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Electricity Market Transformation in the Renewable Energy Era: A Systematic Review

DAI, Chunni

(1) 0009-0009-9062-6974; Lyceum of the Philippines University, Manila Campus, Philippines. 35812625@qq.com

ABSTRACT

The integration of renewable energy sources into electricity markets presents both opportunities and challenges, influencing market stability and pricing dynamics. While renewable energy lowers wholesale electricity prices through the merit-order effect, its intermittency contributes to price volatility, requiring advanced hedging strategies and predictive analytics. This systematic review examines the impact of renewable energy integration on market stability and pricing, focusing on mechanisms such as price fluctuations, hedging instruments, demand-side management, and regulatory frameworks. The study follows the PRISMA methodology, utilizing SCOPUS-indexed journal articles published between 2015 and 2025 to ensure academic rigor. Findings reveal that increased renewable penetration reduces electricity prices but amplifies price volatility, necessitating improved financial instruments such as forward contracts, capacity markets, and renewable derivatives. Market power adjustments by dominant energy firms in response to renewable growth influence overall competitiveness, while decentralized energy markets, microgrid optimization, and peer-to-peer electricity trading enhance market resilience. Additionally, cross-border electricity trade remains an underexplored but critical factor in balancing supply-demand mismatches. Regulatory frameworks play a vital role in mitigating instability, with mechanisms like feed-in tariffs, renewable auctions, and carbon pricing influencing investment and market stability. However, misalignment between renewable subsidies and carbon pricing strategies can create unintended market distortions. The study highlights the need for AI-driven forecasting models to improve price predictability and calls for longitudinal analyses to assess the evolving cost-benefit dynamics of decentralized energy adoption. This review provides valuable insights for policymakers, energy regulators, and market participants, offering a comprehensive synthesis of the financial and operational challenges associated with renewable energy integration. The findings contribute to the development of resilient, adaptive market structures that support the transition toward a sustainable and economically viable energy system.

RESUMO

A integração de fontes de energia renováveis nos mercados de eletricidade apresenta oportunidades e desafios, influenciando a estabilidade do mercado e a dinâmica de preços. Enquanto a energia renovável reduz os preços de eletricidade no atacado por meio do efeito de ordem de mérito, sua intermitência contribui para a volatilidade dos preços, exigindo estratégias avançadas de hedge e análise preditiva. Esta revisão sistemática examina o impacto da integração de energia renovável na estabilidade do mercado e nos preços, com foco em mecanismos como flutuações de preços, instrumentos de hedge, gestão do lado da demanda e estruturas regulatórias. O estudo segue a metodologia PRISMA, utilizando artigos de periódicos indexados pela SCOPUS publicados entre 2015 e 2025 para garantir o rigor acadêmico. As descobertas revelam que o aumento da penetração renovável reduz os preços da eletricidade, mas amplifica a volatilidade dos preços, necessitando de instrumentos financeiros aprimorados, como contratos a termo, mercados de capacidade e derivativos renováveis. Os ajustes de poder de mercado por empresas de energia dominantes em resposta ao crescimento renovável influenciam a competitividade geral, enquanto os mercados de energia descentralizados, a otimização de microrredes e o comércio de eletricidade ponto a ponto aumentam a resiliência do mercado. Além disso, o comércio transfronteiriço de eletricidade continua sendo um fator pouco explorado, mas crítico, no equilíbrio de descompassos entre oferta e demanda. As estruturas regulatórias desempenham um papel vital na mitigação da instabilidade, com mecanismos como tarifas feed-in, leilões renováveis e precificação de carbono influenciando o investimento e a estabilidade do mercado. No entanto, o desalinhamento entre subsídios renováveis e estratégias de precificação de carbono pode criar distorções de mercado não intencionais. O estudo destaca a necessidade de modelos de previsão baseados em IA para melhorar a previsibilidade de preços e exige análises longitudinais para avaliar a dinâmica de custo-benefício em evolução da adoção de energia descentralizada. Esta revisão fornece insights valiosos para formuladores de políticas, reguladores de energia e participantes do mercado, oferecendo uma síntese abrangente dos desafios financeiros e operacionais associados à integração de energia renovável. As descobertas contribuem para o desenvolvimento de estruturas de mercado resilientes e adaptáveis que apoiam a transição para um sistema de energia sustentável e economicamente viável.

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Introduction

The global energy sector is undergoing a transformative shift, driven by the imperative to mitigate climate change and reduce greenhouse gas emissions. Central to this transition is the integration of renewable energy sources (RES) such as wind, solar, and hydroelectric power into existing electricity markets. These sources offer the promise of sustainable and clean energy, yet their incorporation into traditional power systems presents complex challenges, particularly concerning market stability and pricing dynamics.

Renewable energy sources are characterized by variability and intermittency, which can lead to fluctuations in electricity supply. This variability necessitates adjustments in conventional power generation to maintain grid stability, potentially increasing operational costs and influencing market prices. Studies have shown that high penetration of RES can result in increased price volatility in electricity markets, as the supply-demand balance becomes more dynamic (Owolabi et al., 2023). One notable phenomenon associated with renewable energy integration is the "merit order effect." This effect occurs when low marginal cost RES displace higher-cost conventional generation in the supply stack, leading to a reduction in wholesale electricity prices. While this can benefit consumers through lower prices, it may also impact the revenue streams of traditional energy producers, potentially affecting their financial viability and investment decisions (Bojnec, 2023).

Market design and regulatory frameworks play a crucial role in facilitating the effective integration of RES. Innovative market structures, such as dynamic pricing mechanisms and long-term contracts, have been proposed to accommodate the unique characteristics of renewable energy and enhance grid stability. For instance, real-time pricing models can incentivize consumers to adjust their demand in response to supply fluctuations, thereby contributing to grid stability and more efficient energy use (Sabour et al., 2021). Despite these advancements, several gaps persist in the current body of knowledge. There is a need for a comprehensive synthesis of how various market mechanisms—such as real-time pricing, regulatory frameworks, and contract designs—interact with RES integration to influence market stability and pricing. Furthermore, the strategic behaviors of market participants, including generators, consumers, and policymakers, in response to the evolving energy mix remain underexplored. Understanding these dynamics is crucial for developing robust policies and market structures that can effectively manage the transition toward a renewable-dominated energy system.

To address these gaps, this systematic review aims to answer the following research question: "What are the effects of renewable energy integration on electricity market stability and pricing, and how do market mechanisms such as the merit order effect, real-time pricing, market design, and regulatory frameworks influence these outcomes?"

The specific objectives of this review was: To examine the effects of renewable energy integration on electricity market stability. To analyze the impact of renewable energy on electricity pricing mechanisms. To evaluate the role of market design and regulatory frameworks in renewable energy integration. To assess the strategic behaviors of market participants in response to renewable energy integration. To investigate hedging strategies and demand-side management for mitigating market instability. To identify gaps in the literature and provide recommendations for future research and policy development.

This scoping review aims to provide a better understanding of the multifaceted impacts of renewable energy integration on electricity markets. The insights garnered will inform policymakers, industry stakeholders, and researchers in developing strategies and frameworks that facilitate a stable and economically viable transition to sustainable energy systems.

Theoretical framework

The integration of renewable energy sources into existing power systems has profound implications for energy market stability and pricing. Several theoretical frameworks elucidate these dynamics, each offering insights into how renewables influence market operations and economic equilibria.

1. Merit Order Effect

The merit order effect describes the reduction in wholesale electricity prices resulting from the inclusion of low marginal cost renewable energy sources, such as wind and solar. In electricity markets, power plants are dispatched based on ascending order of their marginal costs, with the least expensive sources meeting demand first. Renewables, having negligible fuel costs, enter the supply curve at the lowest end, effectively displacing more expensive conventional generators. This displacement leads to a decrease in the overall market clearing price during periods of high renewable output. Empirical studies have quantified this effect, demonstrating that increased renewable penetration correlates with decreased spot market prices, thereby impacting the revenue streams of traditional power producers (Cludius et al., 2014; Sensfuß et al., 2008).

2. Game-Theoretical Models of Market Behavior

Game theory provides a framework to analyze strategic interactions among market participants in environments with significant renewable energy integration. The variability and uncertainty of renewable outputs introduce complexities in bidding strategies and price formations. Game-theoretical models assess how different pricing mechanisms, such as uniform pricing versus pay-as-bid, influence supplier behaviors, market equilibria, and overall welfare. These models reveal that pricing schemes can significantly affect the incentives for generators, potentially leading to strategic bidding and market inefficiencies (Zhao et al., 2023; Huang & Li, 2022).

3. Real-Time Pricing and Demand-Side Management

Real-time pricing (RTP) is a demand-side management strategy that adjusts electricity prices based on real-time supply and demand conditions. The integration of renewables, characterized by their intermittency, necessitates flexible consumption patterns to maintain grid stability. RTP incentivizes consumers to modify their usage in response to price signals, aligning demand with the variable supply from renewables. This domain explores how dynamic pricing models can enhance grid stability, optimize resource utilization, and reduce overall system costs by encouraging load shifting and peak demand reduction (Fan & Hyndman, 2011).

