

## ENERGY TRANSITION MANAGEMENT IN POLAND IN LIGHT OF THE IBERIAN PENINSULA BLACKOUT: SYSTEM STABILITY CHALLENGES IN THE RENEWABLE ENERGY ERA

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**Purpose:** The purpose of this article is to analyze the implications of the April 28, 2025 Iberian Peninsula blackout for energy transition management in Poland. The study identifies key challenges related to the integration of distributed renewable energy sources (RES) in the context of transmission infrastructure and RES geographical distribution, formulating recommendations for energy policy based on the security of supply principle.

**Design/methodology/approach:** The study employs a triangulation methodology, combining descriptive case study analysis of the Iberian blackout with comparative analysis of power systems and conceptual modeling. The research procedure includes a systematic literature review (2022-2025), analysis of technical documents and reports from transmission system operators (ENTSO-E, Red Eléctrica de España, PSE), statistical data analysis regarding RES installed capacity structure and geographical distribution in Poland, and development of two conceptual models (ISSM and SETM). Artificial intelligence (AI) (Claude 4.5 Sonnet by Anthropic) was used to support the development of analytical models through: (a) structuring initial drafts of conceptual frameworks based on synthesized literature findings, (b) generating Mermaid diagram syntax for visual representation, and (c) iterative refinement through prompt-based interaction. All conceptual content, analytical insights, and final model structures were developed, validated, and approved by the authors.

**Findings:** The analysis revealed that the contemporary threat to system stability stems not from generation capacity deficit but from loss of control over power quality parameters (voltage and frequency) in environments with high variable renewable energy (VRE) penetration. Key findings include: the necessity of active RES participation in ancillary services, critical importance of transmission infrastructure synchronized with RES capacity growth dynamics, strategic role of large-scale energy storage, and the need to maintain cross-border resilience. The study identified that Poland's transmission system faces challenges of spatial mismatch between RES concentration areas and consumption centres, with grid connection permits already issued at a level four times the system's current capabilities.

**Research limitations/implications:** The study covers one case (Iberian blackout) and the Polish power system context, which limits full generalizability of results to other national systems with different configurations. Future research should include empirical verification of proposed models under various RES penetration scenarios.

**Practical implications:** The article provides practical frameworks for managing energy transition under high RES penetration. Two conceptual models (ISSM and SETM) can serve as reference tools for transmission system operators, energy regulators, and energy policy decision-makers. Recommendations address regulatory modernisation, grid infrastructure development, energy storage deployment, and spatial management of RES installations.

**Social implications:** Energy transition management requires development of institutional coordination mechanisms, employee digital competency building, and social dialogue regarding infrastructure investments. The study emphasizes the importance of balancing decarbonization objectives with energy supply security and economic competitiveness.

**Originality/value:** The article fills a research gap in applying lessons from specific power system destabilisation cases to national contexts undergoing intensive energy transition. The work integrates empirical blackout analysis with Poland-specific conditions, developing original conceptual models (ISSM and SETM) that synthesise structural and procedural dimensions of transition management while accounting for geographical RES distribution specifics and transmission system architecture.

**Keywords:** energy transition, power system stability, renewable energy sources, variable renewable energy, blackout, grid voltage management, transmission infrastructure, inverter-based resources.

**Category of the paper:** Research paper.

## 1. Introduction

Energy transition, defined as the process of transitioning from a system based on conventional sources to one dominated by renewable energy sources, represents a fundamental challenge for contemporary power systems (Wojtaszek, 2025). The April 28, 2025 blackout affecting Spain and Portugal revealed a new category of systemic threats not present in the synchronous generation dominance era (Red Eléctrica de España, 2025). This incident is particularly significant for Poland, a country implementing an ambitious policy to increase the share of renewable energy sources (RES) in its generation mix while simultaneously phasing out conventional capacity (Ministry of Climate and Environment, 2024).

The objective of this publication is a multifaceted analysis of the Iberian Peninsula blackout implications for energy transition management in Poland. Three specific objectives guide the study: identification of the systemic causes of the Iberian failure and assessment of their applicability to Polish power system conditions; development of conceptual frameworks for energy transition management that account for system stability challenges under high renewable energy source share conditions; and formulation of recommendations for Polish energy policy regarding RES integration, taking into account the specifics of geographical source distribution and transmission system configuration.

This study employs a triangulation methodology, combining descriptive case study analysis of the Iberian blackout with comparative power system analysis and conceptual modeling. The research procedure comprises the following stages:

Stage 1: Systematic Literature Review – Analysis of scientific publications from 2022-2025 concerning energy transition, power system stability, and renewable energy integration was conducted. Literature search was performed in Scopus, Web of Science, and Google Scholar databases using keywords: "energy transition", "grid stability", "renewable energy integration", "voltage control", "system services", "inverter-based resources". A total of 87 publications were identified and analyzed, with 52 included in the results synthesis.

Stage 2: Technical Document and Report Analysis – Detailed analysis was conducted of official transmission system operator reports (ENTSO-E, Red Eléctrica de España, PSE), European Union strategic documents, and international agency reports (IEA, BloombergNEF, 2025, World Economic Forum) published during 2024-2025.

Stage 3: Statistical Data Analysis – Data was collected and analyzed regarding RES installed capacity structure in Poland, installation geographical distribution, and transmission infrastructure parameters, drawing on data from URE, PSE, and the Institute of Renewable Energy.

