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Navigating the Renewable Energy Transition: A Systematic Review of Economic and Policy Strategies for Grid Integration, Stability, and Viability

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ABSTRACT

Despite extensive research on renewable energy technologies and grid systems, a critical gap persists in understanding the integrated economic and policy frameworks necessary for cost-effective, stable grid operation with high renewable penetration. Current literature remains fragmented across disciplinary boundaries, preventing cohesive strategies that balance technical requirements with economic sustainability. This systematic review synthesizes economic and policy strategies for successful renewable energy integration by examining the intersection between technical challenges, economic viability, and policy framework effectiveness. A multistage analysis adhering to PRISMA 2020 guidelines combined systematic review methodology with bibliometric analysis using VOSviewer and Structural Topic Modeling using R. Comprehensive Scopus database search yielded 507 initial documents, systematically filtered to 142 high-quality studies spanning 2014-2024. Bibliometric analysis revealed a decisive shift from technical integration focus (80% in 2014) toward market design and policy frameworks (60% by 2024). Structural Topic Modeling identified three themes: Renewable Energy Integration (37%), Electricity Market Design and Policy (33%), and Energy Storage and Grid Flexibility (30%). Analysis demonstrates successful transitions require technology-specific support mechanisms, market designs compensating flexibility resources for multiple grid services, and adaptive policy frameworks maintaining investment certainty. This research challenges prevailing assumptions about renewable energy barriers, revealing institutional innovation has become more critical than technical solutions. The findings provide the first comprehensive mapping of interdisciplinary research evolution, demonstrating fragmented approaches hinder optimal resource allocation. Future research should prioritize integrated assessment frameworks evaluating strategies across technical, economic, and policy dimensions simultaneously to support comprehensive institutional transformation required for sustainable energy transitions.

Keywords: Renewable Energy Integration, Electricity Market Design, Energy Policy, Grid Stability, Energy Storage, Systematic Review
JEL Classifications: Q48, L94, Q41, L51, Q42

1. INTRODUCTION

The global energy sector is undergoing an unprecedented transformation as nations worldwide accelerate their transition toward renewable energy sources to address climate change imperatives and enhance energy security (Hassan et al., 2024). This renewable energy transition represents one of the most significant shifts in the global electricity system since the advent of centralized power generation, with renewable capacity additions reaching record levels and variable renewable energy sources such as wind and solar photovoltaics increasingly dominating new generation investments (Newbery et al., 2018). The urgency of this transition has been amplified by international climate commitments, including the Paris Agreement targets, which necessitate rapid decarbonization of electricity systems while maintaining reliable, affordable energy supply for economic development and social welfare (Gomez-Echeverri, 2018; Nwaobi, 2025).

The integration of renewable energy sources into existing electricity grids presents multifaceted challenges that extend far beyond technical considerations to encompass complex economic, policy, and market design dimensions (Hassan et al., 2024; Singh and Singh, 2024). Unlike conventional dispatchable generation sources, renewable energy technologies are characterized by variability, intermittency, and location-specific resource availability, fundamentally disrupting traditional power system operations designed around predictable, controllable generation (Ahmed et al., 2020; Shafiullah et al., 2022). These inherent characteristics create substantial technical challenges including generation uncertainty, power quality issues, voltage and angular stability concerns, and grid balancing requirements that demand sophisticated solutions for maintaining system reliability and stability (Hu et al., 2018).

Beyond technical integration challenges, the economic implications of renewable energy deployment are increasingly recognized as critical determinants of transition success (Przychodzen and Przychodzen, 2020). The economic viability of renewable energy systems depends not only on generation costs but also on complex interactions between system-wide infrastructure requirements, market mechanisms, policy frameworks, and the ability to manage intermittency while maintaining grid stability (Oyewo et al., 2020; Zappa et al., 2021). Current electricity market structures, developed for conventional dispatchable generation, often fail to adequately capture the value that renewable energy sources provide to the system or to properly incentivize the flexibility resources necessary for high renewable penetration scenarios (Green and Staffell, 2021).

The policy and regulatory landscape surrounding renewable energy integration has evolved rapidly, with governments implementing diverse support mechanisms, market design innovations, and regulatory frameworks to facilitate the energy transition while maintaining system reliability and economic efficiency (Pandey et al., 2023). However, the effectiveness of these interventions varies significantly across different contexts, reflecting the complex interplay between technological capabilities, economic incentives, market structures, and regulatory environments (Algarvio, 2023; Zakeri et al., 2023). Understanding how policy instruments and market design elements influence investment decisions, operational efficiency, and cost allocation among stakeholders has become crucial for designing effective pathways toward renewable energy integration (Khan et al., 2014).

The critical role of energy storage and system flexibility mechanisms has emerged as a cornerstone challenge for renewable energy integration, as the intermittent nature of wind and solar resources requires sophisticated solutions to maintain grid stability and reliability (Xu et al., 2023; Sihvonen et al., 2024). Energy storage technologies, demand response programs, and other flexibility resources represent essential components for managing renewable energy variability, yet their deployment faces significant economic and regulatory barriers that require coordinated policy interventions and market design innovations (Zakeri et al., 2021; Haji Bashi et al., 2022).

Despite extensive research on renewable energy technologies and grid systems, a critical gap persists in understanding the integrated economic and policy frameworks necessary for cost-effective, stable grid operation with high renewable penetration. Current literature remains fragmented—technical integration studies rarely address comprehensive economic implications, economic analyses focus narrowly on generation costs rather than system-wide stability economics, and regional case studies fail to provide comparative insights across diverse market structures. This compartmentalization prevents the development of cohesive strategies that effectively balance technical requirements with economic sustainability through appropriate market designs and regulatory mechanisms. A systematic review is urgently needed to identify optimal economic approaches and policy instruments that can support large-scale renewable integration while ensuring grid reliability, addressing intermittency challenges, and maintaining long-term affordability.

This research addresses these gaps through three specific objectives: first, to quantify the complete economic impact profile of renewable integration by analysing both direct infrastructure costs (grid reinforcement, balancing services, curtailment compensation) and system benefits (avoided fuel costs, reduced emissions, enhanced energy security) across different market structures and renewable penetration levels; second, to evaluate the cost-effectiveness of specific grid stability solutions (battery storage systems, pumped hydro storage, demand response programs, enhanced interconnections) by comparing their levelized costs, performance metrics, and investment requirements under varying regulatory environments and renewable deployment scenarios; and third, to assess how specific policy instruments and market design elements (capacity remuneration mechanisms, real-time pricing structures, locational marginal pricing, green certificates, grid connection policies) influence investment incentives, operational efficiency, and cost allocation among stakeholders, with particular attention to identifying replicable frameworks that have successfully maintained affordability while accelerating renewable deployment in diverse economic contexts.