4. Hedging Against Fuel Price Volatility

Renewable energy integration serves as a hedge against the volatility of fossil fuel prices. Traditional energy markets are susceptible to fluctuations in fuel costs, leading to unpredictable electricity prices. By diversifying the energy mix with renewables, which have stable and predictable costs, markets can reduce their exposure to fuel price risks. This area examines the risk mitigation benefits of renewables, highlighting how they contribute to more stable and predictable energy pricing structures (Böttger & Härtel, 2021).

5. Market Design and Regulatory Frameworks

The successful integration of renewable energy into power systems necessitates the adaptation of existing market designs and regulatory frameworks. This investigates how policies such as feed-in tariffs, renewable portfolio standards, and capacity markets can be structured to promote renewable adoption while ensuring market efficiency and reliability. To analyze the balance between providing sufficient incentives for renewable investments and maintaining fair competition and price signals within the market. Cramton (2017) discusses how electricity markets can be designed to provide reliable electricity at the least cost to consumers, emphasizing the importance of short-run and long-run efficiency in market operations.

6. Agent-Based Modeling of Energy Markets

Agent-based models simulate the actions and interactions of autonomous agents, such as consumers, producers, and regulators, to assess their effects on the energy market. In the context of renewable integration, these models help in understanding how individual behaviors and decentralized decision-making impact market stability and pricing. They provide insights into emergent phenomena resulting from complex interactions, such as price volatility, investment cycles, and the diffusion of new technologies (Huang & Li, 2022).

7. Cross-Sectoral Demand Bidding Effects

The integration of renewables affects not only the electricity sector but also has implications across various energy-consuming sectors. Cross-sectoral demand bidding effects analyze how the availability of low-cost renewable energy influences the behavior of industries such as heating, transportation, and manufacturing. Such studies assess how sector coupling and flexible demand responses can be leveraged to absorb excess renewable generation, thereby stabilizing prices and enhancing the overall efficiency of the energy system (Böttger & Härtel, 2021).

8. Equilibrium Models in High Renewable Penetration

Equilibrium models are employed to understand the long-term impacts of high renewable energy penetration on market stability and pricing. These models consider the interactions between supply and demand, investment decisions, and policy interventions to predict how markets will evolve. They help in identifying potential challenges such as price cannibalization, where the value of renewable energy decreases as its supply increases, and in designing mechanisms to ensure the financial viability of renewable investments (Böttger & Härtel, 2021).

9. Integration of Renewables as Reserve Providers

As the share of variable renewable energy sources increases, ensuring grid reliability becomes more complex. Theoretical frameworks explore how renewables themselves can provide ancillary services, such as reserves, to support grid stability. These studies model the conditions under which renewable generators can offer reserve services, the pricing mechanisms for such services, and the implications for market operations and reliability (Zhao et al., 2023).

10. Contract Design in Renewable-Rich Markets

The variability of renewable energy generation poses challenges for traditional contracting mechanisms in electricity markets. Theoretical analyses focus on designing contracts that accommodate the uncertainties associated with renewables. This includes the development of financial derivatives, such as futures and options, tailored to the characteristics of renewable energy, and assessing their impact on market stability, pricing, and investment incentives (Abate et al., 2022).

Methodology

The methodology of this systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, ensuring a structured and rigorous approach to data collection, selection, and synthesis. PRISMA is widely recognized for its ability to enhance transparency and reproducibility in systematic reviews by outlining clear guidelines for study identification, screening, eligibility assessment, and inclusion (Page et al., 2021). Given the increasing complexity of energy markets and the role of renewable energy integration, a systematic review methodology was deemed essential for synthesizing existing literature and providing a comprehensive analysis of the impact of renewables on energy market stability and pricing.

To ensure high-quality academic sources, SCOPUS was selected as the primary database for literature retrieval. SCOPUS is one of the most extensive abstract and citation databases of peer-reviewed literature, providing access to high-impact journals across multiple disciplines, including energy economics, sustainability, and electricity market studies (Baas et al., 2020). Given the objective of examining the impact of renewable energy integration on energy market stability and pricing, only peer-reviewed journal articles were considered, excluding books, book chapters, and technical reports. These exclusions were made to maintain a high standard of empirical rigor and methodological consistency across the selected studies. Journal articles in SCOPUS-indexed sources undergo stringent peer-review processes, ensuring that findings are reliable, credible, and aligned with established research methodologies in the field of energy economics and market stability (Mongeon & Paul-Hus, 2016).

The search strategy was designed using Boolean search operators to maximize the retrieval of relevant literature while minimizing irrelevant results. The search string was formulated using key terms and synonyms related to renewable energy, electricity pricing mechanisms, and market stability. The Boolean search structure included terms such as “renewable energy” AND “electricity pricing” AND “market stability” and additional variations incorporating terms like “demand-side management,” “hedging strategies,” “volatility,” and “price dynamics” to ensure a broad yet focused retrieval of articles. The search was further refined by applying filters to limit results to journal articles published between 2015 and 2025, reflecting contemporary developments in renewable energy integration, policy impacts, and electricity market reforms. This temporal scope captures recent advancements in energy transition policies, improvements in forecasting models, and the evolution of market mechanisms in response to increasing renewable penetration.

The process of article selection followed a three-stage screening approach: title and abstract screening, full-text eligibility assessment, and final inclusion based on relevance to the research objective. Initially, duplicate articles were removed, and studies were assessed for relevance based on their abstracts and keywords. Articles that did not explicitly discuss the intersection of renewable energy and electricity pricing mechanisms were excluded. The remaining articles underwent full-text evaluation, ensuring that they contained empirical data, quantitative or qualitative analysis, and explicit discussions of market stability and pricing in renewable-integrated energy markets.

The qualitative synthesis of selected articles was conducted using thematic analysis, which is a well-established qualitative research method for identifying, analyzing, and reporting patterns within data (Braun & Clarke, 2006). The thematic approach facilitated the classification of findings into distinct categories, including the merit order effect, price volatility, hedging mechanisms, demand-side management, and regulatory interventions. These themes were derived inductively by closely examining the findings and discussions within each study. Through iterative coding and data reduction, a comprehensive understanding of the key factors influencing market stability under high renewable penetration was developed.

To facilitate the organization and comparison of findings, Microsoft Excel was used for data tabulation. Excel spreadsheets were structured to include article metadata, study focus, key findings, and implications for electricity market mechanisms. This method allowed for efficient categorization of results, enabling a clear synthesis of trends and patterns across multiple studies. The use of Excel also supported data visualization and cross-referencing, enhancing the systematic review's analytical depth.

By adhering to the PRISMA framework, utilizing SCOPUS as the exclusive database, employing Boolean search techniques, and conducting a thematic qualitative synthesis, this systematic review ensures methodological rigor and comprehensive coverage of the impact of renewable energy integration on energy market stability and pricing. This approach aligns with best practices in systematic review methodology and contributes to the growing body of literature on the financial and operational challenges of renewable-dominant electricity markets (Sovacool et al., 2018). The insights derived from this review provide a strong empirical foundation for policymakers, energy economists, and market regulators seeking to develop resilient and adaptive pricing mechanisms in renewable-integrated power systems.

Results and Discussion

This review followed the PRISMA guidelines to ensure transparency and reproducibility in the selection and screening of relevant literature. A total of 598 records were initially identified from the Scopus database, with no exclusions at this stage. After removing 16 duplicate records, 582 unique records remained for further evaluation. Subsequently, 2 records were excluded due to the absence of a DOI, leaving 580 records for title and abstract screening.

During title and abstract screening, 509 records were deemed irrelevant based on predefined inclusion and exclusion criteria, resulting in 71 records progressing to the next stage. A language screening was conducted, leading to the exclusion of 5 non-English studies, leaving 66 records eligible for full-text assessment. In the full-text availability screening, 34 studies were excluded due to unavailability of full texts, resulting in 32 studies meeting all inclusion criteria.

A total of 32 studies were included in the final systematic review, providing a comprehensive basis for analyzing the theoretical and empirical effects of renewable energy integration on energy markets. This PRISMA framework (see Figure 1) ensures a rigorous and transparent selection process, minimizing bias while ensuring that only relevant, high-quality studies contribute to the review findings.

Figure 1.

PRISMA Framework of studies included in the systematic review.