Stage 4: Conceptual Modeling – Two conceptual models were developed: (a) the Integrated System Stability Management Model (ISSM) and (b) the Strategic Energy Transition Management Model (SETM). These models synthesise conclusions from the Iberian blackout analysis and Polish power system specifics. Artificial intelligence technology (Claude 4.5 Sonnet by Anthropic) was used as a research assistant in three limited, well-defined roles: (i) generating initial draft structural frameworks based on research findings already synthesised by the authors, (ii) producing Mermaid diagram syntax for visual model representation, and (iii) iterative reformatting and restructuring of drafts through structured prompts. The AI tool did not contribute original analysis, identify source materials, interpret empirical data, or determine the conceptual logic of the models. All analytical content, theoretical frameworks, empirical interpretations, the selection and weighting of model pillars and phases, and final model validation were developed exclusively by the research authors. This disclosure approach aligns with emerging scholarly standards for transparent AI use in academic research (Nature, 2023; Science, 2024).

## 2. Literature Review on Energy Transition Management

### 2.1. Evolution of the Energy Transition Paradigm

Contemporary literature on energy transition has undergone significant evolution in recent years, shifting emphasis from investment deficit issues toward dynamic demand management and ensuring social equity (Wojtaszek, 2025). Meta-analysis of the latest editions of Energy Technology Perspectives 2024 (IEA) and New Energy Outlook 2025 (BloombergNEF, 2025) reveals a fundamental shift in global energy transition trajectory, challenging the established literature thesis regarding electricity demand plateauing (Wojtaszek, 2025). Exponential growth of data centers serving artificial intelligence, intensifying heat waves, and rapidly growing electric vehicle fleets generate new demand vectors that, according to IEA and BNEF forecasts, will increase electricity demand by 2035 by over 2200 TWh compared to 2024 scenarios.

The World Economic Forum report *Fostering Effective Energy Transition 2025* indicates that the Energy Transition Index increased by 1.1 percent year-over-year, more than twice as fast as the three-year average, with the key success factor proving to be simultaneous grid modernisation and administrative procedure streamlining (World Economic Forum, 2025). Only 28 percent of countries managed to balance energy security, affordability, and sustainable development (World Economic Forum, 2025). The UN Energy Transition Report 2025 emphasizes that despite significant progress in renewable technology cost reduction, global energy-related CO<sub>2</sub> emissions increased in 2024 by 0.8 percent, reaching a record level of 37.8 billion tons, although emission growth rate slowed compared to previous years (UN, 2025).

### 2.2. Renewable Energy Source Integration Challenges

Research on RES integration focuses on identifying and mitigating technical challenges related to variable renewable energy (VRE) source variability. A systematic literature review conducted by Nwagu et al. (2024) identifies four main categories of RES integration impacts on power systems: stability and grid control, infrastructure challenges, energy storage and management, and intermittent source integration. The authors emphasize that utilizing RES electricity reduces greenhouse gas emissions, ensures generation mix diversification, and reduces excessive fossil fuel dependence, however integration of these systems encounters numerous technical and economic barriers.

A comprehensive review conducted by an international team indicates that RES integration costs grow exponentially above 30 percent penetration, reaching 25-40 USD/MWh at 50 percent share in the mix, requiring investments in energy storage and grid modernisation valued at USD 2.4 trillion globally in 2024-2030 (Ghodbane et al., 2025). Wind forecasting accuracy improved from 72 percent in 2010 to 96 percent in 2023, while solar production

forecasting accuracy increased from 68 percent to 94 percent, significantly reducing reserve requirements and integration costs (Ghodbane et al., 2025).

### **2.3. Power System Stability in the VRE Era**

The impact of high-VRE penetration on frequency and voltage stability has been the subject of intensive research. Studies demonstrate that high penetration of renewable energy sources interfaced through inverter-based resources (IBRs) significantly affects grid spinning reserve due to the intermittent nature of these sources (Mondal, Mishra, 2022). Consequently, low-inertia grid spinning reserve becomes intermittent, and generation loss can lead to frequency stability problems. The authors identify additional problems occurring in low-inertia grids, such as low short-circuit ratio and system strength, protection device setting changes, and reduced fault ride-through capability.

The CIGRE/IEEE Joint Working Group on voltage stability assessment has emphasized that controllers implemented on IBRs exert a significant influence on both short-term and long-term voltage stability (CIGRE, 2023). Classical power system stability theory highlights the fundamental role of reactive power balance, excitation control, and system strength in preventing voltage collapse phenomena (Kundur, 1994). The presence of IBRs at distribution voltage levels contributes to the dynamic behavior of the power grid, requiring voltage stability assessment methods to incorporate these facts to ensure accurate capture of voltage stability limits (IEEE PES, 2022). Technical challenges include the limitation on output current of IBRs, which is a crucial factor for voltage instability in systems with high VRE penetration (CIGRE, 2021).

Research on optimizing renewable energy integration in modern power grids indicates that with growing variable VRE penetration, grid operators face serious stability problems, including frequency fluctuations, voltage instability, and reduced system inertia (QIT Press, 2025). This work synthesises technical approaches and policy frameworks necessary to support resilient, decarbonised power systems, emphasizing the importance of advanced forecasting models, real-time grid control technologies, energy storage systems, and demand response mechanisms.

### **2.4. Energy Storage System Role**

A comprehensive review published in 2025 analyzes the role of energy storage systems (ESS) in overcoming technical challenges related to large-scale intermittent RES integration (Al-Wahedi et al., 2025). The authors emphasize that although global ESS deployment reached 27 GW in 2023, further intensification is required, particularly regarding battery systems and pumped-storage hydropower. The study provides detailed analysis of various storage system types, including mechanical, electrochemical, electrical, thermal, and chemical, identifying their specific strengths and limitations for supporting grid flexibility and increasing RES adoption.

Chinese experience in energy transition provides empirical evidence of energy storage and grid infrastructure investment effectiveness. Battery storage investments in China increased by 69 percent from the first half of 2024 to the first half of 2025, while grid investments increased by 22 percent (Ember, 2025). Battery storage installed volume tripled over three years to 2024, with China adding more capacity in 2024 than the US and EU combined. Clean generation (wind, solar, other renewable, and nuclear) growth in China accounted for 84 percent of electricity demand growth in 2024, and in the first half of 2025 exceeded demand growth, resulting in a 2 percent decrease in fossil fuel generation (Ember, 2025).