2. MATERIALS AND METHODS

The study employed a multistage data analysis approach that adhered to the PRISMA 2020 guidelines to ensure methodological rigor and transparency in the identification, screening, and synthesis of relevant literature. Following the comprehensive database search and study selection process, bibliometric analysis was conducted using VOS viewer software to visualize collaboration networks, keyword co-occurrence patterns, and citation relationships within the renewable energy economics and policy literature, which provided valuable insights into research trends, influential authors, and thematic clusters that informed the subsequent qualitative analysis. To complement the traditional thematic synthesis, Structural Topic Modeling (STM) was implemented using R statistical software to identify latent topics and themes within the corpus of selected studies, enabling the systematic discovery of hidden patterns in research focus areas and the quantitative assessment of topic prevalence across different publication years, journals, and geographical contexts. This triangulated analytical approach combining PRISMA-guided systematic review methodology, bibliometric visualization, and computational topic modeling provided a robust framework for synthesizing the complex and multidisciplinary literature on renewable energy integration economics and policy, ensuring both comprehensive coverage and objective identification of key research themes while minimizing reviewer bias in the categorization and interpretation of findings. Figure 1 below highlights the multistage data analysis process.

2.1. PRISMA inclusion and exclusion criteria

The Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) criteria were followed in this study to conduct a systematic literature review (Khan and Qureshi, 2020; Qureshi and Khan, 2022). In this study, a sizable database of the literature was subjected to a thorough literature review. Transparency in PRISMA was the criteria of relevance for the inclusion or exclusion of studies must be made explicit, alongside each search string used, according to the PRISMA procedure (Page et al., 2021). The systematic literature search was conducted using Scopus database with a comprehensive search string ("renewable energy" OR "renewable source*" OR "variable renewable*" OR "intermittent renewable*" OR "solar PV" OR "wind power" OR "wind energy") AND ("grid integration" OR "system integration" OR "electricity grid" OR "power system*" OR "grid stability" OR "grid reliability" OR "intermittency") AND ("economic viability" OR "economic impact*" OR "cost-benefit" OR "investment requirement*" OR "market design" OR "electricity market*") AND ("policy framework*" OR "energy policy" OR "regulatory mechanism*" OR "capacity market*"" OR "carbon pricing" OR "support scheme*") combining four key thematic areas: Renewable energy technologies, grid integration challenges, economic considerations, and policy frameworks, which initially yielded 507 relevant documents. Figure 2 below illustrates the inclusion and exclusion of the article.

Following the PRISMA 2020 methodology, inclusion criteria were systematically applied to ensure relevance and quality: temporal boundaries were established from 2014 to 2024 to capture the most current decade of renewable energy transition research, reducing the corpus to 425 documents; subject area filtering was then applied to retain only studies within Energy, Engineering, Environmental Science, Computer Science, Economics, Econometrics and Finance, and Social Sciences disciplines, resulting in 291 documents that aligned with the interdisciplinary nature of the research objectives; document type restrictions were imposed to include only peer-reviewed articles and review papers, eliminating conference proceedings, book chapters, and other non-

Figure 1: Multistage data analysis

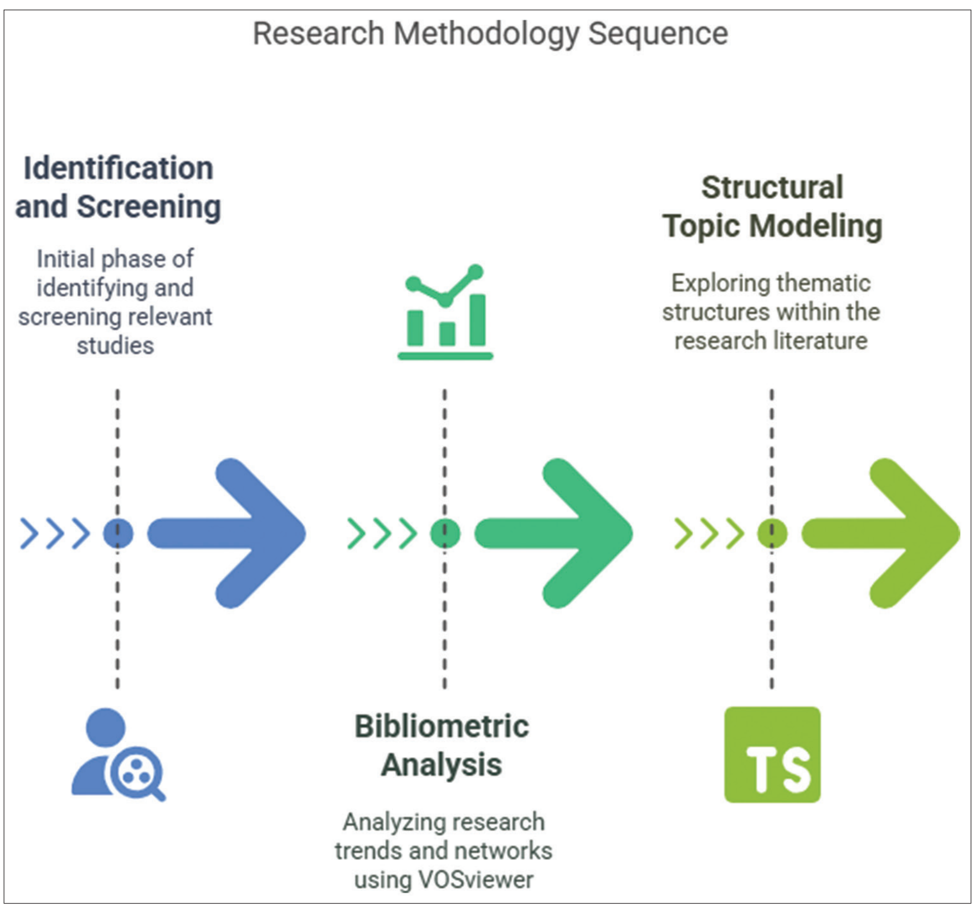
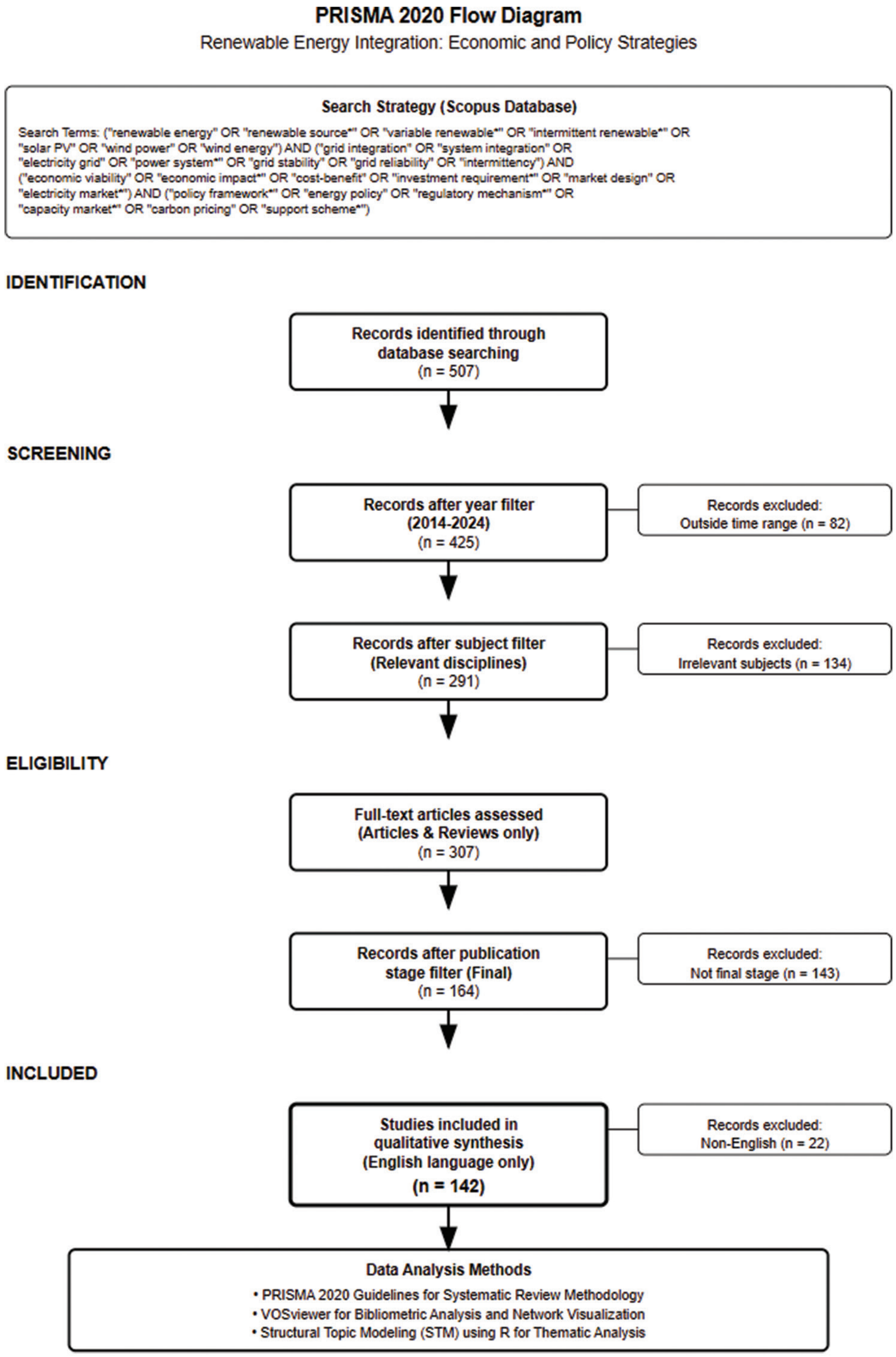