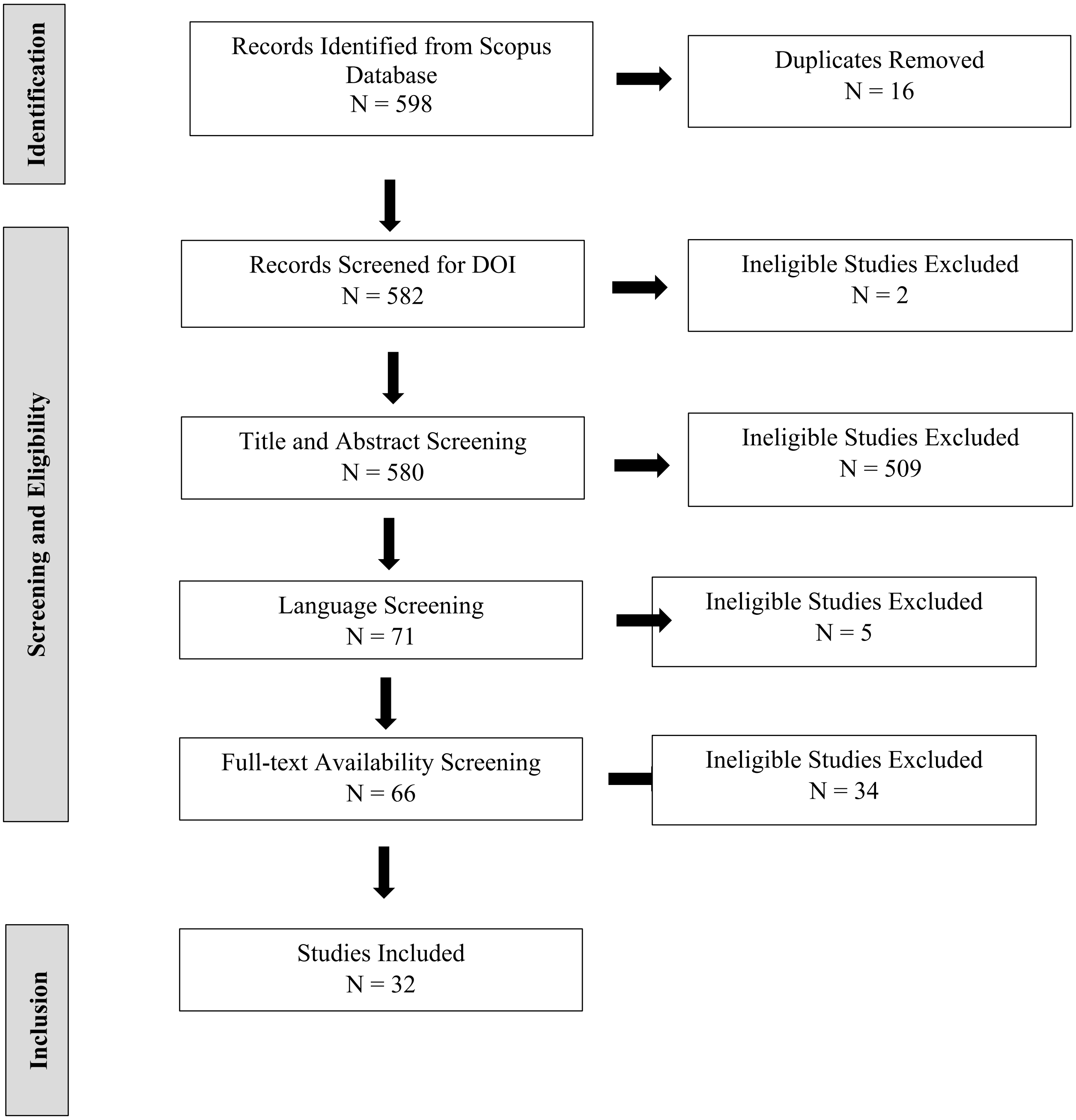
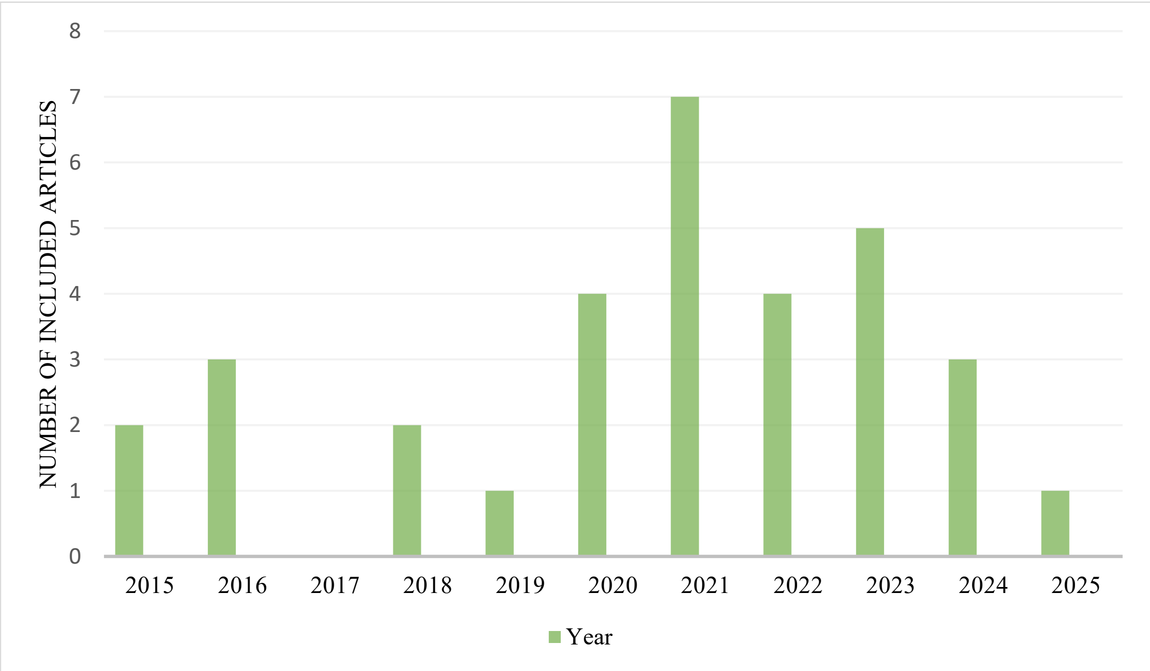


Figure 2 shows that between 2015 and 2016, the number of published studies remained relatively low, with two and three articles, respectively. This period represents the early stages of research engagement with renewable energy's influence on electricity markets. The absence of publications in 2017 suggests a possible gap in academic discourse, potentially due to delays in empirical data collection or a temporary stagnation in research funding and interest.

In 2018 and 2019, the field saw a modest resurgence, with two and one articles published, respectively. This could indicate a growing recognition of renewable energy's role in electricity pricing, though still not at a scale sufficient to drive widespread research momentum. By 2020, a notable increase in publications occurred, with four articles, signaling an expanding academic interest in market transformations driven by renewable energy policies and integration.

Figure 2.

Included SCOPUS-indexed articles per year adhering to renewable energy integration and its impact on market stability and pricing from 2015-2025.



The year 2021 marked a significant peak in research output, with seven articles, the highest in the dataset. This surge aligns with global efforts to transition towards renewable energy sources, driven by ambitious climate policies, advancements in energy storage, and the growing urgency to manage volatility in electricity markets. Studies during this period likely focused on market mechanisms, hedging strategies, and demand-side management to mitigate price fluctuations.

Following the peak in 2021, the number of publications slightly declined in 2022 (four articles), yet it remained higher than pre-2020 levels. This suggests a sustained research interest, though possibly shifting towards more specialized topics, such as decentralized energy markets, carbon pricing mechanisms, and regulatory innovations. The upward trend continued in 2023, with five articles, demonstrating that renewable energy's impact on market stability remained a critical area of study.

In 2024, the number of publications dropped to three, which could indicate either a shift in research focus towards implementation studies rather than exploratory analyses or a stabilization of findings regarding renewable energy integration. By 2025, only one study was recorded, which may suggest that core questions in this domain have been addressed, or that research has transitioned towards emerging challenges in energy market design, resilience strategies, and policy frameworks.

Overall, the trend illustrates an evolving research trajectory, where early years were characterized by sporadic contributions, followed by a significant peak in 2021, likely driven by policy shifts and technological advancements. The subsequent decline suggests that while interest remains, the research focus is becoming more refined, potentially moving towards optimizing renewable energy integration rather than merely understanding its effects.

Table 1.

The Impact of Renewable Energy Integration on Electricity Market Stability

Study	Study Focus	Key Findings
Alsaedi et al. (2021)	Effect of solar and wind prices on Australian electricity markets using VAR analysis.	Renewables lower spot and options market volatility.
Alsaedi et al. (2020)	Impact of solar and wind on global electricity markets with time series analysis.	Solar and wind power integration decreases global electricity price variance.
Alsaedi et al. (2021)	Qualitative analysis of energy management and policy responses in Australia.	Policies significantly impact renewable adoption and pricing.
Ballester & Furio (2024)	Machine learning analysis of renewables' impact on Iberian electricity prices.	Renewables reduce average prices but increase volatility.
Browne et al. (2015)	Assessment of market power and wind investment in energy-only markets.	Market power influences the stability of renewable investments.
Espinosa & Pizarro-Irizar (2018)	Cost-effectiveness of renewable energy in Spanish electricity markets.	Renewables provide cost-effective solutions for emissions reduction.
Frondel et al. (2022)	Market premium for renewables and its effect on German electricity prices.	Higher renewable penetration leads to reduced market premiums.
Gokce et al. (2024)	Impact of renewables on the Turkish electricity market.	Increased renewables contribute to lower wholesale prices.
Haluzan et al. (2023)	Crowding out of conventional electricity generation by renewables.	Higher renewable shares displace fossil fuel generation, affecting pricing.
Houben et al. (2023)	Optimization of renewable energy community microgrids under uncertainty.	Microgrid optimization supports stable integration of renewables.
Imani et al. (2021)	Wind and solar generation effects on Italian zonal electricity prices.	Renewables contribute to lower but more volatile prices.
Katz et al. (2016)	Demand response incentives and pricing in wind-based electricity systems.	Demand-side management helps balance fluctuations in wind energy.
Liebensteiner et al. (2024)	High electricity prices despite renewable energy expansion in Germany.	Structural trends counterbalance price reductions from renewables.
Macedo et al. (2022)	Electricity flows, renewables, and price behavior in the Spanish market.	Renewable electricity production alters price dynamics.

