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Resilience-oriented energy market design: Adapting forecasting and decision systems to increasing uncertainty

Jonathan Boateng *

University of North Dakota.

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Abstract

The ongoing shift to renewable-dominated and decentralized energy systems has created significant operational and market uncertainty, calling established electricity market structures and forecasting methodologies into question. Increasing renewable energy penetration, climate-related disruptions, demand fluctuation, and the expanding participation of dispersed energy resources have highlighted the need for more adaptable and resilient market structures. Conventional market designs, which are mostly built on deterministic assumptions, frequently fail to adjust effectively to changing situations. This study examines the role of resilience-oriented energy market design in enhancing forecasting and operational decision-making under increasing uncertainty. Drawing on existing literature on electricity market design, uncertainty management, forecasting systems, and power system resilience, the study analyzes the limitations of conventional market structures and explores strategies for improving market adaptability. The analysis identifies flexibility, adaptability, redundancy, and real-time responsiveness as core principles of resilient electricity markets. It further highlights the importance of adaptive forecasting, probabilistic decision-making, dynamic reserve management, demand response, energy storage integration, and coordinated resilience planning. A conceptual framework is proposed that integrates forecasting intelligence, risk-aware market operations, flexible resource coordination, and resilience governance. The study concludes that closer coordination between forecasting systems and operational decision-making can strengthen uncertainty management, improve market responsiveness, and enhance overall system reliability. Resilience-oriented market design is therefore essential for supporting secure, efficient, and sustainable electricity markets amid increasing operational complexity and uncertainty.

Keywords: Resilience-oriented energy markets; Electricity market design; Adaptive forecasting; Energy system resilience; Uncertainty management

1. Introduction

As power systems move from centralized fossil fuel-based generation to cleaner, more decentralized energy architectures, electricity markets around the world are changing dramatically. Decarbonization policies, technical advancements, electrification programs, and the growing use of renewable energy sources like solar and wind power are the main forces behind this shift. Modern energy systems are increasingly defined by variability, dispersed generation, and digitalized operating environments, whereas traditional electricity markets were initially built around predictable and controllable generation systems. According to Mentens et al. (2025) and Haugen et al. (2023), energy market operators are now confronted with increasing difficulties in striking a balance between operational flexibility, affordability, and reliability in the face of extreme uncertainty.

The operational dynamics of electricity markets have been drastically changed by the quick incorporation of renewable energy. Renewable energy sources present serious forecasting and balancing issues since they are weather-dependent

* Corresponding author: Jonathan Boateng

and intrinsically unpredictable, in contrast to traditional thermal generation. Recent research shows that reserve requirements, real-time system stability, and power prices can all be significantly impacted by the uncertainty around renewable generation. Weber & Woerman (2024) discovered that the operational and economic effects of renewable prediction uncertainty on power markets are greater than those of intermittency alone, leading to higher balancing costs and conventional generator start-ups. Similarly, modern power systems are becoming increasingly weather-dependent, thereby elevating the level and severity of uncertainty in operational planning and market forecasting (Fan et al., 2022; Mentens et al., 2025; Haugen et al., 2023).

Apart from the intermittent nature of renewable energy, electricity markets are more vulnerable to several types of uncertainty resulting from climate change, cyber-physical risks, geopolitical instability, changing demand patterns, and decentralized energy involvement. Operational hazards in both day-ahead and real-time electricity markets have increased due to extreme weather, volatile fuel prices, transmission bottlenecks, and quickly shifting patterns of electricity demand. High renewable penetration has been linked to severe price volatility, negative pricing events, and higher curtailment of renewable power due to inadequate storage and grid flexibility, according to recent data from European electricity systems (Maguire, 2026). These discoveries show that in increasingly uncertain energy contexts, traditional market processes may no longer be adequate to sustain resilient and efficient system operation.

As a result, resilience-oriented operational frameworks that can adjust to unpredictable and quickly changing system conditions are becoming more important to players in the energy market. By highlighting the capacity of market and operational systems to foresee, absorb, adapt to, and recover from crises, resilience in energy markets goes beyond conventional dependability issues. Modern resilience-oriented approaches increasingly incorporate probabilistic forecasting, adaptive optimization, artificial intelligence, and flexible market coordination mechanisms to improve decision-making under uncertainty. Recent research highlights the growing importance of AI-driven forecasting systems, stochastic market clearing, and flexible short-term electricity markets in improving grid stability and operational responsiveness (Basaran et at., 2026; Mentens et al., 2025; Zhao et al., 2023; Zhang et al., 2025).

Many current market structures and forecasting techniques are still largely reliant on deterministic operating assumptions, which are inadequate for handling the increasing complexity and uncertainty of contemporary energy systems, despite continuous improvements in the modernization of the electrical market. Conventional forecasting models often struggle to accurately capture renewable variability, demand uncertainty, and extreme market events, leading to inefficient dispatch decisions, higher balancing costs, market volatility, and increased reliability risks (O'Connor et al., 2026; Haugen et al., 2023).

Most traditional electricity market frameworks were created for systems with somewhat predictable demand patterns and dispatchable fossil fuel generation. However, more flexible operational procedures that can react quickly to unpredictable system conditions are needed to increase the penetration of renewable energy sources and distributed energy participation. In many energy markets, current market-clearing strategies are still primarily deterministic and may not be able to effectively coordinate day-ahead and real-time operations in the face of unpredictable renewable generation conditions (Zhao et al., 2023; Zhang et al., 2025). Additionally, several studies have found that operational decision-making frameworks and forecasting systems are not sufficiently integrated, which limits the efficacy of existing resilience measures (Fan et al., 2022; Haugen et al., 2023).

Resilience-oriented energy market designs that incorporate adaptive forecasting, probabilistic decision systems, flexible resource coordination, and real-time operational responsiveness are desperately needed as uncertainty in contemporary power systems continues to rise. In the absence of such enhancements, electrical markets may experience increased operational instability, ineffective resource allocation, growing expenses, and diminished energy security during times of system breakdown and market stress.

The purpose of this study is to investigate how resilience-oriented energy market design might enhance operational decision-making and forecasting in the face of growing uncertainty. In particular, the research aims to:

- Examine the major drivers of uncertainty affecting modern electricity markets, including renewable energy variability, climate-related disruptions, demand fluctuations, and operational risks.
- Analyze the limitations of existing forecasting and market decision systems in managing uncertainty within modern electricity markets.
- Explore resilience-oriented market design approaches capable of enhancing operational flexibility, adaptive forecasting, and real-time market responsiveness.
- Investigate the role of probabilistic forecasting, artificial intelligence, and flexible market coordination in strengthening electricity market resilience.