Figure 2: PRISMA inclusion and exclusion criteria



peer-reviewed materials to ensure academic rigor, yielding 307 studies; publication stage filtering retained only final published works to avoid preliminary or incomplete research, reducing the sample to 164 documents; and finally, language restrictions limited inclusion to English-language publications to ensure accessibility and comprehensibility during the analysis phase, resulting in a final corpus of 142 high-quality, peer-reviewed studies that comprehensively addressed the intersection of renewable energy integration economics and policy frameworks within the specified temporal and disciplinary boundaries.

3. RESULTS

3.1. Descriptives

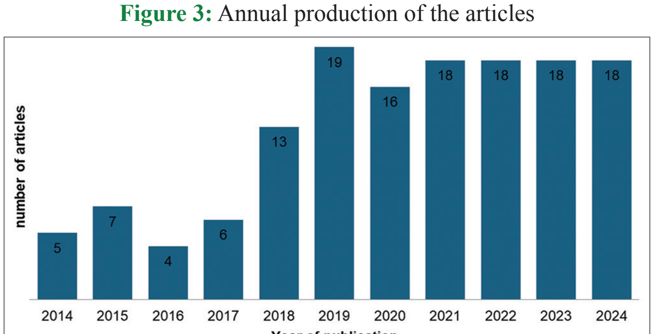
Table 1 presents comprehensive bibliometric characteristics of the 130 documents retrieved from the systematic search, spanning a 10-year period from 2014 to 2024 across 104 distinct publication sources. The dataset demonstrated robust growth dynamics with an impressive annual growth rate of 27.69%, indicating exponential expansion in research output on renewable energy integration economics and policy, while maintaining a relatively recent average document age of 3.09 years that reflects the contemporary relevance of the field. The scholarly impact of the corpus was evidenced by an average of 25.16 citations per document, supported by an extensive reference network of 6,998 citations that underscores the interdisciplinary nature and cumulative knowledge building within this research domain. Author collaboration patterns revealed substantial international engagement, with 477 contributing authors across the dataset, of whom only 16 published single-authored works, resulting in an average of 3.86 co-authors per document and 19.23% international co-authorship rate that demonstrates the global, collaborative nature of renewable energy integration research. The document composition comprised predominantly peer-reviewed articles (121 documents, 93.1%) with a smaller proportion of review papers (9 documents, 6.9%), while the substantial keyword diversity—including 505 Keywords Plus identifiers and 519 author-designated keywords—reflects the multifaceted and evolving terminology within this rapidly expanding research field.

In addition, Figure 3 illustrates the temporal distribution of the 142 included studies across the eleven-year review period, revealing distinct phases in research activity and scholarly attention to renewable energy integration economics and policy. The analysis demonstrated a marked acceleration in publication frequency beginning in 2018, when annual output increased substantially from an average of 5.5 articles per year (2014-2017) to 13 articles, representing a 136% increase that signaled growing academic and policy interest in the economic dimensions of renewable energy integration. This upward trajectory continued through 2019, which recorded the highest single-year output of 19 publications, coinciding with intensified global climate policy commitments and the increasing deployment of variable renewable energy sources that necessitated comprehensive economic and policy frameworks. Following a slight decline to 16 articles in 2020-likely attributable to pandemic-related research disruptions—publication activity stabilized at consistently high levels, with 18 articles published annually from 2021 through 2024, indicating that research focus on renewable energy integration economics and policy has reached a sustained plateau of intensive scholarly engagement.

Table 1: Main information of records

Description	Results
Timespan	2014:2024
Sources (Journals, Books, etc.)	104
Documents	130
Annual Growth Rate %	27.69
Document Average Age	3.09
Average citations per doc	25.16
References	6998
Keywords Plus (ID)	505
Author's Keywords (DE)	519
Authors	477
Authors of single-authored docs	16
Single-authored docs	17
Co-Authors per Doc	3.86
International co-authorships %	19.23
article	121
review	9

Figure 3: Annual production of the articles



Furthermore, Figure 4 presents the distribution of the 142 included studies across the ten most prolific publication sources, revealing distinct publication patterns that reflect the interdisciplinary nature and specialized focus areas within renewable energy integration research. The journal Energies emerged as the dominant publication venue with 27 articles (19.0% of the total corpus), establishing itself as the primary platform for comprehensive renewable energy research that bridges technical, economic, and policy dimensions. Energy Policy ranked as the second most significant source with 14 publications (9.9%), demonstrating the critical importance of policy-oriented research in addressing renewable energy integration challenges, while Applied Energy and IEEE Access each contributed 9 articles (6.3%), representing the strong technical and applied engineering perspectives essential to understanding grid integration economics. The specialized nature of the field was further evidenced by the presence of power systems-focused publications (IEEE Transactions on Power Systems with 7 articles) alongside broader energy economics journals (Energy Economics with 4 articles and Energy with 6 articles), indicating successful integration of technical engineering knowledge with economic analysis. The inclusion of sustainability-focused venues (Sustainability with 4 articles) and renewable energy-specific journals (Renewable Energy with 5 articles, Energy Reports with 5 articles) demonstrates the field's expansion beyond traditional disciplinary boundaries, reflecting the holistic approach required to address the complex interplay between renewable energy technologies, economic viability, and policy frameworks in contemporary energy system transformation.