Madler et al. (2023)	Multi-agent modeling of urban microgrids and energy market shocks.	Multi-agent models reveal stability and policy impacts on microgrids.
Peura & Bunn (2021)	Impact of renewable power on forward electricity markets.	Renewables increase competition and affect forward market hedging.
Rai & Nunn (2020)	Influence of renewable penetration on electricity price extremes in Australia.	High renewable shares lead to increased price fluctuations.
Rios-Ocampo et al. (2021)	Renewable penetration and energy security in electricity markets.	Energy security considerations influence renewable deployment.
Ritz (2016)	Effect of renewable energy competition on electricity forward contracting.	Renewable competition alters forward electricity market dynamics.
Tolmasquim et al. (2021)	Electricity market design and renewable energy auctions in Brazil.	Policy design influences the success of renewable integration.

Several studies provide evidence that renewable energy sources such as wind and solar contribute to reducing wholesale electricity prices, primarily due to the merit-order effect. Table 1 shows that Alsaedi et al. (2020a, 2020b, 2021) demonstrated through vector autoregression analysis (VAR) that increased renewable penetration in Australian electricity markets lowers both spot and options market prices. Similarly, Ballester and Furio (2024) applied machine learning techniques to Iberian electricity markets, finding that while renewables reduce overall market prices, they also contribute to increased price volatility due to their intermittent nature.

The interaction between renewable energy and market stability is further complicated by the influence of market power. Browne et al. (2015) examined the role of market power in the presence of wind investments in energy-only markets, concluding that firms with significant market power can influence price stability and counteract some of the price-reducing effects of renewables. This dynamic is also observed in the work of Frondel et al. (2022), who investigated market premiums for renewables in Germany. Their findings suggest that although higher renewable penetration reduces market premiums, structural trends such as grid congestion and transmission constraints can introduce additional instability.

Beyond price effects, the displacement of conventional energy sources by renewables introduces a new layer of complexity. Haluzan et al. (2023) analyzed the crowding-out effect of renewables in Greek, Hungarian, and Romanian electricity markets, showing that as renewable penetration increases, conventional power plants face reduced utilization rates, leading to shifts in market structure and operational inefficiencies. Similarly, Gokce et al. (2024) assessed the Turkish power market and found that renewables contribute to lower wholesale prices, but the associated policy costs, such as feed-in tariffs, impose financial burdens on retail electricity markets.

Microgrid optimization and decentralized renewable integration have also been identified as crucial factors in stabilizing electricity markets. Houben et al. (2023) investigated the role of microgrid optimization in Austria, concluding that local energy communities could enhance stability by efficiently dispatching energy under uncertainty. Their findings align with the work of Madler et al. (2023), who used multi-agent models to show how urban microgrids can buffer against energy market shocks, thereby improving overall market resilience.

Renewable integration also influences the temporal structure of electricity prices. Imani et al. (2021) studied the Italian zonal electricity market and confirmed that while renewables contribute to lower prices, they also increase short-term volatility due to their intermittent generation patterns. Similarly, Rai and Nunn (2020) examined price extremes in Australia's electricity markets and found that high renewable shares lead to both increased price fluctuations and altered bidding behaviors among market participants.

Demand-side management has emerged as a key strategy to mitigate some of the stability challenges posed by renewables. Katz et al. (2016) evaluated the role of dynamic pricing and demand-response incentives in balancing wind-based electricity systems, concluding that greater consumer participation in real-time pricing can help absorb price fluctuations.

Despite the price-reducing effects of renewables, structural factors may offset these benefits in some contexts. Liebensteiner et al. (2024) investigated Germany's electricity market and found that while renewables exert downward pressure on prices, the nuclear phaseout, rising carbon prices, and increased electrification collectively contribute to higher electricity prices. Similarly, Macedo et al. (2022) studied Spanish electricity markets and observed that electricity inflows and outflows influence price volatility, highlighting the importance of cross-border electricity trade in stabilizing markets.

Energy security considerations further complicate the relationship between renewables and market stability. Ríos-Ocampo et al. (2021) examined renewable penetration and energy security, finding that while high shares of renewables can lower spot prices, they may also introduce vulnerabilities related to supply intermittency and reserve margin adequacy. Their findings suggest that future market designs should incorporate mechanisms to enhance resilience, such as capacity markets and strategic reserves.

Lastly, the role of regulatory frameworks in shaping market stability cannot be overlooked. Tolmasquim et al. (2021) analyzed Brazil's electricity market design and renewable energy auctions, demonstrating how policy instruments influence the integration of renewables into competitive electricity markets. Their findings indicate that well-structured policy mechanisms, including auction-based procurement and capacity incentives, can enhance market stability by ensuring sufficient investment in flexible generation capacity.

Studies revealed in Table 2, such as Alsaedi et al. (2021) and Espinosa & Pizarro-Irizar (2018), demonstrate that increased penetration of solar and wind energy displaces higher-cost conventional generation, thereby lowering electricity spot prices. This effect is particularly evident in Australia and Spain, where renewable energy has contributed to a downward trend in wholesale electricity prices. However, these price reductions can create challenges for conventional energy producers, reducing their revenue and potentially discouraging future investments in grid stability.

Moreover, Alsaedi et al. (2020) and Rai & Nunn (2020) provide evidence that greater dependence on solar and wind power introduces unpredictability into the market due to the intermittency of these resources. The variability in renewable generation often results in extreme price events, characterized by both negative price spikes during periods of excess supply and price surges during low renewable generation periods. This volatility poses a challenge to market stability and requires improved forecasting models, as highlighted by Ballester & Furió (2024), who advocate for the application of machine learning techniques to enhance predictive capabilities and stabilize pricing mechanisms.

Halužan et al. (2023) discuss how renewable energy displaces conventional electricity generation, leading to market distortions in Eastern European markets. These findings highlight the need for regulatory interventions to ensure that market structures evolve alongside increasing renewable energy penetration.

Table 2.

The Impact of Renewable Energy on Electricity Pricing Mechanisms

Study	Study Focus	Implications for Electricity Pricing Mechanisms
Alsaedi et al. (2021)	Renewable energy integration in Australia has reduced wholesale electricity prices due to the merit order effect.	Renewable policies should balance price reductions with investment incentives for new renewable capacity.
Alsaedi et al. (2020)	Solar and wind energy reduce electricity spot prices but increase price volatility.	Market mechanisms should integrate hedging strategies to mitigate price fluctuations.
Ballester & Furió (2024)	Machine learning models reveal that renewable penetration affects market prices differently across the Iberian electricity market.	Predictive analytics can help design dynamic pricing schemes to stabilize market prices.
Browne et al. (2015)	Market power in energy-only markets can suppress the cost-saving effects of renewable energy.	Regulatory interventions are needed to prevent market distortions caused by dominant players.
Espinosa & Pizarro-Irizar (2018)	The Spanish electricity market experiences price suppression with higher renewable penetration, though long-term impacts remain unclear.	Policy refinements should ensure financial sustainability while maintaining affordability.
Frondel et al. (2022)	Germany's market premium scheme has effectively reduced price volatility and negative price events.	Premium market mechanisms can be adapted to other electricity markets to enhance price stability.
Gokce et al. (2024)	Renewable subsidies in Turkey have reduced electricity prices but have also led to retail electricity cost burdens.	Market reforms should consider both wholesale price reductions and end-user cost implications.
Halužan et al. (2023)	Renewable energy crowds out conventional electricity generation, leading to shifts in price dynamics in Eastern European markets.	Market structures need to evolve to support both renewable and conventional energy sources in transition phases.
Imani et al. (2021)	Wind and solar energy contribute to zonal electricity price variations in Italy.	Pricing mechanisms should incorporate location-based adjustments to account for regional renewable variations.
Kaplun et al. (2022)	Electricity pricing models for isolated energy systems with renewables differ significantly from interconnected grids.	Energy islands require unique pricing frameworks to ensure stability and sustainability.
Liebensteiner et al. (2024)	Germany faces rising electricity prices despite increased renewable capacity, influenced by other market trends.	Policy adjustments must consider external economic and geopolitical factors affecting electricity pricing.
Macedo et al. (2022)	Cross-border electricity flows significantly impact Spain’s renewable price dynamics.	International energy trade mechanisms should be optimized to stabilize pricing.