This study is significant because it will help modern energy markets become more resilient, reliable, and adaptable in the face of increasingly unpredictable operating conditions. Policymakers, market operators, and energy stakeholders are increasingly concerned about sustaining grid dependability and operational stability as global power systems continue to shift toward low-carbon and renewable-dominated energy frameworks. The development of more resilient and adaptive market mechanisms that can support secure system operation is necessary due to the growing uncertainty surrounding renewable integration, climate unpredictability, and market volatility (Mentens et al., 2025; Yazdanie et al., 2025; Colback, 2025).

Additionally, this study has significance because sustainable energy transitions and long-term energy security depend on robust electricity markets. Market structures that are adaptable and flexible can raise the capacity of electricity systems to recover from disturbances, improve system balancing, lower operational risks, and improve the incorporation of renewable energy sources. Furthermore, by facilitating accurate market coordination and resource allocation under uncertain circumstances, resilience-oriented forecasting and decision systems can enhance operational efficiency (Basaran et al., 2026; Renkema et al., 2024; Ghasemi et al., 2023).

Additionally, by highlighting the significance of incorporating forecasting intelligence, flexibility mechanisms, and resilience principles into future market design frameworks, the study adds to the continuing conversations on modernizing the energy market. Energy regulators, system operators, legislators, and researchers looking to create more resilient and adaptable electricity market systems that may support future energy transition goals may find the findings to be useful.

2. Literature Review

2.1. Energy Market Design and Operational Structure

Modern electricity markets are structured to coordinate electricity generation, transmission, and consumption while ensuring reliability and economic efficiency. Most liberalized electricity systems operate through interconnected market layers that include day-ahead markets, real-time or balancing markets, and ancillary service markets. These market structures were initially developed around centralized fossil-fuel-based generation systems characterized by predictable output and relatively stable demand patterns. However, the rapid growth of renewable energy resources and decentralized generation has significantly transformed market operational requirements (Bublitz et al., 2019; Silva-Rodriguez et al., 2022).

Day-ahead markets represent the primary mechanism through which electricity is traded before actual delivery. In these markets, generators submit bids based on expected production costs and demand forecasts, while system operators determine market-clearing prices using economic dispatch principles. Real-time markets subsequently balance deviations between scheduled and actual electricity generation and consumption, often through security-constrained economic dispatch models. Ancillary service markets support grid reliability by procuring services such as frequency regulation, spinning reserves, voltage support, and ramping capability. These services are increasingly important in systems with high renewable penetration because renewable generation introduces operational variability and uncertainty (Oureilidis et al., 2020; Gulotta et al., 2023).

Economic dispatch mechanisms are central to electricity market operations because they determine how available generation resources are allocated to meet system demand at minimum cost while respecting operational constraints. Traditional dispatch systems are largely deterministic and assume relatively predictable system conditions. However, several studies have shown that deterministic dispatch frameworks may be inadequate for handling the uncertainty introduced by renewable energy sources. Zhao et al. argued that deterministic security-constrained economic dispatch models used in many real-time electricity markets struggle to manage renewable variability efficiently, leading to increased balancing costs and operational inefficiencies (Zhao et al., 2023).

The integration of distributed energy resources, energy storage systems, and demand-side participation is also reshaping electricity market structures. Oureilidis et al. observed that the growing penetration of distributed renewable energy resources requires substantial redesign of ancillary service markets because traditional synchronous generators are gradually being replaced by converter-based renewable systems that do not inherently provide conventional stability services (Oureilidis et al., 2020). Consequently, modern electricity market design increasingly emphasizes flexibility, short-term balancing capability, and decentralized operational coordination.

Recent studies further indicate that short-term electricity markets are becoming critical instruments for renewable integration and uncertainty mitigation. Flexible intraday and balancing markets enable market participants to adjust generation schedules closer to real-time operations, thereby reducing forecast errors and improving system responsiveness (Mentens et al., 2025; Silva-Rodriguez et al., 2022).

2.2. Uncertainty in Modern Energy Systems

Uncertainty has become one of the defining characteristics of modern electricity systems due to the increasing penetration of renewable energy, climate variability, decentralized generation, and evolving electricity consumption patterns. Unlike conventional thermal generators, renewable energy resources such as wind and solar are highly dependent on weather conditions, making their output variable and difficult to predict accurately. This intermittency introduces operational challenges related to balancing supply and demand, maintaining frequency stability, and ensuring sufficient reserve capacity (Haugen et al., 2023; Hu et al., 2018).

Several studies have identified renewable intermittency as a major source of uncertainty in electricity markets. Haugen et al. emphasized that increasing weather dependency in renewable-dominated power systems significantly elevates operational uncertainty and economic risk within electricity markets (Haugen et al., 2023). Similarly, Hu et al. highlighted that the integration of variable renewable electricity introduces additional system costs associated with flexibility requirements, reserve procurement, transmission congestion, and balancing operations (Hu et al., 2018).

Climate-related disruptions have also intensified uncertainty in modern energy systems. Extreme weather events such as heatwaves, storms, floods, droughts, and wildfires can disrupt electricity generation, damage transmission infrastructure, and create sudden fluctuations in electricity demand. These disruptions challenge conventional operational planning models that were developed under assumptions of relatively stable climatic conditions. Recent literature increasingly emphasizes the importance of climate-resilient operational strategies capable of responding to severe and unpredictable disturbances (Zhu et al., 2025; Haugen et al., 2023).

Demand variability represents another major source of uncertainty. Electrification of transportation, increasing adoption of electric vehicles, smart appliances, and distributed energy systems have altered traditional electricity demand patterns. Furthermore, demand response participation introduces additional uncertainty because consumer responses to pricing signals and operational incentives may vary considerably across time and regions. Ming et al. demonstrated that uncertainty associated with demand response providers can significantly affect day-ahead electricity market clearing and operational reliability (Ming, 2017).

The growing penetration of decentralized and distributed energy resources further complicates electricity market operations. Distributed solar generation, microgrids, battery storage systems, and prosumers have increased bidirectional electricity flows within distribution networks, thereby reducing the effectiveness of traditional centralized operational models. Gulotta et al. noted that decentralized electricity systems require new coordination mechanisms capable of integrating distributed energy resources into balancing and ancillary service markets (Gulotta et at., 2023).