## **2.5. Energy Transition in Developing Countries**

Research on energy transition in developing countries reveals specific structural challenges differentiating these processes from transitions in developed countries. While in developed economies decarbonization objectives and technological progress constitute the main transition determinants (Markard, Rosenbloom, 2022; Li et al., 2022), in emerging economies energy transition represents a complex undertaking encompassing poverty alleviation, electrification, and institutional strengthening (Nasir et al., 2022; Li et al., 2021; Shittu et al., 2024). At the micro level, household energy stacking practices, weak financial systems, and ineffective regulatory frameworks constitute main constraints characteristic of developing country environments (Bajpain, Koul, 2025; Ferdoush et al., 2024).

## **2.6. Systematic Approach to Energy Transition**

Turner et al. (2024) conducted a systematic review of the path to inclusive and sustainable energy transition, identifying strong policy frameworks, technological progress, economic incentives, and international cooperation as key success factors. Utilizing comprehensive literature search from 2001-2023 in the Scopus database, the study identifies energy literacy as a key element for social acceptance and participation, supporting informed decision-making and behaviors conducive to renewable energy initiatives. Energy justice ensures equitable access to energy transition benefits, while case studies of Nordic countries, Germany, and Poland reveal diverse approaches and significant progress, providing valuable lessons for global application.

## **2.7. Research Gap and Publication Contribution**

The literature review reveals a significant research gap regarding application of lessons from specific power system destabilisation cases to national contexts undergoing intensive energy transition. While literature provides rich theory regarding RES integration challenges and a wide range of technological solutions, comprehensive analyses linking empirical failure experience with national energy transition plan specifics accounting for geographical source distribution and transmission system architecture are lacking. This study fills this gap through

a detailed analysis of the April 2025 Iberian blackout in the Polish power system context, formulating specific recommendations based on conceptual modeling integrating failure lessons with local technical and spatial conditions.

### 3. Iberian Peninsula Blackout Characteristics

The April 28, 2025 event represents one of the most significant large-scale voltage stability disturbances in recent European power system history (ENTSO-E, 2025). According to the technical assessment published by Red Eléctrica de España (2025), the incident evolved under stressed voltage control conditions in the transmission network. Contrary to early public speculation, the disturbance was not attributed to renewable overproduction or cyber interference, but rather to a progressive loss of effective voltage regulation capability under specific operating circumstances.

Cascading disconnection of conventional units (nuclear, gas, and coal) followed the activation of internal protection mechanisms designed to prevent equipment damage once operational thresholds were exceeded (Red Eléctrica de España, 2025). As voltage control conditions deteriorated, the progressive withdrawal of synchronous generation reduced system strength and reactive power support, accelerating destabilisation dynamics within a relatively short timeframe.

Independent expert reports and the official Spanish government position (Gobierno de España, 2025) identify three structural factors underlying the cascade. Energy isolation played a central role: limited interconnection capacity with the continental European grid prevented effective external assistance after an N-1 security criterion violation (ENTSO-E, 2025), and the peninsula's connections proved structurally inadequate relative to total system size. Operational coordination also proved challenging, as post-event analyses identified sequencing difficulties in activating available voltage and frequency control resources under stressed conditions. Finally, the absence of RES participation in ancillary services was critical: regulations in force before the incident excluded photovoltaic and wind installations from active grid voltage regulation, reserving those functions exclusively for conventional units (Red Eléctrica de España, 2025).

A structural element of particular relevance is the historically limited interconnection capacity of the Iberian Peninsula with the rest of continental Europe. For many years, the interconnection ratio remained below the European Union's 10% benchmark of installed capacity (European Commission, 2015). Although improvements have been implemented, the peninsula remains comparatively weakly coupled to the continental grid, reducing its ability to rely on external voltage and frequency support during stressed system conditions.

In parallel, the rapid expansion of inverter-based renewable generation has progressively reduced the share of synchronous inertia in the system. As documented in the literature (Ulbig et al., 2014; ENTSO-E, 2023), low-inertia systems are more sensitive to disturbances and exhibit faster dynamic responses, requiring enhanced coordination of voltage control and ancillary service provision. The April 2025 event therefore illustrates a broader integration challenge rather than a technology-specific failure.

The disturbance, which lasted up to eighteen hours in certain regions, caused significant disruptions to transport, telecommunications, and industrial activity, underlining the systemic importance of electricity infrastructure in advanced economies. Paralysis affected transport infrastructure, including complete suspension of AVE high-speed rail traffic and grounding of flight operations at major airports (Gobierno de España, 2025). Telecommunications network interruptions hampered emergency service coordination and crisis communication. The industrial and agricultural sectors sustained measurable financial losses resulting from sudden power disconnection of production processes sensitive to power supply interruptions.

#### **4. Polish Context: RES Development and Transmission Infrastructure Status**

According to Energy Market Agency data, at the end of August 2025, RES installed capacity in Poland reached 36.5 GW, representing a 14.5 percent increase compared to the same period of the previous year (Rynek Elektryczny, 2025a). In the RES installed capacity structure, photovoltaics currently dominates, with capacity exceeding 23.6 GW, constituting approximately 65 percent of all renewable energy source capacity (Rynek Elektryczny, 2025a). Wind energy ranks second with installed capacity of 10.4 GW, accounting for 28.5 percent of RES capacity (Rynek Elektryczny, 2025a).