Peura & Bunn (2021)	Forward market hedging modifies the expected price effects of renewable integration.	Forward contracting strategies can be leveraged to stabilize electricity prices under high renewable penetration.
Rai & Nunn (2020)	Higher renewable penetration increases the frequency of extreme price events in Australia's energy-only market.	Energy market reforms should introduce mechanisms to reduce price spikes and mitigate financial risks.
Ritz (2016)	Increased renewable energy competition impacts forward contracting and long-term price expectations.	Renewable contracting policies should align with market stability goals.
Tolmasquim et al. (2021)	Renewable energy auctions have become a dominant pricing mechanism in Brazil, influencing electricity price structures.	Auction-based pricing models can enhance competitive renewable integration while maintaining price efficiency.

Policy and regulatory mechanisms play a crucial role in shaping the impact of renewable energy on electricity pricing. Several studies explore how different pricing mechanisms have been employed to manage price volatility and incentivize renewable investments. Germany's market premium scheme has been effective in reducing price volatility and minimizing negative price events (Frondel et al.,2022). This approach suggests that well-designed market incentives can enhance price stability while promoting renewable energy adoption. In the study of Gokce et al. (2024), they analyzed the impact of renewable subsidies in Turkey, which have successfully reduced electricity prices but have also imposed financial burdens on retail consumers. This underscores the importance of balancing wholesale price reductions with considerations for end-user affordability. The complexity of renewable energy integration is further highlighted by the interaction between electricity markets and international energy trade. Macedo et al. (2022) demonstrate that cross-border electricity flows play a significant role in shaping renewable price dynamics in Spain, indicating that interconnected markets require coordinated policy frameworks.

The transition toward auction-based pricing models has also been identified as a key strategy for integrating renewables while maintaining market efficiency. The approach of Tolmasquim et al. (2021) fosters competitive renewable integration while ensuring price efficiency, demonstrating the potential for structured procurement mechanisms to mitigate price instability. Despite the benefits of renewable energy integration, some markets continue to experience rising electricity prices despite increased renewable capacity. Liebensteiner et al. (2024) found that external economic and geopolitical factors, such as carbon pricing, fuel costs, and grid constraints, influence electricity pricing trends. These findings suggest that renewable energy alone does not guarantee lower prices and that a holistic approach, considering market-wide interactions, is necessary for effective policy formulation.

A significant challenge identified in this review is the divergence between electricity pricing in interconnected versus isolated energy systems. Kaplun et al. (2022) discuss how energy islands face unique pricing challenges due to their reliance on localized renewable generation. These isolated systems require tailored pricing frameworks that account for supply constraints and energy storage requirements to ensure grid reliability and affordability.

The VAR and time-series analyses of Alsaedi et al. (2020, 2021) in Australian and global electricity markets reveal that policy-driven pricing structures can help absorb the volatility introduced by renewables, thereby preventing disruptive price swings that could deter investment in clean energy infrastructure (see Table 3).

Table 3.

The Role of Market Design and Regulatory Frameworks in Renewable Energy Integration

Study	Study Focus	Key Findings
Alsaedi et al. (2021)	Impact of solar and wind prices on Australian electricity markets using VAR analysis.	Market design influences the stability of renewable energy pricing.
Alsaedi et al. (2020)	Time series analysis of solar and wind energy on global electricity markets.	Policy-driven pricing mechanisms stabilize market fluctuations.
Ballester & Furio (2024)	Machine learning analysis of renewables' impact on Iberian electricity markets.	Regulatory policies shape price behavior and volatility in renewable-heavy markets.
Casalicchio et al. (2022)	Investment optimization and benefit distribution in renewable energy communities.	Market frameworks influence financial viability and equitable distribution of benefits.
Cruz et al. (2023)	Flexible energy system interactions to enhance renewable energy penetration.	Regulatory support for integrated energy systems enhances market efficiency.
Espinosa & Pizarro-Irizar (2018)	Cost-effectiveness of renewable energy policies in Spain.	Market-based incentives drive cost reductions and improve renewable competitiveness.
Gicevskis et al. (2023)	Decentralized renewable energy transition in Latvia.	Policy structures impact decentralization success and market integration.
Halužan et al. (2023)	Crowding out of conventional energy sources by renewables.	Market rules determine the displacement of fossil fuel-based generation.
Houben et al. (2023)	Optimization of multi-energy system microgrids under uncertainty.	Market design frameworks affect the operational efficiency of renewable energy communities.
Kaplun et al. (2022)	Forecasting electricity pricing of energy islands with renewables.	Regulatory predictability reduces price fluctuations and investment risks.
Liebensteiner et al. (2024)	Impact of regulatory trends on electricity prices in Germany.	Policy structures counterbalance price reductions from renewables.
Macedo et al. (2022)	The role of electricity flows and renewable production in pricing behavior.	Transmission regulations influence cross-border energy market dynamics.
Madler et al. (2023)	Multi-agent modeling of urban microgrids and market shocks.	Decentralized energy markets depend on regulatory adaptability.
Meneguzzo et al. (2016)	Renewable energy effects on electricity price formation in Italy.	Tariff designs and subsidies impact price stability.
Peura & Bunn (2021)	Forward market impacts of renewable energy integration.	Market hedging mechanisms reduce risks in high-renewable scenarios.
Rai & Nunn (2020)	Variable renewables and price volatility in Australia's electricity market.	Market price caps and design reforms mitigate extreme price fluctuations.

Richstein et al. (2015)	Interaction between CO2 caps and renewable subsidies.	Carbon pricing must align with renewable energy policies for effective market integration.
Rios-Ocampo et al. (2021)	Energy security and renewable penetration in electricity markets.	Regulatory certainty promotes long-term energy security.
Tolmasquim et al. (2021)	Electricity market design and renewable energy auctions in Brazil.	Competitive auction structures support efficient renewable deployment.
Sheha et al. (2021)	Dynamic electricity pricing and solar penetration in smart grids.	Adaptive pricing models enhance renewable integration and economic feasibility.

Moreover, the work of Ballester & Furio (2024) underscores that market volatility in renewable-heavy markets is largely shaped by regulatory interventions. Similarly, research by Casalicchio et al. (2022) highlights that investment optimization strategies and benefit distribution frameworks within renewable energy communities influence financial viability and the equitable distribution of economic gains. Their findings suggest that without regulatory support, market inefficiencies may arise, particularly in decentralized energy systems where various stakeholders interact.

Regulatory frameworks that facilitate the integration of flexible energy systems have been shown to enhance overall market efficiency. Cruz et al. (2023) examine the role of regulatory support in integrating district heating and industrial energy systems, demonstrating that coordinated policy measures can lead to more efficient market operations. In the Spanish electricity market, Espinosa & Pizarro-Irizar (2018) provide evidence that market-based incentives, such as feed-in tariffs and subsidies, significantly drive cost reductions and improve the competitiveness of renewables. Their study further reveals that changes in regulatory structures can either bolster or hinder the expansion of renewable energy, depending on how they interact with market forces.

Decentralization of energy markets is another key component of effective market design. Gicevskis et al. (2023) examine the transition to decentralized renewable energy markets in Latvia, concluding that policy structures play a crucial role in determining the success of market decentralization efforts. Their findings indicate that financial incentives and regulatory stability are critical in fostering the development of decentralized energy infrastructure. Similarly, Houben et al. (2023) emphasize that regulatory adaptability is essential for optimizing multi-energy system microgrids, particularly in mitigating unpredictability in energy pricing.

The displacement of conventional fossil fuel-based generation by renewables is another regulatory challenge that necessitates careful market structuring. Halužan et al. (2023) provide empirical evidence from electricity markets in Europe showing that market rules significantly impact the extent to which renewable energy can displace fossil fuel generation. Their analysis highlights the importance of regulatory predictability in reducing price fluctuations and fostering a stable investment environment. Liebensteiner et al. (2024) show that while renewable expansion tends to reduce wholesale electricity prices, policy structures counterbalance these reductions through mechanisms that ensure grid reliability and energy security. Their study underscores the need for a balanced approach that incorporates both market liberalization and regulatory safeguards to maintain system stability.

A major regulatory consideration in renewable energy integration is the interaction between carbon pricing and renewable subsidies. Richstein et al. (2015) explore the relationship between CO2 caps and renewable subsidies, demonstrating that carbon pricing mechanisms must align with renewable energy policies to ensure effective market integration.

Without proper alignment, renewable incentives can lead to market distortions that hinder long-term energy transition goals. The stability of electricity markets in the presence of high renewable penetration is also a function of regulatory certainty.

Rios-Ocampo et al. (2021) emphasize that long-term policy stability encourage investor confidence and enhances energy security. Their study suggests that uncertain regulatory environments can deter investment and slow the adoption of renewable technologies. Competitive auction structures have emerged as an effective market design strategy for supporting renewable deployment.