Overall, modern electricity markets are increasingly characterized by multidimensional uncertainty involving weather conditions, market behavior, fuel prices, demand patterns, and infrastructure vulnerabilities. Existing operational frameworks often struggle to represent these uncertainties comprehensively, thereby motivating the need for more adaptive and resilience-oriented market designs (Morales & Pindas, 2017; Haugen et al., 2023).

2.3. Forecasting and Decision Systems

Forecasting systems play a central role in electricity market operations because market clearing, generation scheduling, reserve allocation, and system balancing all depend heavily on accurate predictions of electricity demand, renewable generation, and market prices. Traditional forecasting approaches relied primarily on statistical and deterministic models that assumed relatively stable system conditions. However, increasing renewable penetration and operational uncertainty have significantly reduced the effectiveness of conventional forecasting techniques (Haugen et al., 2023; Mentens et al., 2025).

Load forecasting remains one of the most important operational tools in electricity markets. Short-term load forecasting supports day-ahead market scheduling and unit commitment decisions, while long-term forecasting informs infrastructure planning and investment decisions. Renewable energy forecasting has become increasingly important because wind and solar generation exhibit substantial variability across different temporal and spatial scales. Forecast errors associated with renewable generation can lead to market imbalances, increased reserve procurement, and higher balancing costs (Zhu et al., 2025; Haugen et al., 2023).

To address these challenges, recent studies have explored artificial intelligence and probabilistic forecasting techniques. Machine learning methods, including neural networks, reinforcement learning, support vector machines, and hybrid forecasting frameworks, are increasingly used to improve forecasting accuracy under uncertain conditions. Ghasemi et al. demonstrated that integrated reinforcement learning and time-series forecasting approaches can improve uncertainty management for wind and distributed photovoltaic systems (Ghasemi et al., 2023).

Probabilistic forecasting approaches have gained significant attention because they provide uncertainty ranges rather than single deterministic predictions, thereby enabling more informed operational and market decisions under uncertainty. Renkema et al. demonstrated that probabilistic forecasting methods based on conformal prediction can improve stochastic decision-making for photovoltaic power participation in day-ahead electricity markets by enhancing bidding strategies and reducing market imbalance risk (Renkema et al. 2024).

Decision-support systems are also evolving to accommodate increasing operational uncertainty. Conventional market-clearing approaches often separate day-ahead and real-time operational decisions, which may lead to inefficient dispatch outcomes under uncertain renewable generation conditions. Morales and Pineda showed that stochastic market-clearing frameworks that co-optimize forward and balancing markets can significantly improve operational efficiency compared to deterministic merit-order dispatch systems (Morales & Pindas, 2017).

Recent studies further suggest that stochastic and adaptive dispatch systems may become essential components of future electricity markets. Zhao et al. demonstrated that stochastic look-ahead dispatch frameworks can improve real-time electricity market clearing efficiency and provide better uncertainty management than traditional deterministic dispatch approaches (Zhao et al., 2023). Consequently, modern electricity market research increasingly emphasizes integrated forecasting and decision systems capable of supporting flexible, adaptive, and risk-aware market operations.

2.4. Resilience in Energy Markets

The concept of resilience has become increasingly important in electricity market research due to growing concerns regarding operational reliability, climate-related disruptions, cyber-physical threats, and renewable integration challenges. Resilience generally refers to the ability of a system to anticipate, absorb, adapt to, and recover from disturbances while maintaining essential operational functionality. In electricity markets, resilience extends beyond conventional reliability concepts by emphasizing adaptive operational capability under uncertain and rapidly changing conditions (Zhu et al., 2025).

Several dimensions of resilience have been discussed in modern energy system literature, including technical, operational, economic, and institutional resilience. Technical resilience generally refers to the ability of electricity infrastructure to withstand and recover from physical disruptions, while operational resilience concerns the capability of system operators and control mechanisms to maintain reliable system functionality during disturbances. Economic resilience relates to the capacity of energy systems and markets to minimize economic losses and sustain efficient resource allocation under disruptive conditions. Institutional resilience involves governance coordination, regulatory adaptability, stakeholder collaboration, and organizational capacity to support effective resilience planning and recovery processes (Lee et al., 2019; Gasser et al., 2021, Rehak et al. 2022)

Existing resilience-oriented operational strategies increasingly emphasize flexibility, decentralization, and adaptive market coordination. Short-term electricity markets, flexibility services, distributed energy resource participation, and advanced reserve mechanisms are widely recognized as important tools for improving resilience in renewable-dominated systems. Recent studies indicate that flexibility-oriented market designs can reduce balancing uncertainty and improve renewable integration efficiency (Granado et al., 2021; Mentens et al., 2025)

The integration of distributed energy resources into ancillary service markets also contributes to system resilience by diversifying operational support resources and reducing dependence on centralized generation systems. Gulotta et al. observed that distributed energy resources are expected to play a growing role in frequency regulation, balancing services, and reserve provision within future electricity markets (Gulotta et al., 2023).

Artificial intelligence, probabilistic forecasting, and adaptive optimization techniques are also emerging as important resilience-enhancing tools. Zhu et al. emphasized that future electricity markets with high renewable penetration will require advanced simulation and adaptive decision systems capable of responding dynamically to uncertainty and market volatility (Zhu et al., 2025).

2.5. Research Gap

Despite substantial progress in electricity market modernization, important research gaps remain regarding the integration of resilience principles into market design and operational decision-making frameworks. Existing electricity markets continue to rely heavily on deterministic operational assumptions that may not adequately represent multidimensional uncertainty associated with renewable integration, climate disruptions, decentralized generation, and demand variability. Haugen et al. noted that most existing power market models still use deterministic approaches despite increasing recognition of uncertainty-related operational risks (Haugen et al., 2023).

Furthermore, the coordination between forecasting systems and operational decision-making remains insufficient in many electricity market structures. Although advanced forecasting methods have improved prediction accuracy, these forecasting outputs are often not fully integrated into market-clearing and dispatch optimization processes. This weak coordination reduces the effectiveness of uncertainty management and limits operational adaptability under rapidly changing system conditions (Zhao et al., 2023; Morales & Pindas, 2017).