Geographical distribution analysis of wind farms indicates their strong concentration in the northwestern part of the country (Atmosfera, 2024). The West Pomeranian and Pomeranian Voivodeships lead in terms of the number of wind installations, owing to favourable wind conditions in these areas (Atmosfera, 2024). According to Institute of Renewable Energy data, at the end of June 2025, total wind farm installed capacity reached 10,350 MW, with the largest new capacity increase recorded in the West Pomeranian Voivodeship (Rynek Elektryczny, 2025b; IEO, 2024).

Photovoltaic installation distribution is characterised by greater geographical diversification. The most photovoltaic farms operate in the Warmian-Masurian, Greater Poland, and Lubusz Voivodeships (Agro-Rydz, 2025; Gramzielone, 2024). According to Institute of Renewable Energy data, at the end of the first quarter of 2024, 48 PV farms with total capacity

of 233.57 MW operated in the Warmian-Masurian Voivodeship, while 34 farms with capacity of 307.49 MW operated in the Greater Poland Voivodeship (IEO, 2024).

Prosumer microinstallation development dynamics constitute an important element of the Polish energy landscape. According to the Energy Regulatory Office report, at the end of 2024, 1,544,574 microinstallations with total capacity of 12,749.891 MW were connected to electricity grids (URE, 2025a). The vast majority of microinstallations – nearly 98.6 percent – belonged to prosumers, accounting for nearly 95 percent of installed capacity in this category (URE, 2025a).

The Polish transmission system, managed by PSE S.A. (Polskie Sieci Elektroenergetyczne, the Polish Transmission System Operator), comprised at the end of December 2024 a total of 311 lines with a combined length of 16,601 km, including 140 lines at 400 kV voltage (9416 km) and 171 lines at 220 kV voltage (7,183 km) (PSE, 2024). This infrastructure was largely built in the mid-twentieth century and requires modernisation and expansion to ensure the country's energy security (PSE, 2024).

The transmission grid development plan for 2025-2034, approved by the President of the Energy Regulatory Office (URE) in December 2024, calls for construction of 4700 km of new 400 kV transmission lines, construction of 28 new electrical substations, and modernisation of 110 existing stations (PSE, 2024). Total estimated expenditures for these investments amount to over PLN 64 billion (PSE, 2024). A key plan element is construction of an HVDC connection on the north-south axis, designed to enable power transmission from new generation sources located in the northern part of the country to consumers without excessive burden on the remaining transmission grid (PSE, 2024).

The Transmission Grid Development Plan is designed to facilitate grid integration of approximately 18 GW of offshore wind farms, 45 GW of photovoltaic sources, and over 19 GW of onshore wind farms (PSE, 2024). Simultaneously, global grid infrastructure expansion is not keeping pace with capacity growth in renewable energy sources. According to the International Energy Agency's Renewables 2024 report, as many as 1650 GW of wind, solar PV, and hydropower capacity in advanced development stages were awaiting grid connection by mid-2024, representing an increase of 150 GW from the previous year (IEA, 2024).

#### **4.1. Spatial Distribution of RES in Poland: Critical Analysis**

Analysis of issued grid connection permits reveals a significant disproportion between RES development potential and transmission system capabilities. According to PSE Vice President Tomasz Sikorski's testimony before the Parliamentary Subcommittee on Critical Infrastructure in June 2024, approximately 28 GW of renewable sources were operational, while grid connection permits had been issued for an additional 48 GW, indicating that the grid would need to accommodate nearly 76 GW of renewable capacity—effectively tripling the existing renewable energy system (Sikorski, 2024). Separately, industry analysis by Arthur D.

Little (2025) reports that in 2024 alone, connection requests for approximately 74 GW of theoretical capacity, including roughly 42 GW from renewable energy sources, were declined—exceeding Poland's total installed system capacity of 72 GW. These figures demonstrate that grid connection applications substantially exceed transmission system capabilities, creating significant queuing challenges for project developers.

Uneven geographical RES distribution in Poland generates additional challenges for the transmission system, revealing a critical spatial mismatch between generation concentration areas and consumption centres. Wind energy capacity demonstrates strong geographical clustering, with the West Pomeranian Voivodeship hosting approximately 3200 MW of installed wind capacity, representing the country's largest concentration (Atmosfera, 2024). The neighbouring Pomeranian Voivodeship accounts for an additional 2600 MW, while the Warmian-Masurian Voivodeship in northeastern Poland contributes approximately 1800 MW of wind capacity (Rynek Elektryczny, 2025b; IEO, 2024). This pronounced northern concentration of wind resources results from favourable meteorological conditions in coastal and near-coastal regions but creates significant transmission challenges.

Photovoltaic capacity exhibits greater geographical diversification than wind, though still demonstrates regional clustering patterns. The Warmian-Masurian Voivodeship, in addition to its wind capacity, hosts significant solar installations totalling approximately 350 MW (IEO, 2024). The Greater Poland Voivodeship in west-central Poland accounts for approximately 480 MW of photovoltaic capacity across 34 farms, while the Lubusz Voivodeship in western Poland contributes an additional 290 MW (IEO, 2024; Agro-Rydz, 2025). The combined RES capacity concentration in northern and northwestern regions creates an asymmetric generation distribution relative to national consumption patterns.

Poland's major consumption centres demonstrate an inverse geographical distribution relative to generation concentration. Warsaw, located in the Masovian Voivodeship in central-eastern Poland, represents the country's largest demand centre with peak consumption exceeding 4500 MW. Kraków in southern Poland (Lesser Poland Voivodeship) accounts for approximately 2200 MW of peak demand, while Wrocław in southwestern Poland (Lower Silesian Voivodeship) represents 1800 MW. Additional significant consumption centres include Poznań (Greater Poland Voivodeship, 1400 MW) and Gdańsk (Pomeranian coast, 1100 MW). The geographical distribution reveals that four of the five largest consumption centres (Warsaw, Kraków, Wrocław, Poznań) are located in central and southern Poland, while the bulk of wind generation capacity is concentrated in northern coastal regions.