Tolmasquim et al. (2021) examined that well-structured renewable energy auctions enhance competition and lead to cost reductions. Their findings support the argument that carefully designed market instruments can accelerate the transition to renewable energy while maintaining affordability. As importantly, the role of dynamic electricity pricing in optimizing renewable energy integration is highlighted in the work of Sheha et al. (2021). Their study explores the effectiveness of adaptive pricing models in smart grid environments, demonstrating that real-time pricing mechanisms can enhance economic feasibility and facilitate the large-scale deployment of solar energy.

Table 4.

Strategic Behaviors of Market Participants in Response to Renewable Energy Integration

Study	Study Focus	Key Findings
Alsaedi et al. (2021)	Impact of solar and wind prices on Australian electricity markets using VAR analysis.	Market participants adjust pricing strategies to mitigate volatility risks in response to renewable penetration.
Alsaedi et al. (2020)	Time series analysis of solar and wind energy on global electricity markets.	Hedging mechanisms and demand-side responses stabilize fluctuations caused by renewables.
Alsaedi et al. (2021)	Energy management responses to solar and wind pricing policies.	Regulatory policies influence investor and utility strategies in electricity markets.
Browne et al. (2015)	Effect of large-scale wind investment on market power in wholesale markets.	Large energy producers adjust market power strategies to maintain profitability amid increasing wind generation.
Casalicchio et al. (2022)	Investment optimization and fair benefit distribution in energy communities.	Renewable energy community participants adopt strategic cooperation models for cost-sharing and revenue optimization.
Cruz et al. (2023)	Flexible energy system interactions across industries to increase renewables.	Market participants leverage cross-sector flexibility to optimize renewable integration.
Frondel et al. (2022)	Impact of market premia for renewables on German electricity prices.	Participants strategically adjust bidding behaviors in response to renewable incentives and price signals.
Gicevskis et al. (2023)	Transitioning to decentralized renewable energy in Latvia.	Decentralized energy providers adapt pricing models based on local policy incentives.
Halužan et al. (2023)	Crowding out of conventional electricity generation by renewables.	Fossil-fuel-based producers modify capacity strategies to compete with renewables.

Houben et al. (2023)	Multi-energy system microgrid optimization under uncertainty.	Energy community participants engage in strategic dispatch optimization to minimize market exposure.
Kaplun et al. (2022)	Forecasting electricity pricing of energy islands with renewables.	Market actors use predictive models to adjust bidding strategies in renewable-dominated markets.
Liebensteiner et al. (2024)	High electricity prices despite renewable expansion in Germany.	Market trends indicate that suppliers adjust pricing strategies to counteract price suppression effects.
Macedo et al. (2022)	Role of electricity flows and renewable production in Spanish pricing behavior.	Market participants alter cross-border trading strategies in response to renewable supply variability.
Madler et al. (2023)	Multi-agent modeling of urban microgrids and market shocks.	Decentralized energy participants use real-time trading strategies to manage price risks.
Peura & Bunn (2021)	Impact of forward markets on renewable electricity pricing.	Participants engage in forward market hedging to mitigate renewable price variability.
Rai & Nunn (2020)	Renewable penetration and price volatility in Australian electricity markets.	Market actors react to renewables by adjusting supply-side and demand-side participation.
Richstein et al. (2015)	CO2 cap adjustments in response to renewable subsidies.	Firms shift compliance strategies to align with evolving carbon and renewable energy policies.
Rios-Ocampo et al. (2021)	Energy security and renewable penetration in electricity markets.	Utilities and grid operators develop resilience strategies to address renewable variability.
Sheha et al. (2021)	Dynamic electricity pricing and solar penetration in smart grids.	Market participants use adaptive pricing mechanisms to balance supply-demand fluctuations.
Tolmasquim et al. (2021)	Renewable energy auctions and electricity market design in Brazil.	Competitive bidding strategies evolve to maximize profitability in auction-based renewable procurement.

Market participants engage in a variety of strategic responses, ranging from pricing adjustments and forward market hedging to the development of decentralized energy systems and the strategic participation in renewable energy auctions (see Table 4).

One of the fundamental strategic behaviors observed among market participants is the modification of pricing strategies in response to renewable energy fluctuations. Studies conducted by Alsaedi et al. (2020a, 2020b, 2021) highlight how electricity producers and traders utilize pricing adjustments, demand-side management strategies, and hedging mechanisms to stabilize fluctuations in electricity prices caused by increased penetration of solar and wind energy. Specifically, market actors use forward contracts and spot market participation to mitigate the price volatility introduced by the intermittency of renewables.

Browne et al. (2015) reveal that in energy-only markets, fossil-fuel-based producers adopt market power strategies such as adjusting capacity bidding and withholding supply to counteract the downward pressure that renewables exert on electricity prices. This is corroborated by the findings of Halužan et al. (2023), who demonstrate that conventional energy providers are forced to modify their capacity management approaches in response to the crowding-out effect caused by renewables. Similarly, Liebensteiner et al. (2024) discussed that suppliers have strategically adjusted their pricing mechanisms to counterbalance price suppression effects, ensuring revenue stability.

Decentralized energy providers and renewable energy communities have also evolved their market participation strategies in response to policy changes and economic incentives. Casalicchio et al. (2022) demonstrate that energy community participants optimize cost-sharing mechanisms and revenue distribution models to enhance financial viability in renewable-dominated markets. Additionally, Houben et al. (2023) highlight that renewable energy communities employ predictive dispatch optimization techniques to minimize exposure to market fluctuations, improving overall efficiency in decentralized systems.

The research by Frondel et al. (2022) indicates that the introduction of market-based incentives has driven strategic bidding behaviors among renewable energy producers, reducing price volatility and optimizing returns. Similarly, Tolmasquim et al. (2021) emphasize that competitive bidding in renewable energy auctions has evolved, demonstrating how market participants continuously refine procurement strategies to maximize investment returns.

Macedo et al. (2022) illustrate how electricity market participants adjust trading mechanisms to account for the variability of renewable energy supply, thereby mitigating risks associated with transmission constraints and supply-demand mismatches. Furthermore, Ríos-Ocampo et al. (2021) find that utilities and grid operators develop resilience strategies to address energy security concerns, implementing adaptive mechanisms to balance the intermittency of renewables within interconnected power markets.

Another crucial strategic adaptation involves the use of predictive models and data-driven trading approaches. Kaplun et al. (2022) demonstrate that energy market participants leverage forecasting models to optimize bidding strategies in renewable-heavy markets, enhancing price predictability and investment confidence. Madler et al. (2023) further support this by showing that decentralized energy participants adopt real-time trading algorithms in urban microgrids, enabling more dynamic responses to energy-market shocks and optimizing financial outcomes. Richstein et al. (2015) provide evidence that firms strategically realign compliance efforts with CO_2 pricing mechanisms and renewable subsidies, ensuring regulatory compliance while optimizing cost structures. Similarly, Rai and Nunn (2020) suggest that market actors in Australia adjust supply-side and demand-side participation to accommodate regulatory changes associated with renewable energy penetration.

Lastly, the increasing adoption of adaptive pricing mechanisms among market participants underscores the role of dynamic electricity pricing in facilitating renewable energy integration. Sheha et al. (2021) show that energy providers and consumers implement adaptive pricing models that align with real-time supply-demand fluctuations, thereby improving economic feasibility. The effectiveness of such pricing adjustments in maintaining market equilibrium is further emphasized by Cruz et al. (2023), who highlight the role of cross-sector flexibility in enhancing renewable energy integration across industry, district heating, and power generation sectors.

Renewable energy reduces electricity spot prices where the merit order effect leads to a decrease in wholesale prices due to the preferential dispatch of low-marginal-cost renewable energy sources (Alsaedi et al., 2019; 2020a). However, this price suppression is accompanied by higher price fluctuations, suggesting the need for dynamic hedging mechanisms to protect market participants from excessive financial exposure (see Table 5). Peura and Bunn (2021) illustrate how forward markets modify expected price effects, indicating that hedging strategies incorporating renewable derivatives and long-term contracts can stabilize price fluctuations.

Table 5.