Another major gap concerns the limited incorporation of resilience metrics into electricity market evaluation frameworks. Most existing market designs prioritize economic efficiency and short-term cost minimization while paying comparatively less attention to adaptive capability, recovery performance, and operational flexibility during disruptions. As renewable penetration continues to increase, market structures that focus solely on efficiency may become increasingly vulnerable to operational instability and market volatility (Bublitz et al., 2019; Silva-Rodriguez et al., 2022).

Additionally, although several studies have explored flexibility markets, stochastic dispatch systems, and ancillary service reforms, there remains limited research on integrated resilience-oriented market architectures that combine adaptive forecasting, probabilistic operational planning, decentralized resource coordination, and real-time market responsiveness within a unified framework. Existing literature often examines these components separately rather than as interconnected elements of a broader resilience-oriented market design strategy (Mentens et al., 2025; Zhu et al., 2025; Granado et al., 2023).

Therefore, further research is needed to develop comprehensive resilience-oriented electricity market frameworks capable of integrating uncertainty-aware forecasting systems, adaptive operational decision-making, and flexible market coordination mechanisms to support reliable and secure electricity system operation under increasingly uncertain conditions.

3. Resilience-Oriented Market Design Framework

3.1. Principles of Resilient Energy Markets

The importance of resilience-oriented market designs that can withstand dependable and effective operations in the face of disruptions has increased due to the growing complexity and uncertainty of modern electrical systems. The main goal of traditional electricity market arrangements was to maximize economic efficiency in comparatively stable operating conditions. Efficiency-oriented markets alone, however, might not be enough to guarantee long-term operational stability and system adaptability, as seen by the swift expansion of renewable energy integration, decentralized energy resources, and climate-related disturbances. As a result, resilience is being emphasized more in recent energy market research as a fundamental element of future electricity market design (Zhu et al., 2025).

Flexibility is a key component of robust energy markets. The ability of electrical systems to react quickly to changes in supply and demand while preserving operational stability is referred to as flexibility. Through mechanisms like short-term balancing markets, demand response programs, fast-ramping generation, and energy storage participation, flexible market structures facilitate the integration of fluctuating renewable energy resources. To sustain system reliability in low-carbon energy systems and manage uncertainty related to renewable intermittency, Ulbig and Andersson contend that operational flexibility is crucial (Ulbig & Andersson, 2015).

Adaptability also represents a critical component of resilient electricity markets. Adaptive market systems continuously adjust operational strategies, pricing signals, and resource coordination mechanisms in response to changing system conditions. Adaptive electricity markets rely increasingly on advanced forecasting systems, digital monitoring infrastructure, and automated optimization tools to support dynamic operational decision-making. Panteli and Mancarella emphasized that resilient power systems require adaptive operational capability that allows electricity networks and market operators to anticipate, absorb, and recover from disturbances effectively (Panteli & Mancarella, 2015).

Redundancy, or the availability of alternate operational resources and backup equipment that can maintain system reliability during disturbances or component failures, is another crucial component of resilient energy systems. Reserve generation capacity, dispersed energy resources, backup transmission pathways, and energy storage devices that offer extra operational support during disturbances are examples of redundancies. Resilience research indicates that well-designed redundancy can improve the capacity of electrical systems to withstand disruptions, maintain essential functionality, and recover more successfully from extreme events, even though maintaining redundant resources may increase infrastructure and operating costs (Watson et al., 2014; National Academies of Sciences et al., 2017; Panteli & Mancarella, 2015).

The importance of real-time response in resilient electricity markets is becoming more widely acknowledged. Because electricity demand and renewable energy generation fluctuate so quickly, modern power systems need constant operational coordination. The ability of market mechanisms and system operators to identify operational disruptions and quickly take corrective action to preserve system stability and balance is known as real-time responsiveness. In order to improve operational responsiveness and system management under uncertainty, many electricity market regions are gradually implementing shorter dispatch intervals, real-time balancing markets, and sophisticated grid monitoring technologies (Fang et al., 2011; Ela et al., 2011).

Collectively, flexibility, adaptability, redundancy, and real-time responsiveness form the operational foundation of resilience-oriented electricity market design. These principles enable electricity systems to manage multidimensional uncertainty while supporting reliable and efficient market operations under increasingly dynamic conditions.

3.2. Adaptive Forecasting Systems

Forecasting systems are fundamental components of modern electricity markets because generation scheduling, market clearing, reserve procurement, and operational planning all depend heavily on accurate predictions of electricity demand, renewable generation, and market conditions. However, increasing uncertainty associated with renewable integration and decentralized energy participation has reduced the effectiveness of conventional deterministic forecasting methods. As a result, adaptive forecasting systems capable of continuously responding to changing operational conditions are becoming increasingly important in resilience-oriented market frameworks (Haugen et al., 2023).

Probabilistic forecasting approaches have gained substantial attention because they provide uncertainty ranges and probability distributions rather than single deterministic predictions. These methods improve operational awareness by allowing system operators to evaluate forecast uncertainty and associated operational risks more effectively. In electricity markets, probabilistic forecasting is increasingly applied to renewable energy forecasting, electricity price forecasting, and reserve requirement estimation. Renkema et al. demonstrated that conformal prediction techniques improved stochastic decision-making for photovoltaic participation in electricity markets by reducing imbalance risks and improving bidding strategies under uncertainty (Renkema et al. 2024).

Artificial intelligence and machine learning methods are also transforming forecasting systems within modern electricity markets. Neural networks, reinforcement learning algorithms, deep learning architectures, and hybrid forecasting frameworks are increasingly used to improve predictive performance under highly variable system conditions. Ghasemi et al. showed that integrated reinforcement learning and time-series forecasting methods can improve uncertainty management for wind and distributed photovoltaic generation systems (Ghasemi et al., 2023).

Real-time data integration is another major feature of adaptive forecasting systems. The expansion of smart grids, advanced metering infrastructure, and Internet of Things (IoT)-enabled devices has increased the availability of high-frequency operational data. Real-time monitoring systems provide continuous information regarding electricity demand, renewable generation output, grid frequency, and market conditions, thereby improving situational awareness and operational forecasting accuracy. According to Fang et al., smart grid technologies significantly enhance operational visibility and support more responsive forecasting and control systems within modern electricity networks (Fang et al., 2011).