This north-south spatial asymmetry creates fundamental challenges for transmission system planning. Concentration of offshore wind farms—planned to reach 18 GW by 2034—and a significant portion of onshore wind installations in the northern region requires construction of extensive transmission infrastructure enabling energy transport to main consumption centres located in central and southern Poland (PSE, 2024). The transmission grid development plan calls for offshore wind power plant connections to stations in Choczewo,

Słupsk, and Krzemienica, requiring coordinated investments in transmission and distribution infrastructure (OffshoreWindPoland, 2025). The planned HVDC north-south connection, with capacity of approximately 2000 MW, represents a critical infrastructure investment designed to address this spatial mismatch, though construction timelines and capital requirements (estimated at PLN 8 billion for the HVDC component alone) present significant implementation challenges.

## 5. Comparative Analysis: Spain and Poland

Both the Spanish and Polish systems are characterised by high-RES capacity growth dynamics while simultaneously facing challenges regarding transmission infrastructure modernisation. Both countries face the challenge of uneven geographical distribution of RES relative to energy consumption centres. In Spain, photovoltaic and wind farm concentration in regions with high solar and wind potential requires long-distance energy transmission, as does Poland, where wind source concentration in the northern part of the country necessitates reinforcement of connections with central and southern regions.

A key difference between Spanish and Polish systems is the degree of energy isolation. The Iberian Peninsula is characterised by limited interconnection capacity with the rest of Europe, which in the case of the blackout prevented effective external assistance (ENTSO-E, 2025). The Polish power system is better integrated with the European continental grid, in principle increasing resilience to disruptions through mutual support from neighbouring systems (PSE, 2024).

Another important differentiating factor is the structure of the generation mix. Spain was characterised at the time of the failure by a higher RES share in the generation mix compared to Poland, where coal units still maintain a significant share. The latter, despite negative environmental impact, provide important system regulation capabilities, particularly for voltage and frequency control.

The Iberian Peninsula blackout provides three fundamental lessons for energy transition management in Poland:

First, the failure proved that the contemporary threat to system stability stems not from generation capacity deficit but from loss of control over power quality parameters – voltage and frequency – in environments with high VRE saturation. The Spanish case proved that traditional conventional units may be insufficient to maintain grid parameters within operational norms if not supported by appropriate operational procedures and regulation technologies.

Second, the incident demonstrated the necessity of active RES installation participation in providing ancillary services. Exclusion of renewable sources from voltage and frequency regulation processes, practiced in Spain before April 2025, proved to be a structural error that was corrected in the June amendment to procedure P.O. 7.4 (Red Eléctrica de España, 2025).

Third, the event emphasized the importance of cross-border resilience of power systems. The energy isolation of the Iberian Peninsula accelerated system destabilisation and hindered the power restoration process. For Poland, this means the necessity of maintaining and developing interconnections with neighbouring countries.

## **6. Recommendations for Energy Transition Management in Poland**

### **6.1. Regulatory Framework Modernization**

In response to lessons from the Iberian blackout, the Polish regulatory framework requires comprehensive updating with regard to technical requirements for RES installations. An amendment to grid regulations, as part of the so-called anti-blackout legislative package, should introduce mandatory ancillary service provision, including voltage regulation, by wind and photovoltaic farms (Gobierno de España, 2025). The Spanish experience shows that excluding RES from active participation in system stabilisation represents a fundamental gap in the power security architecture.

PSE S.A. should develop detailed technical requirements for new and existing RES installations regarding capabilities for:

- rapid active and reactive power regulation,
- grid voltage support,
- frequency regulation participation,
- fault ride-through capability.

### **6.2. Stabilizing Unit Maintenance Strategy**

Conclusions from the Spanish failure strengthen argumentation for maintaining in reserve a portion of coal blocks as voltage stabilizing units until full alternative solution implementation (Gobierno de España, 2025). Iberian experience proved that premature conventional unit phase-out can lead to loss of system regulatory capabilities, even with sufficient RES generation capacity.

The transitional strategy for Poland should identify the key conventional blocks of strategic significance for system stability, develop compensation mechanisms for maintaining these units in operational readiness, and establish the timeline and technical conditions that would allow their final shutdown once adequate alternative solutions have been deployed.

### **6.3. Energy Storage Infrastructure Development**

Large-scale energy storage is a key element of the system's defence against sudden grid parameter fluctuations (Gobierno de España, 2025). Given the high share of weather-dependent sources in Poland's generation mix, storage is of particular significance for absorbing production surpluses during periods of high RES output, providing voltage and frequency support, and maintaining power reserves during periods of low RES generation. The transmission grid development plan should account for the strategic placement of storage at critical network nodes, with priority given to offshore wind farm connection areas in Pomerania and regions of high photovoltaic density in central Poland.

### **6.4. Cross-border Resilience Building**

Accelerating the synchronisation and expansion of interconnection capacity with neighbouring countries is the cornerstone of avoiding the energy island effect, which in Spain's case accelerated system destabilisation (ENTSO-E, 2025). For Poland, the priority development directions are: strengthening interconnections with Germany to enable energy exchange with the western market; expanding interconnection capacity toward the Baltic states and Scandinavia; modernising interconnections with the Czech Republic and Slovakia; and developing new cross-border links, including prospective connections with Ukraine following its integration with the European power system.

### **6.5. RES Spatial Distribution Management**

Uneven geographical RES distribution in Poland requires spatial planning mechanisms that account for transmission infrastructure constraints. Concentration of renewable sources in specific regions generates local grid bottlenecks that may necessitate curtailment even in the absence of a national capacity deficit. Recommended actions include developing grid connection potential maps for individual RES technologies across different regions, introducing preferential mechanisms for projects located in areas with adequate transmission capacity, coordinating RES development plans with grid infrastructure investment schedules, and supporting distributed generation near major consumption centres to reduce the burden on the transmission system.

