; Wang, L.; Gu, K. Dynamic Load Identification Using SVR under Interval Uncertainties. *Appl. Soft Comput.* **2021**, *110*, 107599. [[CrossRef](#)]
47. Zeng, J.; Qiao, W. Short-Term Solar Power Prediction Using Support Vector Machine. *Renew. Energy* **2013**, *52*, 118–127. [[CrossRef](#)]

48. Baumes, L.A.; Serra, J.M.; Serna, P.; Corma, A. SVM for Predictive Modeling in Heterogeneous Catalysis. *J. Comb. Chem.* **2006**, *8*, 583–596. [[CrossRef](#)]
49. Parveen, N.; Zaidi, S.; Danish, M. SVR Model for Predicting Sorption Capacity of Lead (II). *Perspect. Sci.* **2016**, *8*, 629–631. [[CrossRef](#)]
50. Sen, A.; Srivastava, M. Multiple Regression. In *Regression Analysis: Theory, Methods and Applications*; Wiley: New York, NY, USA, 1990; pp. 28–59.
51. Abdelhedi, M.; Jabbar, R.; Said, A.B.; Fetais, N.; Abbes, C. Prediction of Compressive Strength in Carbonate Rocks Using ML. *Earth Sci. Inform.* **2023**, *16*, 1473–1487. [[CrossRef](#)]
52. Vivas, E.; Allende-Cid, H.; Salas, R. Review of ML Methods for Power Forecasting. *Entropy* **2020**, *22*, 1412. [[CrossRef](#)]
53. Burns, P. *Robustness of the Ljung-Box Test and Its Rank Equivalent*; SSRN: Rochester, NY, USA, 2002.
54. Shapiro, S.S.; Wilk, M.B. An Analysis of Variance Test for Normality. *Biometrika* **1965**, *52*, 591–611. [[CrossRef](#)]
55. Hellwig, Z. Application of the Taxonomic Method. *Przegl. Stat.* **1968**, *4*, 307–326.
56. Jędrzejczak-Gas, J.; Barska, A.; Wyrwa, J. Economic Development of the European Union in the Relation of Sustainable Development—Taxonomic Analysis. *Energies* **2021**, *14*, 7488. [[CrossRef](#)]
57. Łogwiniuk, A. Taxonomic Analysis of ICT Access in Polish Schools. *Econ. Manag.* **2011**, *3*, 7–23.
58. Kukuła, K. *Zero Unitarization Method*; PWN: Warsaw, Poland, 2000.
59. Busu, C.; Busu, M. Circular Economy Processes at the EU Level Using Shannon Entropy. *Processes* **2018**, *6*, 225. [[CrossRef](#)]
60. Karaca, Y.; Moonis, M. Shannon entropy-based complexity quantification of nonlinear stochastic process: Diagnostic and predictive spatiotemporal uncertainty of multiple sclerosis subgroups. In *Multi-Chaos, Fractal and Multi-Fractional Artificial Intelligence of Different Complex Systems*; Academic Press: Cambridge, MA, USA, 2022; pp. 231–245.
61. Kacprzak, D. Fuzzy SAW Method with Fuzzy Entropy-Based Weights. *Stat. Rev.* **2018**, *65*, 25–40. [[CrossRef](#)]
62. Dziechciarz, J. *Econometric Methods, Examples, Tasks*; WUE Publishing: Wrocław, Poland, 2003.
63. Kasztelan, A. Evaluation of Green Growth in OECD Using Hellwig Model. In Proceedings of the 29th International-Business-Information-Management-Association, Vienna, Austria, 3–4 May 2017; pp. 3–4.
64. Bliemel, F. Theil's Forecast Accuracy Coefficient: A Clarification. *J. Mark. Res.* **1973**, *10*, 444–446. [[CrossRef](#)]
65. Du, Y.; Xue, Y.; Wu, W.; Shahidehpour, M.; Shen, X.; Wang, B.; Sun, H. Coordinated planning of integrated electric and heating system considering the optimal reconfiguration of district heating network. *IEEE Trans. Power Syst.* **2023**, *39*, 794–808. [[CrossRef](#)]

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