Continuous forecast updating further improves the resilience of electricity market operations. Unlike static forecasting systems that rely on periodic updates, adaptive forecasting models continuously revise predictions based on incoming operational data and evolving market conditions. Dynamic forecasting approaches are particularly valuable in systems with high renewable penetration because weather conditions and electricity demand patterns can change rapidly over short time intervals. Haugen et al. emphasized that operational planning in renewable-dominated electricity systems increasingly depends on dynamic uncertainty representation and continuously updated forecasting models (Haugen et al., 2023).

Overall, adaptive forecasting systems strengthen electricity market resilience by improving uncertainty awareness, operational responsiveness, and decision-making accuracy under volatile system conditions.

3.3. Resilient Decision Systems

Decision systems that can handle uncertainty while preserving system flexibility, operational dependability, and economic efficiency are necessary for resilient electricity markets. Traditional deterministic dispatch and scheduling methods frequently make the assumption that predicting uncertainty is low and operating circumstances are steady. However, the shortcomings of traditional operational decision frameworks have been shown by rising renewable penetration and market instability. As a result, risk-aware and adaptive decision systems that can support resilient energy market operations are becoming increasingly important in recent study (Zhao et al., 2023).

In today's electricity market, risk-aware dispatch and scheduling mechanisms are becoming indispensable. These systems lower operational risk and increase system reliability by incorporating uncertainty estimates into reserve allocation and dispatch optimization decisions. The application of robust optimization approaches, scenario-based operational planning frameworks, and stochastic economic dispatch models to control forecasting uncertainty and renewable variability is growing. Under unpredictable renewable generation conditions, Morales and Pineda showed how stochastic market-clearing mechanisms that co-optimize day-ahead and balancing markets may reduce balancing costs and improve operational efficiency (Morales & Pindas, 2017).

Dynamic reserve management also plays a major role in resilience-oriented electricity market design. Reserve requirements traditionally relied on fixed operational assumptions; however, renewable-dominated systems require more adaptive reserve allocation strategies capable of responding to changing operational risks. Dynamic reserve management systems continuously adjust reserve procurement based on renewable forecast uncertainty, system conditions, and real-time operational risk indicators. According to Ela et al., flexibility-oriented reserve management is increasingly necessary for maintaining operational reliability in electricity systems with high levels of renewable energy integration (Ela et al., 2011).

Demand response and energy storage integration are also important components of resilient decision systems. Demand response programs allow electricity consumers to modify consumption patterns in response to market signals or operational conditions, thereby improving balancing capability and reducing peak demand pressure. Energy storage systems provide operational flexibility by storing excess electricity generation and supplying electricity during periods of system stress or renewable generation shortfalls. Denholm et al. noted that energy storage technologies significantly enhance system flexibility and support renewable integration within modern electricity markets (Denholm et al., 2010).

By diversifying operational support resources and lowering reliance on centralized generation systems, the integration of distributed energy resources into market operations enhances resilience further. Electricity markets can react to operational disturbances and uncertainty more successfully when dispersed generation, storage systems, and responsive demand resources are coordinated flexibly. As a result, adaptive optimization frameworks that can support dynamic electricity market operations and decentralized coordination mechanisms are becoming more and more important in robust decision systems.

3.4. Integrated Market Coordination

The significance of integrated coordination between forecasting systems, operational decision-making frameworks, and resilience planning mechanisms has been brought to light by the increasing complexity of modern electricity systems. The separate management of forecasting, scheduling, reserve purchase, and balancing operations in many conventional electricity markets can hinder adaptation under unpredictable system situations and lower operational efficiency. The necessity of integrated market coordination frameworks that can connect operational decision-making, resilience management, and forecasting intelligence is being emphasized more and more in recent research (Haugen et al., 2023).

Integrated market coordination involves continuous interaction between forecasting systems, market-clearing mechanisms, reserve allocation processes, and operational resilience strategies. Forecasting systems provide uncertainty estimates regarding renewable generation, electricity demand, and market conditions, while operational decision systems use this information to optimize dispatch schedules, reserve procurement, and balancing operations.

Resilience planning mechanisms subsequently evaluate system vulnerability, operational flexibility, and recovery capability under different disruption scenarios. Zhao et al. argued that coordinated stochastic dispatch frameworks can improve real-time market efficiency by integrating uncertainty-aware forecasting directly into operational decision-making processes (Zhao et al., 2023).

Within a resilience-oriented market design framework, adaptive forecasting systems continuously provide updated uncertainty information to operational control systems. Market operators then use this information to implement dynamic dispatch decisions, activate demand response resources, allocate reserves, and coordinate distributed energy resources. Real-time monitoring infrastructure supports continuous feedback between operational conditions and forecasting models, thereby enabling continuous system adaptation under changing market conditions.

As a result, the proposed conceptual framework for resilience-oriented market design has four interrelated layers. Real-time data acquisition and adaptive forecasting systems that continuously track operating circumstances and forecast uncertainty make up the first layer. Risk-aware market-clearing and dispatch systems that can incorporate uncertainty data into operational decision-making are part of the second layer. Reserve markets, energy storage systems, distributed energy resources, and demand response programs are examples of flexible operational resources found in the third layer. Resilience governance, which includes long-term infrastructure planning, market oversight, and regulatory coordination, is the last layer.

This integrated coordination structure strengthens electricity market resilience by improving uncertainty management, operational flexibility, and system responsiveness under disruptive conditions. Additionally, by promoting continuous interaction among forecasting intelligence, operational decision-making, and resilience planning processes, the framework facilitates the shift toward decentralized and renewable-dominated energy systems.

4. Challenges and Policy Implications

The transition from conventional electrical market structures to adaptive, uncertainty-aware systems is nevertheless hampered by a number of institutional, technical, and financial issues, despite increasing advancements in resilience-oriented energy market design. In contrast to isolated technological advancements, the literature on power system resilience consistently emphasizes that achieving resilient electricity markets necessitates coordinated progress across infrastructure modernization, regulatory reform, and economic incentive alignment (Panteli & Mancarella, 2015; Ulbig & Andersson, 2015).

4.1. Technical and Infrastructure Challenges

4.1.1. Data limitations

A foundational challenge in implementing adaptive forecasting and resilience-oriented decision systems is the availability, quality, and interoperability of energy data. Advanced forecasting models, particularly probabilistic and AI-based systems, depend on high-resolution, real-time datasets from generation units, transmission infrastructure, and end-use demand. However, many electricity systems still face fragmented data architectures, inconsistent measurement standards, and limited cross-platform integration. Smart grid literature emphasizes that insufficient data granularity and interoperability significantly reduce the effectiveness of real-time operational decision-making and predictive analytics in electricity markets (Fang et al., 2011). Consequently, these limitations create significant barriers to integrating forecasting systems with market operations within a fully resilience-oriented framework.