## **7. Conceptual Models of Energy Transition Management**

Both the ISSM and SETM models are designed for power systems where variable renewable energy (VRE) penetration exceeds approximately 30% of installed capacity, or is on a clear trajectory toward that threshold. Below this level, conventional synchronous

generation typically provides sufficient inertia and reactive power support to maintain stability without structured multi-pillar intervention. The Iberian Peninsula was operating at a VRE share of approximately 55-60% of instantaneous generation at the time of the April 2025 blackout (Red Eléctrica de España, 2025), illustrating the high-penetration context for which the models are intended. For Poland, RES installed capacity of 36.5 GW against a total system capacity of approximately 72 GW places it in the range where both models are already applicable. Their relevance increases as weather-dependent dispatch hours grow and VRE penetration rises further. The relative emphasis among ISSM pillars and the pace of SETM phase implementation should be calibrated to the current and projected VRE share, as summarised in Table 1.

### 7.1. Integrated System Stability Management Model (ISSM)

The Integrated System Stability Management Model (ISSM Model) is a comprehensive conceptual framework describing the key dimensions of power system stability management under conditions of high variable renewable energy (VRE) penetration. This model synthesizes lessons from the Iberian blackout with recommendations for the Polish energy system, identifying five key pillars of system stability.



**Figure 1.** Integrated System Stability Management Model (ISSM) structure.

Source: Authors' own elaboration using AI-based tools (Claude 4.5 Sonnet, Anthropic) and Mermaid software.

#### 7.1.1. Characteristics of ISSM Pillars

**Pillar 1: Technical Regulation** – This dimension is derived directly from the Iberian blackout finding that pre-event exclusion of wind and photovoltaic installations from voltage regulation services was a structural root cause of the cascade (Red Eléctrica de España, 2025). It covers the revision of legal and technical frameworks to enable active RES participation in ancillary services. Key elements include mandatory voltage regulation by wind and PV farms, technical requirements for grid-forming inverters, and market mechanisms that incentivise the provision of system services by renewable sources.

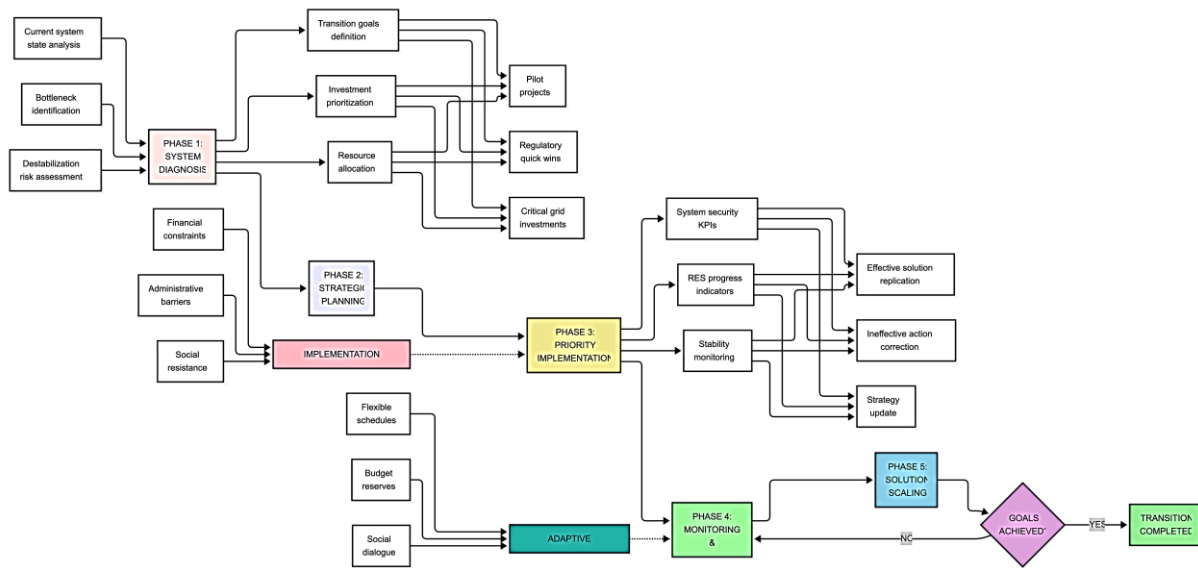
- Pillar 2: Grid Infrastructure – This dimension reflects the blackout lesson that transmission constraints amplify instability once voltage control deteriorates. It focuses on the physical expansion and modernisation of the transmission network. Priority actions include construction of 400 kV lines on the north-south axis, HVDC connections to transmit power from offshore wind farms, and modernisation of substations to handle bidirectional power flows.
- Pillar 3: Energy Storage – The Iberian event exposed how the absence of fast-response reactive power reserves accelerates voltage collapse once synchronous units begin tripping. This pillar addresses the need to develop electrical energy storage at various temporal and power scales: large-scale battery storage at critical network nodes, pumped-storage hydropower, and distributed storage at the distribution level.
- Pillar 4: Cross-border Integration – This dimension is drawn directly from the structural isolation factor of the Iberian Peninsula: the peninsula's historically low interconnection ratio (below the EU's 10% benchmark for many years) prevented effective external support once the cascade began, prolonging the outage (ENTSO-E, 2025). Key actions include increasing interconnection capacity with neighbouring countries, strengthening ENTSO-E cooperation mechanisms, and harmonising operational procedures for rapid emergency response.
- Pillar 5: Spatial Management – This pillar addresses the north-south generation-consumption mismatch in Poland, which mirrors the Spanish pattern of renewable concentration far from load centres. It focuses on optimising the geographical placement of new RES installations relative to transmission capacity. Actions include connection potential maps, preferential mechanisms for projects in grid-accessible areas, and coordination of RES development plans with infrastructure investment schedules.