Hedging Strategies and Demand-Side Management for Mitigating Market Instability

Study	Study Focus	Implications for Hedging Strategies and Demand-Side Management
Alsaedi et al. (2019)	Renewable energy reduces electricity spot prices but increases volatility in the Australian market.	Risk management instruments such as hedging contracts should be enhanced to mitigate volatility.
Alsaedi et al. (2020)	Solar and wind energy lower electricity prices but introduce higher price fluctuations.	Development of market mechanisms that integrate dynamic hedging strategies to counteract price variability.
Ballester & Furió (2024)	Machine learning models predict renewable-induced price variations in the Iberian electricity market.	Advanced predictive analytics should be incorporated to optimize hedging strategies.
Browne et al. (2015)	Market power can suppress renewable cost benefits and distort pricing in energy-only markets.	Regulatory oversight is required to ensure fair pricing and effective risk management mechanisms.
Cruz et al. (2023)	Flexible energy system interactions between industries and district heating can improve grid stability.	Demand-side management policies should promote cross-sector energy flexibility to balance demand fluctuations.
Frondel et al. (2022)	Market premium schemes in Germany reduce negative price events and stabilize electricity markets.	Implementation of premium-based hedging strategies to ensure price stability.
Gokce et al. (2024)	Renewable subsidies lower electricity prices but increase financial burdens on retail consumers.	Demand response programs should be optimized to offset cost burdens and enhance market resilience.
Houben et al. (2023)	Microgrids provide localized renewable energy security and enhance economic viability.	Distributed energy storage and peer-to-peer trading can be leveraged as hedging mechanisms.
Kaplun et al. (2022)	Isolated energy systems exhibit distinct pricing behaviors with renewables.	Hedging strategies should be tailored for energy islands to maintain financial stability.
Liebensteiner et al. (2024)	Despite renewable expansion, Germany experiences high electricity prices due to geopolitical and economic factors.	Policy frameworks should integrate external economic considerations into hedging models.
Macedo et al. (2022)	Cross-border electricity flows significantly impact renewable price stabilization in Spain.	Regional electricity trading agreements should incorporate hedging instruments to enhance pricing predictability.
Madler et al. (2023)	Microgrid systems reduce vulnerability to market shocks and enhance local energy resilience.	Demand-side flexibility should be encouraged to provide decentralized stability against market instabilities.

Peura & Bunn (2021)	Forward markets modify expected price effects of renewable integration.	Renewable energy derivatives and forward contracts should be expanded to mitigate risk exposure.
Rai & Nunn (2020)	Increased renewable penetration in Australia leads to higher frequency of extreme price events.	Real-time demand-side response mechanisms should be strengthened to address sudden price fluctuations.
Richstein et al. (2015)	CO_2 cap adjustments are inadequately linked to renewable energy policies, affecting market stability.	Carbon pricing strategies should be integrated into hedging frameworks to balance environmental and financial objectives.
Ríos-Ocampo et al. (2021)	Renewable energy penetration influences energy security and pricing risks.	Market mechanisms should include resilience-based hedging models to address risks associated with high renewable integration.
Ritz (2016)	Renewable energy competition impacts forward contracting and long-term pricing expectations.	Electricity contracting policies should be refined to align long-term price stability with renewable integration.
Sheha et al. (2020)	Dynamic electricity pricing and solar penetration influence the feasibility of distributed storage systems.	Storage-based demand response solutions should be integrated into hedging and market stabilization strategies.
Tolmasquim et al. (2021)	Renewable energy auctions in Brazil play a crucial role in electricity price determination.	Auction-based hedging mechanisms should be explored to manage financial risks in renewable markets.

The influence of regulatory and policy frameworks is also evident in mitigating market instabilities. Frondel et al. (2022) has effectively analyzed the reduction on price volatility and minimized negative price events by aligning market incentives with renewable generation. Cruz et al. (2023) argue that flexible energy system interactions, including industrial load adjustments and district heating coordination, can enhance grid stability by redistributing demand in response to renewable supply variability.

Studies by Houben et al. (2023) and Madler et al. (2023) suggest that decentralized microgrid systems equipped with real-time optimization capabilities can mitigate the effects of market shocks and reduce reliance on centralized energy markets. Macedo et al. (2022) explore how cross-border electricity flows influence Spain’s renewable price dynamics, emphasizing that regional energy trade agreements can serve as implicit hedging mechanisms by balancing excess supply and demand across interconnected markets.

Studies of Rai and Nunn (2020) and Reichstein et al. (2015) study suggest highlighting the importance of developing real-time demand response programs and financial risk mitigation strategies. Ritz (2016) finds that increased renewable energy competition impacts forward contracting incentives, necessitating revised electricity contracting policies to maintain long-term price stability while supporting continued investment in renewables. These localized energy solutions provide hedging benefits by enabling direct energy trading within communities and enhancing economic viability through distributed generation.

Table 6 divulges the exploration of advanced predictive analytics in mitigating market instability remains inadequate, particularly in the application of artificial intelligence (AI) and machine learning for forecasting price volatility. Ballester and Furió (2024) emphasize that while these technologies have the potential to improve market predictability, their practical implementation is still in its early stages. The use of AI-driven market simulations could enhance forecasting accuracy and enable policymakers to anticipate extreme price fluctuations, yet there is limited empirical evidence supporting their effectiveness in real-world electricity markets.

Table 6.

Identified Research Gaps and Recommendations for Future Research and Policy Development

Study	Research Gap Identified	Recommendations for Future Research and Policy
Alsaedi et al. (2021)	Limited analysis on the long-term hedging effectiveness of renewables in Australian electricity markets.	Extend studies to incorporate long-term market behavior and policy interactions.
Alsaedi et al. (2020)	Lack of global comparative analysis on renewable-induced price fluctuations.	Conduct cross-country analyses to compare market responses to renewable integration.
Ballester & Furio (2024)	Inadequate exploration of machine learning in renewable market volatility predictions.	Improve predictive analytics and develop robust forecasting models for policymakers.
Browne et al. (2015)	Market power effects of large-scale renewables remain underexplored.	Investigate the role of oligopolistic market structures in renewable integration.
Casalicchio et al. (2022)	Unequal benefit distribution in renewable energy communities.	Design policy frameworks to ensure equitable participation in decentralized energy systems.
Cruz et al. (2023)	Lack of sectoral integration strategies for renewable energy adoption.	Promote cross-sector collaboration to enhance system flexibility and market stability.
Espinosa & Pizarro-Irizar (2018)	Cost-effectiveness of renewables in mitigating carbon emissions not fully addressed.	Assess the trade-offs between cost and emissions reduction in renewable deployment strategies.
Frondel et al. (2022)	Market premia effects on investment incentives remain ambiguous.	Investigate how incentive schemes influence long-term investment behavior.
Gicevskis et al. (2023)	Economic feasibility of decentralized renewable transitions remains uncertain.	Conduct longitudinal studies on cost-benefit dynamics of decentralized energy models.
Gokce et al. (2024)	Lack of adaptive hedging mechanisms for renewable energy price volatility.	Develop real-time pricing models that mitigate renewable intermittency risks.
Halužan et al. (2023)	Insufficient evaluation of conventional energy crowding out by renewables.	Model long-term effects of renewables on conventional generation investment.
Houben et al. (2023)	Uncertainty in microgrid economic viability and resilience strategies.	Investigate real-world applications of microgrid optimization under policy constraints.
Liebensteiner et al. (2024)	Price suppression effects of renewables not well quantified.	Analyze pricing trends to understand policy adjustments necessary for market sustainability.
Macedo et al. (2022)	Limited research on cross-border electricity trading in renewable-dominant markets.	Develop cross-national energy trading models to enhance grid reliability.

Madler et al. (2023)	Uncertainty in decentralized energy resilience during market shocks.	Evaluate microgrid and P2P trading frameworks to improve market shock absorption.
Peura & Bunn (2021)	Insufficient focus on forward market hedging in high renewable penetration scenarios.	Study interactions between forward market participation and renewable energy price risks.
Rai & Nunn (2020)	Limited analysis on extreme price fluctuations in energy-only markets.	Investigate policy interventions that can mitigate price extremes in renewable-heavy grids.
Richstein et al. (2015)	CO2 cap adjustments not adequately linked to renewable energy policies.	Explore integrated carbon pricing strategies that align with renewable deployment.
Ríos-Ocampo et al. (2021)	Energy security risks in renewable transition poorly addressed.	Develop resilience indicators for electricity markets undergoing high renewable penetration.
Tolmasquim et al. (2021)	Renewable auction mechanisms lack policy coherence for long-term stability.	Design regulatory frameworks that ensure competitive and sustainable renewable procurement.

Oligopolistic market structures and their interaction with renewable energy integration remain underexplored. Browne et al. (2015) highlight that large-scale renewable investments significantly alter competitive conditions, yet the extent to which market power is redistributed among key players remains ambiguous. The evolving role of dominant market participants in shaping electricity pricing under increased renewable penetration requires further scrutiny. Similarly, the financial benefits of community-based energy models are not well understood.

Casalicchio et al. (2022) argue that while decentralized energy systems and community-driven electricity trading platforms have gained attention, there is little empirical research on the fair distribution of economic gains among participants. Ensuring equitable benefit-sharing mechanisms is critical to maintaining market efficiency and preventing distortions in decentralized energy markets.

The integration of renewable energy into broader energy systems, including industrial and heating sectors, is another area where research remains limited. Cruz et al. (2023) stress that energy systems should not operate in isolation, as sectoral interactions can enhance grid stability through flexible demand-side management. However, the lack of studies on sectoral integration limits understanding of how industrial processes and district heating can offset renewable intermittency and improve market resilience.

The cost-effectiveness of renewables in reducing carbon emissions presents another unresolved challenge. Espinosa and Pizarro-Irizar (2018) reveal that while renewable energy deployment contributes to emission reductions, the economic trade-offs between regulatory subsidies, consumer electricity prices, and CO_2 mitigation remain poorly quantified. Moreover, current carbon pricing strategies do not adequately reflect the changing dynamics of renewable deployment (Richstein et al., 2015). Market-based incentives such as market premium schemes also introduce uncertainties regarding long-term investment stability. Frondel et al. (2022) demonstrate that while such schemes encourage renewable investments, their broader influence on market stability remains unclear, particularly in the face of evolving policy frameworks and shifting electricity demand patterns.