4.1.2. Grid modernization requirements

The requirement for a considerable grid upgrade is another significant obstacle. While modern power systems increasingly depend on distributed energy resources, bidirectional power flows, and decentralized renewable generation, traditional electricity infrastructure was built for centralized generation and unidirectional power flows. Advanced metering infrastructure, adaptable transmission and distribution systems, and digital control technologies that enable real-time coordination between market players and system operators are all necessary for this shift. The literature on smart grids and energy systems emphasizes that to reliably integrate dispersed energy resources and variable renewable generation, current grid resilience depends on increasing digitalization, automation, and improved system observability (NREL, 2026a; NREL, 2026b).

4.1.3. Cybersecurity concerns

The increasing reliance on digital platforms, automated control systems, and interconnected communication networks introduces significant cybersecurity risks. As electricity markets become more data-driven and digitally coordinated, vulnerabilities in communication infrastructure can be exploited to disrupt forecasting systems, manipulate market operations, or destabilize grid operations. Energy systems literature identifies cyber-physical security as a critical component of resilience, requiring integrated protection strategies across both physical and digital layers of the electricity system (Roege et al., 2014). Consequently, cybersecurity is not only a technical issue but also a fundamental constraint on the implementation of real-time adaptive market systems.

4.2. Economic and Regulatory Challenges

4.2.1. Investment uncertainty

The transition toward resilience-oriented electricity markets requires substantial investment in flexible generation of resources, energy storage systems, digital infrastructure, and advanced forecasting technologies. However, investment decisions are frequently affected by regulatory uncertainty, evolving market structures, and uncertain long-term revenue mechanisms. In many liberalized electricity markets, short-term market signals and energy pricing structures may not provide sufficient incentives for long-term investment in flexibility and resilience-enhancing infrastructure. The International Energy Agency (IEA) has emphasized that achieving reliable and resilient low-carbon electricity systems will require sustained investment frameworks capable of supporting long-term infrastructure development and system flexibility (IEA, 2023). This situation can create a misalignment between broader system resilience objectives and private investment incentives.

4.2.2. Market incentives for flexibility

Flexibility services are not usually sufficiently valued in existing electricity market designs, even though flexibility is widely acknowledged as a fundamental requirement for renewable-dominated systems. Traditional energy-only markets underinvest in fast-ramping generation, storage, and demand response capabilities because they primarily recompense energy production rather than flexibility provision. According to Ulbig and Andersson (2015), market pricing methods frequently fall short of capturing the whole system value of operational flexibility, despite its growing importance in contemporary power systems. The efficacy of market-based strategies for fostering resilience is diminished by this imbalance.

4.2.3. Regulatory adaptation needs

Electricity market regulation was largely developed under assumptions of centralized generation, predictable demand, and limited operational uncertainty. However, modern electricity systems require regulatory frameworks capable of adapting to decentralized generation, probabilistic forecasting, and real-time operational control. Panteli and Mancarella (2015) highlight that resilience is not only a technical attribute but also an institutional capability, requiring governance systems that can evolve in response to emerging operational challenges. Regulatory rigidity therefore remains a major barrier to implementing adaptive and resilience-oriented electricity market structures.

4.3. Policy Implications

4.3.1. Market reform strategies

A key policy implication is the need for electricity market reforms that explicitly incorporate uncertainty and flexibility into market-clearing processes. This includes the adoption of stochastic and probabilistic market designs, shorter settlement intervals, and enhanced real-time balancing mechanisms. Such reforms allow markets to better reflect system variability and improve operational responsiveness under uncertain conditions. Recent literature suggests that integrating uncertainty directly into market optimization improves dispatch efficiency and reduces balancing costs in renewable-dominated systems (Zhao et al., 2023).

4.3.2. Incentives for resilient infrastructure

The creation of financial and regulatory incentives for infrastructure that improves resilience should also be given top priority in policy frameworks. These include expenditures for digital grid technologies, demand response initiatives, flexible generation assets, and energy storage systems. In order to guarantee sufficient investment in infrastructure that can resist and recover from disturbances, resilience must be expressly valued in energy system planning and market design, according to the (National Academies of Sciences ,2017). Resilience-based procurement plans, flexibility markets, and capacity mechanisms can all be crucial in coordinating investment incentives with system requirements.

4.3.3. Governance and institutional coordination

Finally, robust governance and institutional coordination between regulatory bodies, system operators, and market players are necessary for the successful implementation of resilience-oriented electricity markets. Integrated governance frameworks are important to maintain coherence between forecasting systems, operational decision-making, and long-term infrastructure planning. Resilience necessitates coordinated action across technical, operational, and institutional domains, according to Panteli and Mancarella (2015), underscoring the need of adaptive governance structures that can react to changing system risks and uncertainties.

5. Future Research Directions

The growing complexity of modern electricity systems and the increasing uncertainty associated with renewable integration, climate change, and decentralized energy participation continue to create new research opportunities in resilience-oriented electricity market design. Existing studies have made substantial progress in forecasting, operational flexibility, and resilience planning; however, several emerging areas require further investigation to support the long-term transformation of electricity markets into adaptive, uncertainty-aware systems.

5.1. AI-Enabled Autonomous Market Systems

The electricity market of the future will be fundamentally different and powerfully improved through widespread use of artificial intelligence (AI). Machine learning techniques are already prevalent in current electricity markets (forecasting, optimization and operational planning), but future work is increasingly focusing on autonomous market systems that can help decision making in real-time adaptive environments under uncertainty. These systems could combine reinforcement learning approaches, predictive analytics for temporal and spatial forecasts, and automated decision making to make optimum dispatch on behalf of all market participants, system operators, or distributed energy resources.

AI helped electricity system can enhance operational responsiveness by helping with adaptive forecasting, real-time optimization and decision making in the presence of uncertainty in renewable generation and demand. It has been recently shown in the power system literature, though, that artificial intelligence applications are diversifying very fast between forecasting, operational control and grid optimization increasing both system efficiency and flexibility. Nevertheless, papers also highlight that issues concerning transparency, explainability, reliability and trust are still major challenges to the large-scale implementation of AI-based decision systems in operational power system management (Li et al., 2024).