### *7.1.2. Interaction Mechanisms Between Pillars*

The ISSM Model emphasizes synergistic relationships among individual pillars. Regulatory framework modernisation (Pillar 1) creates legal foundations for implementing technical solutions in other dimensions. Grid infrastructure development (Pillar 2) conditions the effective utilization of energy storage (Pillar 3) and determines cross-border connection capacity (Pillar 4). Spatial management (Pillar 5) influences requirements for all other pillars, optimizing the location of new sources relative to existing and planned infrastructure.

## **7.2. Strategic Energy Transition Management Model (SETM)**

The SETM Model describes the energy transition management process as a sequence of integrated stages, considering implementation challenges and adaptive mechanisms necessary to achieve strategic objectives while maintaining energy supply security.



**Figure 2.** Strategic Energy Transition Management Model (SETM) structure.

Source: Authors' own elaboration using AI-based tools (Claude 4.5 Sonnet, Anthropic) and Mermaid software.

### 7.2.1. Characteristics of SETM Phases

Phase 1: System Diagnosis – Informed by the Iberian experience, which revealed that prevent voltage control weaknesses went unaddressed, this phase requires comprehensive analysis of the current power system state. It covers identification of infrastructure bottlenecks and assessment of destabilisation risk under increasing VRE penetration. For Poland, this means mapping existing and planned RES installations relative to transmission capacity, identifying congestion-prone regions, and assessing regulatory capabilities.

Phase 2: Strategic Planning – Based on diagnostic results, energy transition goals are formulated within technical and financial constraints. Investment priorities are ranked by the criterion of maximising system security per unit of capital expenditure. For Poland, this directs attention toward grid integration of offshore wind farms (north-south HVDC line) and reinforcing critical nodes in high-RES concentration areas.

Phase 3: Priority Implementation – Action implementation focuses on pilot projects enabling verification of technical solutions, regulatory quick wins generating immediate system parameter improvements, and critical grid investments with highest priority for supply security. Spanish experience suggests starting with operational procedure amendments enabling RES participation in voltage regulation, which does not require significant capital expenditure but generates measurable stability improvement.

Phase 4: Monitoring and Adaptation – Continuous monitoring of key performance indicators (KPIs) enables early detection of deviations from assumed trajectories and introduction of corrections. Indicators cover technical parameters (frequency, voltage, line congestion), economic indicators (balancing costs, energy prices), and transition progress indicators (RES share in the generation mix, emissions reduction). The monitoring system

should contain early warning mechanisms for destabilisation risk, informed by lessons from the Iberian failure.

Phase 5: Solution Scaling – Solutions verified in pilot projects are replicated in other regions or system segments. Ineffective measures are corrected or removed. The transition strategy is updated based on accumulated experience through an iterative feedback loop to Phase 4, triggered whenever assumed goals are not met or significant deviations are detected.

#### *7.2.2. Implementation Barriers and Adaptive Mechanisms*

The SETM Model identifies three main categories of implementation barriers. Financial constraints arise because implementation of the Transmission Grid Development Plan requires expenditure exceeding PLN 64 billion, representing a significant challenge for the energy system; adaptive mechanisms include flexible investment schedules, technology optimisation, and diversification of financing sources (EU funds, public-private partnerships). Administrative barriers stem from the complexity of permitting procedures for transmission infrastructure, and can be addressed through streamlined decision-making processes, improved coordination across administrative levels, and dedicated procedural pathways for projects of strategic energy security significance. Social resistance to new transmission lines and large-scale RES installations can be mitigated through early-stage social dialogue, public education on the necessity of the energy transition, and mechanisms for local communities to share in the economic benefits of hosted infrastructure.

### **7.3. Model Application in Polish Energy Transition Context: Practical Implementation Scenarios**

Both conceptual models – ISSM and SETM – constitute complementary frameworks for energy transition management. The ISSM Model defines structural dimensions of system stability, while the SETM Model describes the procedural dimension of change implementation. Their integrated application in the Polish context requires:

#### *7.3.1. Temporal Synchronization Example*

##### **Scenario: Baltic Offshore Wind Integration (2025-2030)**

Applying ISSM Pillar 2 (Grid Infrastructure) in conjunction with SETM Phases 1-3:

- **Years 2025-2026 (SETM Phase 1: System Diagnosis):** PSE conducts a detailed analysis of existing transmission capacity from the Pomeranian coast to central Poland consumption centres. The assessment reveals that the current 220 kV infrastructure can transmit a maximum of 4 GW from the planned 18 GW of offshore capacity, identifying a critical bottleneck.
- **Years 2026-2027 (SETM Phase 2: Strategic Planning + ISSM Pillar 2 activation):** Prioritization determines that north-south HVDC line (2000 MW capacity, estimated cost PLN 8 billion) takes precedence over less critical grid reinforcements. Simultaneously, ISSM Pillar 1 (Technical Regulation) is activated: URE mandates that

all new offshore wind farms  $\geq 100$  MW must provide voltage regulation services (grid-forming capability).

- **Years 2027-2030 (SETM Phase 3: Priority Implementation):** HVDC line construction proceeds in parallel with regulatory enforcement. Pilot offshore wind farm (400 MW) at Choczewo demonstrates grid-forming capability, validating technical requirements before full-scale deployment.

This sequencing ensures that regulatory framework (ISSM Pillar 1) and infrastructure development (ISSM Pillar 2) advance synchronously, preventing situations where either advanced infrastructure lacks compatible sources or vice versa.