3.2. Bibliometric analysis

Following the comprehensive database search and study selection process, bibliometric analysis was conducted using VOSviewer software to visualize collaboration networks, keyword co-occurrence patterns, and citation relationships within the renewable energy economics and policy literature, which provided valuable insights into research trends, influential authors, and thematic clusters that informed the subsequent qualitative analysis (Waltman et al., 2010).The keyword co-occurrence analysis presented in Table 2 and visualized in Figure 5's network diagram reveals the conceptual landscape and thematic interconnections within renewable energy integration economics and policy research. The analysis identified "energy policy" as the most prominent keyword with 109 occurrences and a total link strength of 1,058, establishing it as the central organizing concept that connects technical, economic, and regulatory dimensions of renewable energy integration.

Figure 4: Most relevant sources

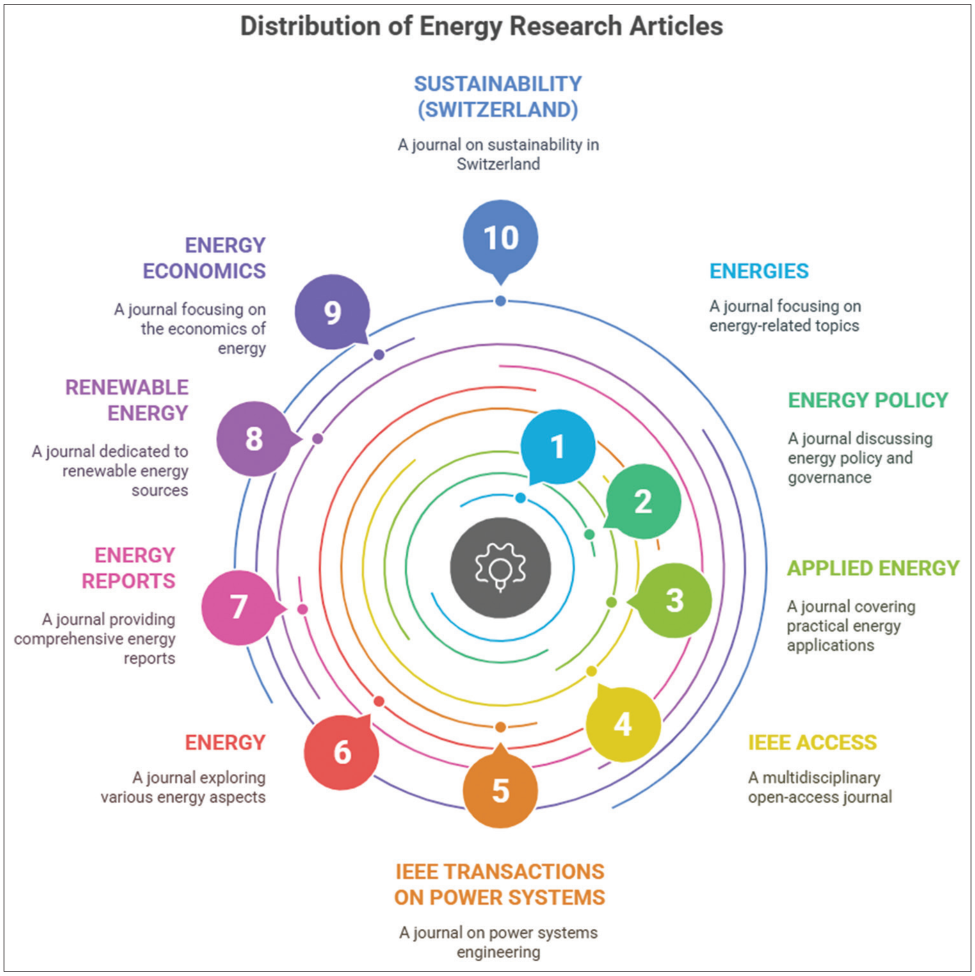
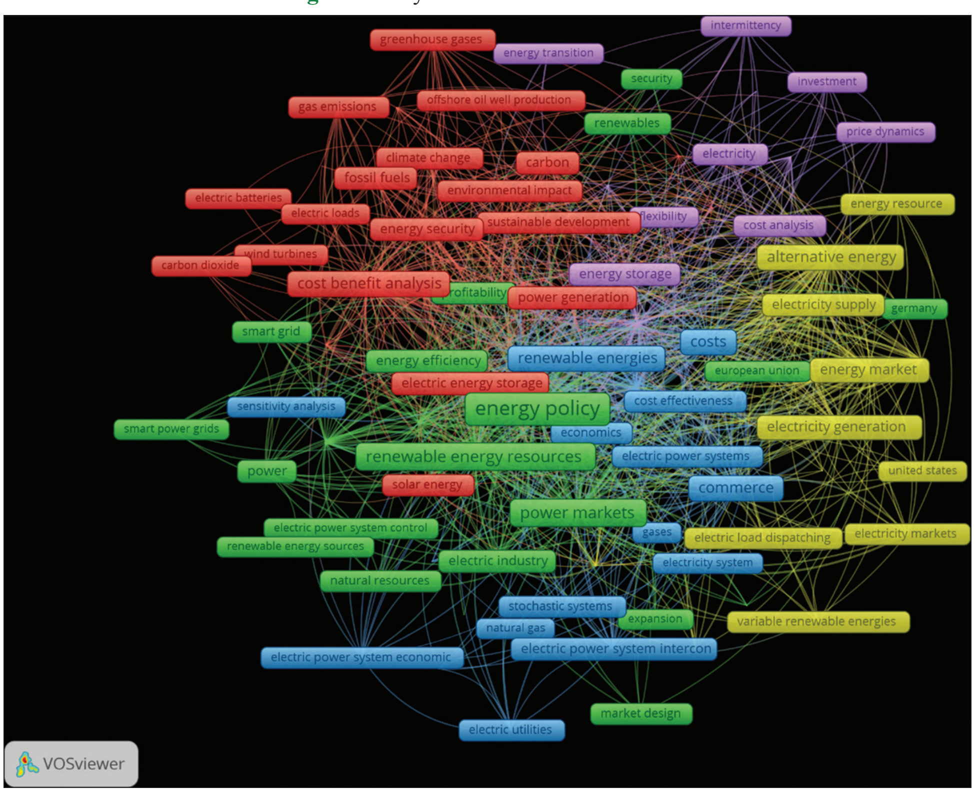


Figure 5: Key terms occurrences network



The network visualization demonstrates four distinct thematic clusters: a red cluster cantered on environmental and climate considerations (greenhouse gases, climate change, carbon emissions), a green cluster focused on renewable energy technologies and grid integration (smart grid, renewable energy resources, power generation), a blue cluster emphasizing economic analysis and market mechanisms (costs, economics, electricity markets), and a yellow cluster representing energy systems and policy frameworks (energy market, alternative energy, electricity supply). The strong interconnectivity between "power markets" (52 occurrences, 523 link strength), "renewable energy resources" (50 occurrences, 453 link strength), and "wind power" (40 occurrences, 423 link strength) reflects the field's emphasis on market-based integration mechanisms for variable renewable sources. This network structure validates the systematic review's focus on the intersection of economic viability, policy frameworks, and technical integration challenges, demonstrating that contemporary research successfully bridges these previously fragmented domains through comprehensive approaches that address both the technical complexities of renewable energy integration and the economic and policy mechanisms necessary for large-scale deployment.