Hence, future work should involve the coproduction of these three elements namely explanatory AI frameworks recourse human-in-loop operational control and cyber-secure autonomous decision systems that are able to adapt and adjust market based electricity generation functions while providing technical transparency and operational integrity in todays dynamic markets.

5.2. Climate-Resilient Market Structures

Climate change is increasing the frequency and severity of extreme weather events, including heatwaves, floods, droughts, and storms, all of which significantly affect electricity system reliability and market stability. As a result, future electricity markets must evolve beyond traditional efficiency-oriented objectives to incorporate climate resilience directly into market design and operational planning.

Recent literature highlights that climate-related disruptions can simultaneously affect electricity demand, renewable generation availability, fuel supply chains, and transmission infrastructure. Panteli and Mancarella (2015) emphasized that resilient power systems must possess the capability to anticipate, absorb, adapt to, and recover from high-impact disturbances while maintaining essential system functionality. Future research should therefore explore electricity market structures that explicitly integrate climate risk into operational scheduling, reserve procurement, infrastructure planning, and market-clearing mechanisms.

Potential research directions include climate-informed forecasting systems, resilience-adjusted electricity pricing models, and long-term market planning frameworks capable of accounting for physical climate risks and infrastructure vulnerability under changing environmental conditions.

5.3. Decentralized and Transactive Energy Markets

The shift to decentralized electrical systems is being accelerated by the quick development of distributed energy resources (DERs), rooftop solar systems, battery storage, electric cars, and smart grid technology. Transactive energy markets, in which decentralized market players dynamically swap electricity and flexibility services through digitally coordinated market platforms, are gaining popularity as a result of this shift.

By reacting to local system conditions and real-time pricing signals, transactive energy systems enable dispersed resources, consumers, and prosumers to actively engage in electricity market operations. Transactive energy is a paradigm for coordinating dispersed energy resources through value-based operational exchanges that increase system flexibility and efficiency, according to research from Pacific Northwest National Laboratory (Melton, 2019).

Future research should examine how decentralized and transactive market structures can improve resilience under uncertain operating conditions. Attention should be given to peer-to-peer electricity trading, distributed market coordination algorithms, blockchain-enabled energy transactions, and local energy balancing mechanisms capable of supporting resilient grid operations during large-scale disturbances.

5.4. Advanced Resilience Assessment Metrics

The growing complexity of electricity systems has shown shortcomings in traditional reliability measurements, which are primarily concerned with component failure probability and outage frequency. Modern energy systems necessitate larger resilience evaluation frameworks capable of assessing adaptive capacity, recovery performance, operational flexibility, and uncertainty management under disruptive conditions.

Existing resilience research recommends that resilience evaluation should include technical, operational, economic, and institutional dimensions rather than only traditional reliability metrics. Roege et al. (2014) contended that resilience measures must assess not only system robustness but also the ability of electricity systems to adapt and recover efficiently from disruptions. Similarly, Panteli and Mancarella (2015) emphasized the importance of multidimensional resilience models that consider both infrastructure performance and operational adaptability.

Future research should therefore focus on developing standardized resilience metrics capable of quantifying adaptive operational capability, forecasting uncertainty management, cyber-physical resilience, and market recovery performance. Such metrics could support more effective resilience benchmarking, policy evaluation, and long-term infrastructure planning within modern electricity markets.

6. Conclusion

The growing integration of renewable energy supplies, decentralized energy systems, climate-related disturbances, and shifting demand patterns have all exacerbated unpredictability in modern power markets. Conventional market mechanisms and deterministic operational frameworks are increasingly unable to manage the complexity and variability of modern power systems. As a result, resilience-oriented market design has emerged as a key technique for increasing market adaptability, flexibility, and reliability.

This study investigated important uncertainty sources in electricity markets and assessed the limitations of traditional forecasting and decision-making systems. The findings show that adaptive forecasting, probabilistic decision-making, and flexibility-oriented operational strategies are critical for achieving consistent market performance in renewable-dominated systems. The study also identified flexibility, adaptability, redundancy, and real-time responsiveness as core principles of resilient market design.

In addition, the study identified significant implementation challenges such as infrastructure upgrading, cybersecurity threats, investment uncertainties, and regulatory adaptation requirements. Overall, future electricity markets should build resilience, uncertainty management, and operational flexibility into their structures. Continued research into AI-enabled systems, climate-resilient markets, decentralized energy coordination, and resilience evaluation criteria will be important in facilitating long-term and reliable electrical market transformation.

References

[1] Basaran, K., Chandrakala, K. V., Lazaroiu, G. C., Parhamfar, M., Roscia, M., Lazaroiu, A. C., & Siano, P. (2026). AI and digitalization in electricity markets with renewables and electric vehicles: A review of price volatility, forecasting, and stability approaches. *Energy*, 141068.

[2] Bublitz, A., Keles, D., Zimmermann, F., Fraunholz, C., & Fichtner, W. (2019). A survey on electricity market design: Insights from theory and real-world implementations of capacity remuneration mechanisms. *Energy Economics, 80*, 1059-1078.

[3] Colback, L. (2025). Building energy resilience in an uncertain world. *Financial Times*. https://www.ft.com/content/45d4962d-b4d7-49ac-959a-82a1dbee059f

[4] Denholm, P., Ela, E., Kirby, B., & Milligan, M. (2010). *The role of energy storage with renewable electricity generation*.

[5] Ela, E., Milligan, M., & Kirby, B. (2011). Operating reserves and variable generation. *Contract, 303*(August), 275-3000.

[6] Fan, H., Wang, C., Liu, L., & Li, X. (2022). Review of uncertainty modeling for optimal operation of integrated energy system. *Frontiers in Energy Research, 9*, 641337.

[7] Fang, X., Misra, S., Xue, G., & Yang, D. (2011). Smart grid: The new and improved power grid: A survey. *IEEE Communications Surveys & Tutorials, 14*(4), 944-980.

[8] Gasser, P., Lustenberger, P., Cinelli, M., Kim, W., Spada, M., Burgherr, P., ... & Sun, T. Y. (2021). A review on resilience assessment of energy systems. *Sustainable and Resilient Infrastructure, 6*(5), 273-299.

[9] Ghasemi, A., Shojaeighadikolaei, A., & Hashemi, M. (2023). Combating uncertainties in wind and distributed PV energy sources using integrated reinforcement learning and time-series forecasting. *arXiv preprint arXiv:2302.14094*.