### 7.3.2. Institutional Coordination Framework

#### Multi-stakeholder Implementation Structure

Implementation of both models requires coordinated action across multiple institutional levels:

- **Strategic Level:** Ministry of Climate and Environment sets policy direction aligned with SETM Phase 2 (goal definition: 30% VRE by 2030, 50% by 2035).
- **Regulatory Level:** URE translates policy into technical requirements (ISSM Pillar 1), establishing mandatory ancillary service provision for RES installations  $>5$  MW effective January 2027.
- **Operational Level:** PSE implements ISSM Pillars 2-4 through transmission development plan execution, storage procurement, and interconnector enhancement. Monthly coordination meetings with URE ensure SETM Phase 4 (Monitoring) feedback informs ongoing ISSM Pillar implementation.
- **Market Level:** Distribution system operators (DSOs) coordinate with PSE on ISSM Pillar 5 (Spatial Management), rejecting connection applications in grid-constrained areas while incentivizing developments in zones with available capacity.
- **Stakeholder Level:** RES developers receive transparent connection potential maps (ISSM Pillar 5 output) updated quarterly, enabling informed investment decisions and reducing speculative applications that overwhelm system capacity.

### 7.3.3. Adaptive Flexibility: Response to Implementation Deviations

#### Example: Budget Constraint Scenario (Hypothetical)

Suppose in 2028, national fiscal constraints reduce available transmission investment budget by 30%. Adaptive flexibility mechanisms include:

- **SETM adaptation:** Extend Phase 3 (Priority Implementation) timeline from 3 years to 5 years, maintaining critical HVDC line but deferring less essential 400 kV reinforcements.
- **ISSM Pillar rebalancing:** Increase emphasis on Pillar 3 (Energy Storage) and Pillar 5 (Spatial Management) as partial substitutes for delayed Pillar 2 (Infrastructure). Procure 1 GW battery storage at strategic Pomeranian substations (lower capital cost than transmission construction) to buffer offshore wind variability. Simultaneously

strengthen Pillar 5 enforcement: temporarily suspend new RES connections in northern Poland, redirect development to central regions closer to consumption.

- **SETM Phase 4 (Monitoring) trigger:** KPI tracking detects growing north-south congestion. System activates adaptive mechanism: PSE negotiates accelerated HVDC completion with EU co-financing (Innovation Fund), restoring original timeline by 2029.

This example illustrates how SETM's iterative structure (Phase 4 feedback to Phase 2 planning) enables dynamic rebalancing of ISSM pillars in response to implementation realities.

#### 7.3.4. Timeline-Based Integration Roadmap (2025-2034)

**Table 1.**

*Phase-Pillar Integration Schedule*

Period	SETM Phase	Active ISSM Pillars	Key Deliverables
2025-2026	Phase 1: Diagnosis	Pillar 5 (Spatial)	Connection potential maps, bottleneck identification
2026-2027	Phase 2: Planning	Pillars 1, 2 (Regulation, Infrastructure)	Updated grid code, HVDC line contract award
2027-2030	Phase 3: Implementation	Pillars 1, 2, 3 (+ Storage)	Regulatory enforcement, HVDC construction, 2 GW storage deployment
2030-2032	Phase 4: Monitoring	All Pillars	KPI dashboard operational, first deviation corrections
2032-2034	Phase 5: Scaling	Pillars 2, 3, 4 (Infrastructure, Storage, Cross-border)	Replicate successful models to other regions, enhance interconnections

Source: Own study.

This roadmap demonstrates that model application is not static but evolves across the transition timeline, with different ISSM pillars gaining prominence as corresponding SETM phases activate.

## 8. Implementation Challenges and Barriers

Implementation of the Transmission Grid Development Plan requires expenditure exceeding PLN 64 billion by 2034 (PSE, 2024), representing a significant burden for the energy system and ultimately for end consumers. These costs must be distributed over time and optimised through prioritisation of investments of greatest significance for system security.

The complexity of administrative procedures related to transmission infrastructure construction is a significant barrier to timely investment implementation. According to the European Union Agency for the Cooperation of Energy Regulators (ACER), in 2024 over 60 percent of major transmission infrastructure projects in Europe were delayed relative to their planned commissioning dates, perpetuating reliance on expensive interim congestion management measures (ACER, 2024). Poland is no exception to this trend, requiring

streamlining of decision-making processes and increased coordination among different administration levels.

Construction of new transmission lines and location of large-scale RES installations often encounters resistance from local communities. Energy transition management therefore requires parallel conduct of educational and consultative actions, ensuring understanding and acceptance of necessary infrastructure investments.

## 9. Summary and Conclusions

The April 28, 2025 Iberian Peninsula blackout marks a turning point in European power system history, revealing a new category of threats related to high renewable energy source share integration. This incident provides valuable lessons for Poland, a country implementing ambitious energy transition amid a growing VRE share in the generation mix.

Key conclusions from the analysis include:

Five conclusions emerge from the analysis. First, the Iberian blackout confirms a paradigm shift in energy security: the contemporary threat to system stability stems not from generation capacity deficit but from loss of control over power quality parameters in environments dominated by variable-output sources. Second, excluding renewable installations from voltage and frequency regulation processes represents a fundamental gap in the power security architecture that must be addressed immediately through appropriate regulations and technical requirements. Third, grid expansion must be synchronised with RES capacity growth, with particular attention to strengthening transmission corridors between regions of high renewable concentration and major consumption centres. Fourth, the Iberian case demonstrates that premature phase-out of conventional units can erode system regulation capabilities; a transitional strategy should therefore identify key blocks to be maintained in operational readiness until alternative solutions are fully deployed. Fifth, large-scale energy storage is a critical infrastructure element required to absorb VRE output fluctuations and support system stability.

Energy transition management in Poland requires a holistic approach accounting for not only technical and economic aspects but also social and regulatory dimensions. Spanish experience proves that transition success depends on the ability to anticipate and proactively address systemic challenges before they translate into crisis events threatening energy supply security.

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