The financial viability of decentralized energy systems, particularly concerning energy storage costs and regulatory support mechanisms, remains uncertain. Gicevskis et al. (2023) note that the sustainability of decentralized models depends on the economic feasibility of energy storage and the effectiveness of supportive regulatory structures. Additionally, conventional hedging strategies often fail to accommodate the unpredictable nature of renewable generation (Gokce et al., 2024). This unpredictability raises questions about whether existing financial instruments adequately mitigate risks associated with price fluctuations in high-renewable electricity markets.

Renewable energy policies continue to reshape electricity markets, but their impact on conventional generation investment remains ambiguous. Halužan et al. (2023) argue that while renewable support policies accelerate the transition to cleaner energy sources, they also introduce uncertainties regarding the long-term viability of conventional generation assets. Houben et al. (2023) point out that while theoretical models suggest that microgrids enhance energy security and grid stability, real-world applications remain insufficiently studied. Assessing the economic and operational efficiency of microgrid deployments under different market conditions is crucial to understanding their role in future energy systems.

The price suppression effects of renewables have also not been adequately quantified. Liebensteiner et al. (2024) highlight that while renewables can drive down wholesale electricity prices through the merit-order effect, the long-term sustainability of such price reductions remains uncertain, especially as markets adapt to fluctuating supply and demand conditions. Additionally, cross-border electricity trading under high renewable penetration is insufficiently studied. Macedo et al. (2022) emphasize that there is limited research on how international electricity markets interact when renewables dominate energy generation, particularly in the context of price arbitrage and grid stability.

The potential of decentralized P2P electricity trading to mitigate market disruptions also requires further empirical validation. Madler et al. (2023) indicate that while decentralized trading models could enhance market efficiency, real-world implementation studies are still lacking. Similarly, Peura and Bunn (2021) argue that forward contracting mechanisms must evolve to accommodate increased renewable variability, yet research on the design of adaptive financial instruments remains limited. The challenges introduced by high renewable penetration further necessitate the development of new resilience indicators for electricity markets. Ríos-Ocampo et al. (2021) suggest that market stability assessments must incorporate metrics that account for the variability and intermittency of renewable generation, yet such frameworks remain underdeveloped.

Finally, while renewable energy auctions have been widely adopted as a market mechanism, their long-term sustainability remains uncertain. Tolmasquim et al. (2021) demonstrate that while auctions effectively stimulate competition and drive investment in renewable energy projects, their ability to maintain stable pricing structures and ensure long-term investor confidence is still unclear. Further analysis is needed to understand how auction-based procurement mechanisms evolve as renewable capacity continues to expand and market conditions shift.

Future research should prioritize the refinement of AI algorithms to incorporate diverse economic and climatic variables that influence renewable energy supply, ensuring greater predictive accuracy and market stability. A deeper understanding is needed regarding how major energy producers adapt their pricing strategies and exercise market power in response to increasing renewable energy penetration, particularly in deregulated electricity markets where competitive dynamics are more complex. Additionally, studies should examine the social equity implications of decentralized energy markets and develop mechanisms that equitably distribute financial benefits among prosumers and consumers, preventing economic disparities in renewable energy adoption.

Cross-sector collaboration models should be explored to align energy consumption patterns with renewable availability, thereby enhancing grid stability and market efficiency. Comprehensive cost-benefit analyses are necessary to determine whether existing subsidy structures provide the most effective balance between financial incentives and environmental benefits. Future research should also assess how various incentive mechanisms interact with electricity market dynamics and whether they inadvertently contribute to price distortions that affect both investors and consumers.

Longitudinal studies on the cost-benefit evolution of decentralized energy adoption are essential to evaluate their long-term economic and operational viability. Scenario modeling should be developed to assess the feasibility of transitioning toward a predominantly renewable-based electricity market, taking into account economic sustainability, technological advancements, and policy interventions. Understanding the efficiency of microgrid deployments under different market conditions is crucial to determining their potential role in enhancing grid reliability and energy security.

Balancing renewable growth with pricing mechanisms that maintain profitability for both renewable and conventional generators remains a pressing concern. Future research should focus on developing robust cross-border trading models that optimize renewable energy utilization while ensuring grid stability. Additionally, the development of decentralized trading frameworks should be explored as a means of enhancing system reliability during supply-demand imbalances.

Further studies should investigate the role of forward market participation in mitigating renewable energy price risks and improving overall market efficiency. Research should also examine policy frameworks that proactively address extreme pricing events, ensuring that regulatory interventions support both investor confidence and market stability. Policymakers should focus on designing energy security metrics specifically tailored to renewable-intensive markets, incorporating factors such as intermittency risks and grid resilience. Finally, the development of regulatory frameworks that facilitate competitive yet stable renewable procurement should be a key priority to ensure the long-term sustainability of electricity markets under high renewable penetration.

Conclusion

The findings of this systematic review underscore the profound impact of renewable energy integration on electricity market stability and pricing. The analysis reveals that the merit-order effect, whereby low-marginal-cost renewable energy sources such as wind and solar displace higher-cost conventional generation, is a primary driver of price reductions in wholesale electricity markets. Studies demonstrate that this effect has significantly lowered electricity prices in markets with high renewable penetration, including Australia, Germany, and Spain. However, while the cost savings for consumers are evident, the economic viability of conventional energy producers has been challenged, leading to concerns regarding long-term investment in grid stability and capacity adequacy.

Despite the downward pressure that renewables exert on electricity prices, their inherent intermittency introduces volatility into market dynamics. This review highlights that increased renewable penetration correlates with heightened price fluctuations, necessitating the implementation of hedging mechanisms and financial instruments to mitigate extreme price events. The integration of forward markets, renewable derivatives, and real-time pricing adjustments has been identified as crucial in stabilizing markets that experience high renewable variability. The role of AI and machine learning in forecasting price fluctuations remains underexplored, yet emerging studies indicate that predictive analytics could enhance market responsiveness and price stability.

The interaction between renewable integration and market structures is complex, particularly in energy-only markets where firms with significant market power can influence pricing strategies. The findings suggest that oligopolistic behavior in wholesale markets can suppress the cost-saving benefits of renewables, underscoring the necessity for regulatory interventions that prevent market distortions. Additionally, cross-border electricity trading is emerging as a key determinant of price stability in interconnected markets, with studies indicating that regional energy trade agreements can facilitate the efficient distribution of renewable energy surpluses while mitigating local price volatility.

Decentralization has been identified as a critical component of future market designs, with microgrids and peer-to-peer trading systems offering localized solutions for enhancing energy security and price stability. Studies demonstrate that community-driven renewable energy models can mitigate market disruptions, but challenges remain regarding financial viability, regulatory support, and equitable benefit distribution. Furthermore, demand-side management strategies, including real-time pricing mechanisms and industrial load flexibility, have been shown to enhance grid resilience by aligning consumption patterns with renewable energy availability.

The regulatory landscape plays a fundamental role in shaping the impact of renewable energy on market stability. This review highlights that well-designed policy frameworks, including feed-in tariffs, capacity markets, and market premium schemes, have successfully mitigated price volatility while encouraging renewable investments. However, the long-term sustainability of these mechanisms remains uncertain, particularly as markets transition toward higher shares of renewable generation. The alignment of carbon pricing mechanisms with renewable energy policies has also been identified as a crucial factor in ensuring market stability while promoting environmental objectives.

While renewables have been effective in reducing overall electricity costs, their integration has also introduced new challenges related to energy security and grid reliability. Studies indicate that high shares of renewables can lower reserve margins, necessitating the development of new resilience indicators and strategic market adaptations. The potential for renewables to provide ancillary services, such as frequency regulation and reserve capacity, remains an area requiring further exploration. Additionally, energy islands and isolated power systems face unique challenges in integrating renewables, necessitating specialized pricing frameworks to ensure economic and operational sustainability.

The findings of this review point to a critical need for continued research into optimizing market designs that balance renewable expansion with pricing mechanisms that ensure both investor confidence and consumer affordability. While auction-based procurement models have proven effective in promoting competitive renewable integration, their long-term effects on price stability warrant further investigation. The development of adaptive financial instruments, decentralized energy trading frameworks, and predictive market analytics will be instrumental in shaping the future of renewable-dominant electricity markets.

In conclusion, renewable energy integration has reshaped electricity markets by reducing wholesale prices, increasing price volatility, and necessitating new regulatory and market mechanisms to maintain stability. The transition toward a predominantly renewable-based electricity system requires coordinated policy efforts, investment in predictive analytics, and the refinement of market structures to accommodate renewable variability while ensuring economic sustainability. This review provides a comprehensive synthesis of the complex interactions between renewable energy, market stability, and pricing, offering insights for policymakers, energy economists, and market regulators seeking to navigate the evolving energy landscape.

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