[10] Granado, P. C. D., Rajasekharan, J., Pandiyan, S. V., Tomasgard, A., Kara, G., Farahmand, H., & Jaehnert, S. (2023). Flexibility characterization, aggregation, and market design trends with a high share of renewables: A review. *Current Sustainable/Renewable Energy Reports, 10*(1), 12-21.

[11] Gulotta, F., Daccò, E., Bosisio, A., & Falabretti, D. (2023). Opening of ancillary service markets to distributed energy resources: A review. *Energies, 16*(6), 2814.

[12] Haugen, M., Farahmand, H., Jaehnert, S., & Fleten, S. E. (2023). Representation of uncertainty in market models for operational planning and forecasting in renewable power systems: A review. *Energy Systems*, 1-36.

[13] Hu, J., Harmsen, R., Crijns-Graus, W., Worrell, E., & van den Broek, M. (2018). Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design. *Renewable and Sustainable Energy Reviews, 81*, 2181-2195.

[14] International Energy Agency (IEA). (2026). *Electricity Market Report 2023*. https://www.iea.org/reports/electricity-market-report-2023

[15] Lee, N., Stout, S. R., & Cox, S. L. (2019). *Institutional solutions to enhance power sector resilience* (No. NREL/TP-7A40-73645). National Renewable Energy Laboratory.

[16] Li, Y., Ding, Y., He, S., Hu, F., Duan, J., Wen, G., ... & Zeng, Z. (2024). Artificial intelligence-based methods for renewable power system operation. *Nature Reviews Electrical Engineering, 1*(3), 163-179.

[17] Maguire, G. (2026). Europe's solar glut shunts power system into tricky new transition phase. *Reuters*. http://reuters.com/business/energy/europes-solar-glut-shunts-power-system-into-tricky-new-transition-phase-2026-05-06/

[18] Melton, R. B. (2019). *GridWise transactive energy framework (v. 1.1)* (No. PNNL-22946-Ver. 1.1). Pacific Northwest National Laboratory.

[19] Mentens, L., Peremans, H., Springael, J., & Nimmegeers, P. (2025). Flexibility in short-term electricity markets for renewable integration and uncertainty mitigation: A comprehensive review. *Smart Energy, 18*, 100183.

[20] Ming, H., Xie, L., Campi, M. C., Garatti, S., & Kumar, P. R. (2017). Scenario-based economic dispatch with uncertain demand response. *IEEE Transactions on Smart Grid, 10*(2), 1858-1868.

[21] Morales, J. M., & Pineda, S. (2017). On the inefficiency of the merit order in forward electricity markets with uncertain supply. *European Journal of Operational Research, 261*(2), 789-799.

[22] National Academies of Sciences, Engineering, and Medicine. (2017). *Enhancing the resilience of the nation's electricity system*. The National Academies Press. https://doi.org/10.17226/24836

[23] National Renewable Energy Laboratory (NREL). (2026a). Advanced distribution management systems. https://www.nrel.gov/grid/advanced-distribution-management

[24] National Renewable Energy Laboratory (NREL). (2026b). Distribution system planning, analysis, and grid integration. https://www.nrel.gov/grid/distribution-integration

[25] O'Connor, C., Bahloul, M., Prestwich, S., & Visentin, A. (2026). The evolution of probabilistic price forecasting techniques: A review of the day-ahead, intra-day, and balancing markets. *Energies, 19*(8), 1929.

[26] Oureilidis, K., Malamaki, K. N., Gallos, K., Tsitsimelis, A., Dikaiakos, C., Gkavanoudis, S., ... & Demoulias, C. (2020). Ancillary services market design in distribution networks: Review and identification of barriers. *Energies, 13*(4), 917.

[27] Panteli, M., & Mancarella, P. (2015). The grid: Stronger, bigger, smarter? Presenting a conceptual framework of power system resilience. *IEEE Power and Energy Magazine, 13*(3), 58-66.

[28] Rehak, D., Slivkova, S., Janeckova, H., Stuberova, D., & Hromada, M. (2022). Strengthening resilience in the energy critical infrastructure: Methodological overview. *Energies, 15*(14), 5276.

[29] Renkema, Y., Brinkel, N., & Alskaif, T. (2024). Conformal prediction for stochastic decision-making of PV power in electricity markets. *Electric Power Systems Research, 234*, 110750.

[30] Roege, P. E., Collier, Z. A., Mancillas, J., McDonagh, J. A., & Linkov, I. (2014). Metrics for energy resilience. *Energy Policy, 72*, 249-256.

[31] Silva-Rodriguez, L., Sanjab, A., Fumagalli, E., Virag, A., & Gibescu, M. (2022). Short term wholesale electricity market designs: A review of identified challenges and promising solutions. *Renewable and Sustainable Energy Reviews, 160*, 112228.

[32] Ulbig, A., & Andersson, G. (2015). Analyzing operational flexibility of electric power systems. *International Journal of Electrical Power & Energy Systems, 72*, 155-164.

[33] Watson, J. P., Guttromson, R., Silva-Monroy, C., Jeffers, R., Jones, K., Ellison, J., ... & Walker, L. T. (2014). Conceptual framework for developing resilience metrics for the electricity oil and gas sectors in the United States. Sandia National Laboratories.

[34] Weber, P., & Woerman, M. (2024). Intermittency or uncertainty? Impacts of renewable energy in electricity markets. *Journal of the Association of Environmental and Resource Economists, 11*(6), 1351-1385.

[35] Yazdanie, M., Dramani, J. B., & Orehounig, K. (2025). Strengthening energy system resilience planning under uncertainty by minimizing regret. *Renewable and Sustainable Energy Transition, 6*, 100093.

[36] Zhang, Y., Wen, H., Bian, Y., & Shi, Y. (2025). Improving sequential market coordination via value-oriented renewable energy forecasting. *IEEE Transactions on Energy Markets, Policy and Regulation*.

[37] Zhao, H., Tanneau, M., & Van Hentenryck, P. (2023). On the viability of stochastic economic dispatch for real-time energy market clearing. *arXiv preprint arXiv:2308.06386*.

[38] Zhu, Z., Bu, S., Chan, K. W., Li, F., Ye, Y., Chung, C. Y., & Strbac, G. (2025). Designing the future electricity spot market with high renewables via reliable simulations. *Nature Reviews Electrical Engineering, 2*(5), 320-337.