Table 2: Keywords and occurrences of each term

Keyword	Occurrences	Total link strength
Energy policy	109	1058
Power markets	52	523
Renewable energy resources	50	453
Renewable energies	40	408
Wind power	40	423
Cost benefit analysis	39	367
Investments	39	413
Costs	38	414
Alternative energy	37	424
Commerce	36	339
Renewable energy	33	336
Renewable energy source	31	286
Energy market	25	293
Electric power transmission networks	23	243
Electricity generation	22	235
Electric industry	21	210
Electric energy storage	18	215
Electricity supply	17	207
Energy security	17	181
Energy storage	17	208
Renewable resource	17	209
Economic analysis	16	141
Electric power system interconnection	16	139
Power generation	16	185
Fossil fuels	15	162
Power	15	143
Solar power generation	15	171
Carbon	14	152
Electricity market	14	138
Energy efficiency	14	160
Climate change	13	124
Electricity markets	13	122
Optimization	13	138
Economics	12	121
Gas emissions	12	130
Greenhouse gases	12	122
Solar energy	12	125
Decision making	11	96
Electric power systems	11	117
Profitability	11	130
Sustainable development	11	103
Cost analysis	10	129
Electric load dispatching	10	99
Electric utilities	10	85
Energy	10	108
Smart grid	10	108

Furthermore, the bibliographic citation analysis presented in Table 3 and the corresponding author collaboration network in Figure 6 reveal the intellectual structure and influential contributions within renewable energy integration economics and policy research. The study of (Sorin et al., 2019) emerged as the most highly cited work with 429 citations, establishing foundational knowledge in the field, followed by (Ajanovic et al., 2022) with 374 citations and (Ahmed et al., 2020) with 353 citations, indicating the sustained relevance of recent comprehensive analyses in renewable energy economics. The network visualization demonstrates distinct research clusters with varying degrees of interconnectedness: a prominent red cluster anchored by highly collaborative authors such as Ajanovic (2022) and (Shafiullah et al., 2022), representing contemporary policy and economic analysis perspectives; a blue cluster centered around (Pfenninger and Keirstead, 2015) and associated researchers focusing on technical-economic modeling approaches; and a green cluster led by (Newbery et al., 2018) and (Hu et al., 2018), emphasizing market design and integration strategies.

The total link strength analysis reveals that while (Sorin et al., 2018) has the highest citation count, authors like (Hu et al., 2018) with 40 total link strength and (Newbery et al., 2018) with 31 total link strength demonstrate greater collaborative influence and knowledge integration across the field. The temporal distribution of influential works, spanning from foundational studies by Anuta (2014) and Pfenninger (2015) to recent contributions by Ajanovic (2022) and Shafiullah (2022), illustrates the field's evolution from early technical feasibility studies toward comprehensive economic and policy frameworks, with the network structure indicating increasing collaboration and knowledge synthesis as the field has matured into an interdisciplinary domain requiring integrated approaches to renewable energy transition challenges.

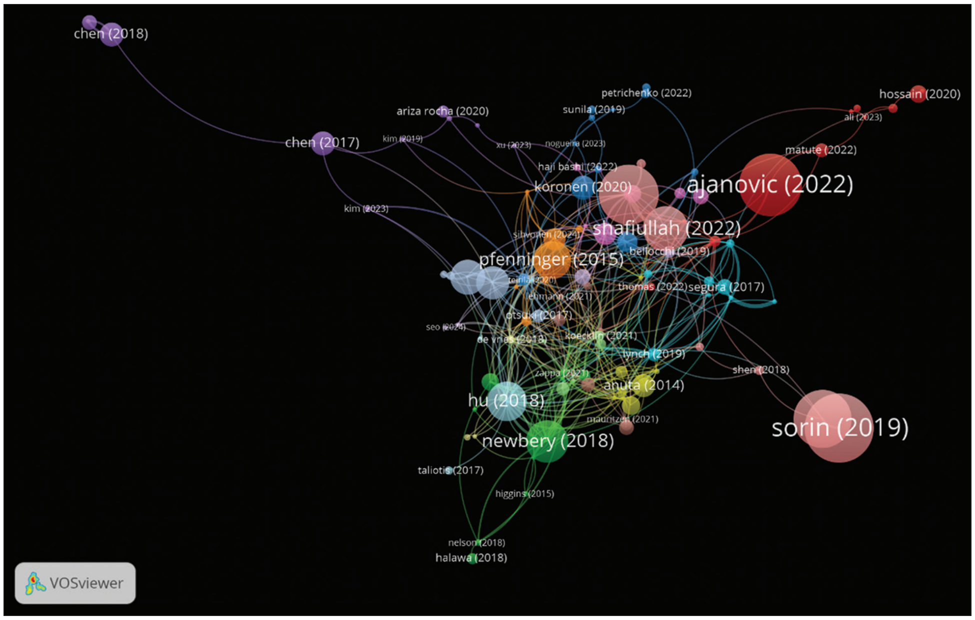
3.3. Topics/themes identified through STM

A Structural Topic Model (STM) approach was selected for this research due to its advanced capabilities in uncovering latent thematic structures while accounting for document-level metadata, which is particularly crucial for analysing the renewable energy

Table 3: The documents citations and strength of bibliographic analysis

Document	Citations	Total link strength
Sorin et al., 2019	429	5
Ajanovic et al., 2022	374	5
Ahmed et al., 2020	353	21
Moret (2019)	336	8
Shafiullah et al., 2022	237	9
Newbery et al., 2018	214	31
Hu et al., 2018	192	40
Pfenninger and Keirstead, 2015	179	15

Figure 6: The network of bibliographic analysis of citations



research (Tamakloe and Park, 2023). STM extends traditional topic modelling by incorporating document-level covariates, enabling the examination of how research themes vary across different journals and time periods (Sharma et al., 2021).

First, the document-topic attention distribution is modeled using a logistic-normal distribution:

~_d| Xd, _ _ Logistic Normal (μ = Xd, _)

where X_d represents document covariates, Γ captures coefficient relationships, and Σ is the covariance matrix.

Second, the topic-word distributions are formed by combining multiple components:

βd,k∝exp(m+κk(t)+κyd(c)+κyd,k(i)).

where m represents the baseline word distribution, $\kappa^{(t)}_k$ captures topic-specific deviations, $\kappa^{(c)}_{y_d}$ represents covariate effects, and $\kappa^{(i)}_{y_d,k}$ models interactions.

Third, the topic assignment for each word follows a multinomial distribution:

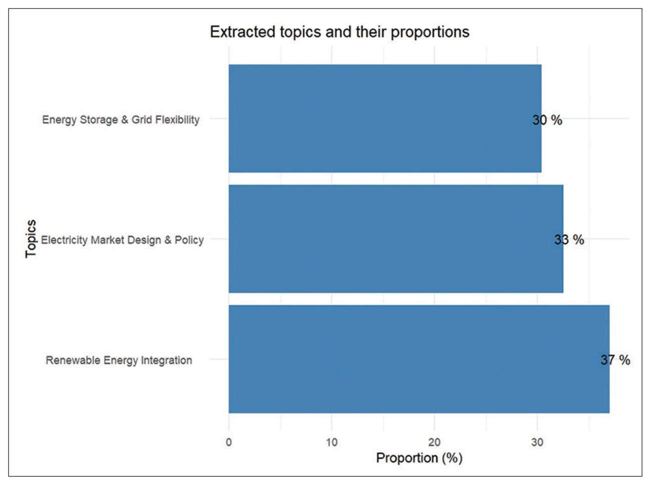
zd,n∣θd∼Multinomial(θd).

Finally, the observed words are generated conditional on their topics:

wd, n∣zd,n,βd,k=zd,n∼Multinomial(βd,k=zd,n).

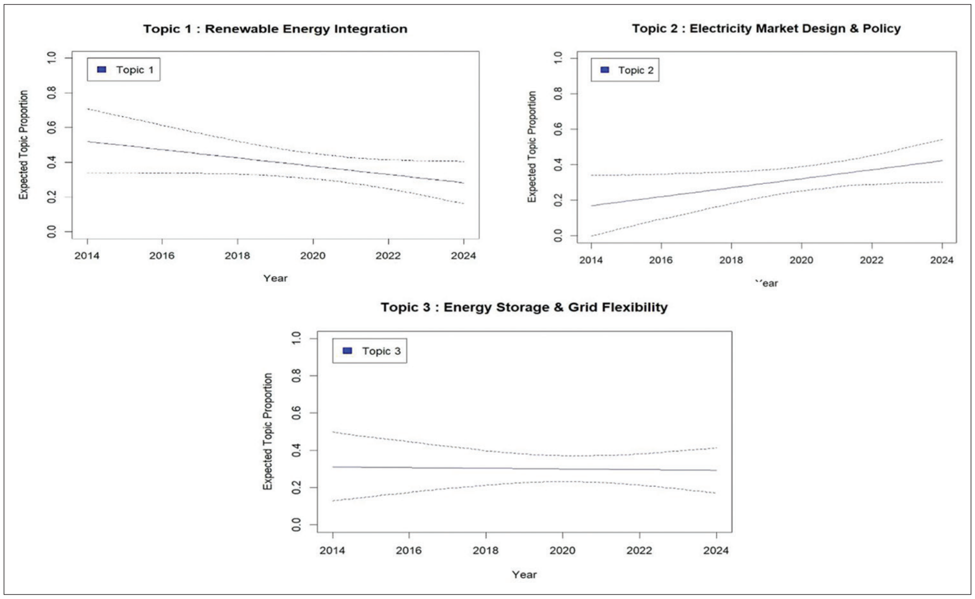
This mathematical framework enables STM to effectively model relationships between document metadata and topical content while maintaining computational tractability through variational inference methods (Roberts et al., 2019).

Figure 7: Extracted topics and their proportions



The Structural Topic Modeling analysis presented in Figure 7 reveals the thematic distribution of research focus within the 142-document corpus, identifying three primary research domains that collectively encompass the renewable energy integration literature. "Renewable Energy Integration" emerged as the dominant theme, comprising 37% of the research corpus and reflecting the field's core emphasis on technical and operational aspects of incorporating variable renewable sources into existing power systems. "Electricity Market Design and Policy" constituted 33% of the literature, demonstrating the substantial scholarly attention devoted to regulatory frameworks, market mechanisms, and policy instruments that facilitate renewable energy deployment while maintaining system reliability and economic efficiency. "Energy Storage and Grid Flexibility" represented 30% of the research focus, highlighting the critical importance of technological solutions and system adaptability measures required to manage intermittency challenges and grid stability concerns associated with high renewable penetration. The relatively balanced distribution across these three themes validates the systematic review's comprehensive approach and

Figure 8: Temporal dynamics of the three identified research themes

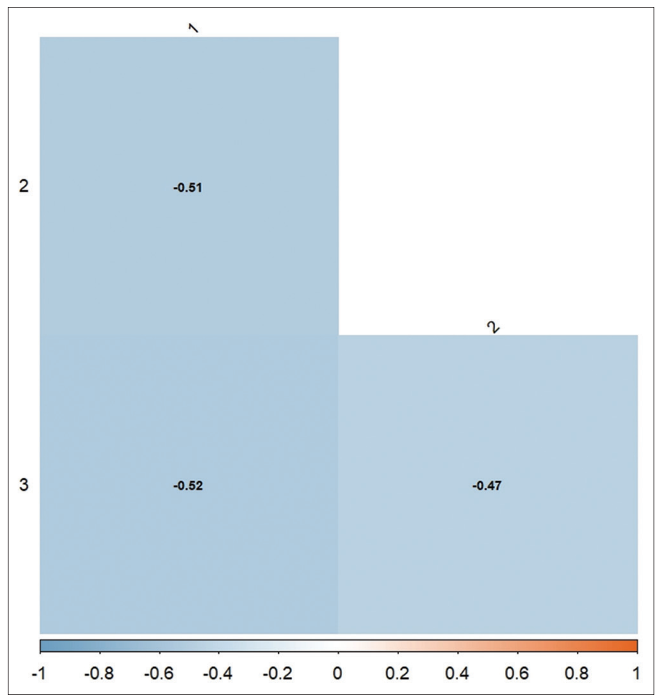


confirms that contemporary research successfully addresses the interconnected technical, economic, and policy dimensions of renewable energy transitions, with no single aspect dominating the discourse.

In addition, Figure 8 illustrates the temporal dynamics of the three identified research themes, revealing distinct evolutionary patterns that reflect the maturation and shifting priorities within renewable energy integration research over the past decade. Topic 1 (Renewable Energy Integration) demonstrated a consistent downward trend from approximately 0.8 expected topic proportion in 2014 to 0.2 by 2024, indicating that while technical integration challenges remained foundational to the field, research emphasis has gradually shifted toward more specialized and policy-oriented concerns as basic integration methodologies became established. Conversely, Topic 2 (Electricity Market Design and Policy) exhibited a pronounced upward trajectory, rising from roughly 0.2 in 2014 to 0.6 by 2024, reflecting the increasing recognition that successful renewable energy transitions require sophisticated market mechanisms, regulatory frameworks, and policy instruments rather than purely technical solutions. Topic 3 (Energy Storage and Grid Flexibility) maintained relative stability throughout the period, fluctuating between 0.2 and 0.4 with a slight declining trend, suggesting that while storage and flexibility solutions remain consistently important, they have not experienced the dramatic research growth seen in policy-focused studies.

Furthermore, Figure 9 presents the correlation matrix between the three identified research topics, revealing the interconnected nature of renewable energy integration research themes and their complementary relationships within the scholarly discourse. The analysis demonstrates moderate negative correlations across all topic pairs: Topic 1 (Renewable Energy Integration) and Topic 2 (Electricity Market Design and Policy) exhibit a correlation coefficient of −0.51, Topic 1 and Topic 3 (Energy Storage and Grid Flexibility) show a correlation of −0.52, while Topic 2

Figure 9: Correlation matrix of the three identified research themes



and Topic 3 display a correlation of −0.47. These negative correlations indicate that when research focus intensifies on one theme, attention to the other themes proportionally decreases within individual studies, suggesting that while these topics are conceptually interconnected and complementary in addressing renewable energy integration challenges, scholarly work tends to specialize in specific aspects rather than adopting truly integrated approaches. The relatively moderate strength of these correlations (all falling between −0.47 and −0.52) indicates that the topics are distinct yet related research domains, with some overlap in terminology and conceptual frameworks but sufficient differentiation to warrant separate thematic classification.

4. THEMATIC ANALYSIS

4.1. Integration of renewable energy sources (RES) into power systems and markets

The technical challenges associated with renewable energy integration stem primarily from the variable and intermittent nature of wind and solar resources, which fundamentally disrupts traditional power system operations designed around dispatchable generation. According to (Ahmed et al., 2020) provide a comprehensive analysis of wind energy integration challenges, identifying generation uncertainty, power quality issues, angular and voltage stability concerns, and fault ride-through capability as critical technical barriers that hamper reliable grid operation. These findings are complemented by (Shafiullah et al., 2022), who examine similar challenges for solar photovoltaic systems, emphasizing non-dispatchability, reactive power support requirements, and voltage stability issues as primary concerns for grid operators. The convergence of these technical challenges across different renewable technologies highlights the systematic nature of integration difficulties, suggesting that solutions must address the fundamental characteristics of variable renewable energy rather than technology-specific issues.

The implications of these technical challenges extend beyond immediate operational concerns to affect long-term system planning and investment decisions. The study of (Hu et al., 2018 n.d.) demonstrate through their systematic literature review that these technical barriers create significant obstacles to large-scale variable renewable electricity integration in European Union markets, particularly when existing market structures fail to accommodate the operational requirements of high renewable penetration. The transformation of electricity markets to accommodate high renewable penetration requires comprehensive redesign of market structures, pricing mechanisms, and regulatory frameworks. The study of (Newbery et al., 2018) provide seminal guidance for this transition, developing policy recommendations for European electricity system market design that can support dominant renewable energy shares. Their framework addresses wholesale market design, electricity storage integration, renewable energy support mechanisms, and distributed generation accommodation, establishing a comprehensive approach to market evolution that balances technical feasibility with economic efficiency. Building upon these foundational market design principles, (Kwon et al., 2023) examine the strategic implications of different market structures on renewable energy investment and resource adequacy. Their game-theoretical analysis demonstrates that energy-only markets, capacity markets, and clean energy markets each produce different investment incentives and system outcomes, with significant implications for renewable energy deployment rates and system reliability.

The evolution toward more sophisticated market mechanisms is further illustrated by (Wang et al., 2024), who propose joint energy-frequency regulation market designs specifically tailored for renewable-rich power systems. Their bi-level optimization approach addresses the dual challenges of environmental cost management and frequency regulation service provision, demonstrating how market design innovations can simultaneously support renewable energy integration while maintaining system reliability and economic efficiency. The practical implementation of renewable energy integration varies significantly across different regional contexts, reflecting diverse resource endowments, existing infrastructure, and policy frameworks. Findings of (Oyewo et al., 2020) provide comprehensive analysis of renewable energy transition pathways for West Africa, using linear optimization modeling to demonstrate that fully renewable-based power systems represent the least-cost, lowest-emission, and most job-rich option for the region through 2050. Their findings indicate that solar photovoltaics can supply 81-85% of regional electricity demand while reducing costs from €70/MWh to €36-41/MWh, illustrating the economic attractiveness of renewable energy transitions in regions with abundant solar resources. Table 4 of studies related to theme grid integration challenges and market design solutions for renewables illustrate the details of authors and research focus.

The economic viability of renewable energy transitions is further supported by (Zappa et al., 2021), whose analysis of Central Western Europe demonstrates that liberalized electricity markets can support decarbonized portfolios aligned with Paris Agreement targets under appropriate market design conditions. The empirical evaluation of renewable energy policies reveals important insights about the relative effectiveness of different support mechanisms. According to (Green and Staffell, 2021) Shapley values from game theory to quantify policy contributions to B ritish electricity decarbonization, finding that subsidized renewable investment, carbon pricing, regulation-driven coal closures, and energy efficiency measures each contributed 19-29 $MtCO_2$ reductions annually. The study of (Kim et al., 2023) analyze variable renewable energy participation in US ancillary services markets, finding incremental revenues from regulation market participation range from \$0.0-2.9/MWh for standalone

Table 4: Grid integration challenges and market design solutions for renewables

Author and Year	Focus	Setting
Ahmed et al. (2020)	Wind grid integration issues	Global review
Shafiullah et al. (2022)	Solar PV grid challenges	Global review
Hu et al. (2018)	VRE market barriers	EU electricity markets
Newbery et al. (2018)	Policy for renewables market design	EU energy transition
Kwon et al. (2023)	Incentives and market impact	Game-theory, global models
Wang et al. (2024)	Energy-frequency market design	China, bi-level model
Oyewo et al. (2020)	Decarbonization pathways	West Africa (2015-2050)
Zappa et al. (2021)	Market design and VRE support	Central Western Europe
Green and Staffell (2021)	Policy impact on decarbonization	UK (2012-2019), Shapley analysis
Kim et al. (2023)	VRE in ancillary markets	7 US ISO/RTO markets

systems and $1-33/MWh for hybrid systems with battery storage, highlighting the importance of market access and revenue diversification for renewable energy economic viability. The synthesis of these research findings indicates that renewable energy integration represents not merely a technological challenge but a comprehensive transformation of electricity system architecture, market structures, and policy frameworks, requiring simultaneous advancement in grid flexibility, market design innovation, policy coordination, and investment framework development.

4.2. Electricity market design, policy, and economic viability

The transformation of electricity markets to accommodate renewable energy integration while maintaining economic efficiency represents a fundamental challenge in contemporary energy policy. The foundational framework for modern electricity market design in high-renewable scenarios has been comprehensively addressed by Newbery et al. (2018), who establish critical principles for European electricity system transformation. Their analysis demonstrates that traditional market structures require systematic redesign across wholesale markets, storage integration mechanisms, renewable energy support schemes, and distributed generation accommodation to achieve technical feasibility while maintaining economic efficiency.

The empirical evaluation of policy effectiveness provides crucial insights into successful energy transitions. The study of Green and Staffell (2021) employ game-theoretical analysis to quantify individual policy contributions to British electricity decarbonization between 2012 and 2019, revealing that subsidized renewable investment, carbon pricing, regulation-driven coal closures, and energy efficiency measures each contributed 19-29 $MtCO_2$ reductions annually. The critical role of pricing mechanisms becomes particularly complex in renewable-dominated systems. The research of (Zakeri et al., 2015) provide comprehensive analysis of natural gas influence on European electricity pricing, revealing that fossil fuel-based power plants set electricity prices approximately 58% of the time while generating only 34% of electricity, with natural gas determining prices for over 80% of hours in several countries by 2021.

The effectiveness of different support mechanisms reveals important distinctions between policy design intentions and market outcomes. The study of (Rosales-Asensio et al., 2024) examine Spanish electricity market evolution from regulated feed-in tariffs to competitive market mechanisms, demonstrating that while transitional support schemes effectively promote renewable energy integration under proper supervision, excessive support costs can destabilize entire markets and increase final energy costs substantially. Regulatory pricing mechanisms significantly influence market participant behavior and system efficiency outcomes. Findings of (Clò and Fumagalli, 2019) analyze the transition from single to dual pricing schemes in Italian electricity markets, demonstrating that dual pricing schemes better align economic incentives with balancing responsibilities, reducing intentional imbalances and improving market efficiency. The broader economic implications extend beyond generation costs to comprehensive electricity pricing effects. Further, (Halkos and Tsirivis, 2023) analyze household electricity prices across 26 European Union countries from 2003 to 2019, revealing complex relationships between renewable energy deployment, generation concentration, and final electricity prices.

Market design innovations continue evolving to address renewable energy integration challenges. The findings of (Zheng and Nan, 2024) propose reliability-constrained capacity market frameworks that incorporate system reliability criteria rather than simple supply-demand equilibrium, addressing adequacy challenges created by increasing renewable penetration. The study of (Mauritzen, 2021) analyzes COVID-19 impacts on Nordic electricity markets with high renewable penetration, revealing both flexibility benefits and economic challenges during periods of abundant generation. In addition, (Hao et al., 2023) examines risk-sharing contracts that can mitigate spot price volatility while reducing tariff deficits, illustrating how advanced market mechanisms balance renewable energy support with system economic stability. Table 5 below illustrates the studies related to theme policy and market mechanisms for renewable energy viability.

Contemporary challenges increasingly focus on hydrogen economy integration. The study of (Ajanovic et al., 2022) analyze different hydrogen production pathways, revealing that only green hydrogen from renewable electricity achieves truly low emissions, emphasizing the critical importance of policy frameworks supporting the transition from conventional to green hydrogen production. The synthesis reveals that successful electricity market design for renewable energy integration requires adaptive, multi-dimensional approaches coordinating technical requirements with economic incentives and regulatory frameworks, emphasizing flexible, evidence-based policy development that can respond to changing market conditions while maintaining system reliability and economic efficiency.

Table 5: Policy and market mechanisms for renewable energy viability

Author and Year	Focus	Setting
Newbery et al. (2018)	Market design for renewables	EU electricity policy
Green and Staffell (2021)	Policy impact on decarbonization	UK (2012-2019), game theory
Ajanovic et al. (2022)	Hydrogen market economics	Global policy analysis
Clò and Fumagalli (2019)	Price regulation effects	Italy, quasi-experiment
Halkos and Tsirivis (2023)	EU electricity price drivers	26 EU countries (2003-2019)
Hao et al., (2023)	VRE support and risk contracts	Spain, 12-year scheme analysis
Zakeri et al. (2023)	Gas versus low-carbon price setting	EU+UK/Norway, econometrics
Zheng and Nan (2024)	Capacity market with renewables	IEEE-RTS-79, multi-objective model
Mauritzen (2021)	COVID-19 effects on low-carbon grid	Denmark and Sweden, pandemic impact
Rosales-Asensio et al. (2024)	RES support scheme evaluation	Spain, tariff-to-market shift

4.3. Energy storage and system flexibility for grid stability

The intermittent nature of renewable energy sources creates fundamental challenges for electricity grid stability, necessitating sophisticated energy storage solutions and flexibility mechanisms to maintain reliable power system operation. The economic viability of energy storage at residential and utility scales represents a cornerstone challenge for renewable energy integration. According to Zakeri et al. (2021) analyze policy options for enhancing residential solar photovoltaic systems paired with battery energy storage, demonstrating that replacing generation incentives with self-consumption bonuses can provide returns equivalent to 70% battery capital subsidies while reducing regulatory costs by two-thirds. The technical performance and economic benefits of advanced storage technologies become increasingly important as power systems accommodate higher renewable penetration levels. In addition, (Xu et al., 2023) provide comprehensive analysis of hybrid Li-ion battery-supercapacitor systems for multitype frequency response services in renewable-dominated power systems, demonstrating robust performance and competitive advantages in providing frequency regulation services.

The comparative performance of different storage technologies reveals important trade-offs between technical capabilities, economic costs, and system integration requirements. The study of (Sihvonen et al., 2024) examine combined utilization of electricity and thermal storage in highly renewable energy systems, comparing small-scale pumped hydro storage with high-temperature thermal energy storage performance. Their analysis demonstrates that both storage types promote renewable energy integration, with thermal storage reducing curtailment by 77% compared to 4% for pumped hydro, while revealing competitive dynamics when multiple storage systems operate in the same market. Market integration mechanisms for utility-scale energy storage face significant regulatory and economic challenges that require comprehensive policy frameworks. Further, (Haji Bashi et al., 2022) analyze electricity market integration of utility-scale battery energy storage units in Ireland, identifying policy recommendations for enabling full storage potential through regulatory alignment with European-level directives.

The broader landscape of energy storage applications in deregulated electricity markets reveals systematic challenges and opportunities across different storage technologies and market structures. The study of (Saha et al., 2022) provide comprehensive review of energy storage systems in renewable-integrated deregulated markets, demonstrating that optimal storage placement can maximize social welfare by better utilizing existing power system capacity through enhanced steady-state power flow regulation and dynamic stability management. International experiences with energy storage deployment reveal common regulatory and market barriers that limit widespread adoption despite technical capabilities. The study of (Anuta et al., 2014) examine grid-scale electricity storage emergence across countries with high renewable targets, identifying three major challenges: undetermined asset classification limiting stakeholder ability to realize multiple storage benefits, low electricity market liquidity with changing conditions, and lack of common standards for storage evaluation and operation. Table 6 below illustrates the studies related to energy storage strategies for renewable-based power systems.

Advanced storage investment strategies require sophisticated optimization approaches that account for renewable energy variability and market dynamics. The research of (Abrell et al., 2019) analyze storage investments and technology-specific renewable energy support, finding that optimal renewable energy subsidies should be technology-specific reflecting heterogeneous system integration values, with differentiated subsidies reducing curtailment and preventing costly storage investments.in addition, (Gandhi et al., 2022) extend this analysis through mixed-integer optimization frameworks for cryogenic energy storage integration, addressing key decision-making questions about energy costs, storage requirements, and optimal integration strategies for complete renewable energy transitions.

Emerging flexibility mechanisms beyond traditional storage technologies offer additional pathways for managing renewable energy variability. Furthermore, (Lynch et al., 2019) examine power-to-gas as a system flexibility mechanism, finding that while the technology itself operates at a loss, it increases electricity demand and prices during low-load hours, making renewable generation more profitable and justifying investment despite direct economic losses. Finally, the study of (Wang et al., 2020) demonstrate how datacenter power consumption regulation can provide grid flexibility through multiple storage devices and demand management, illustrating the potential for integrating diverse flexibility resources across different sectors. The synthesis of these research findings indicates that achieving grid stability in renewable-dominated systems requires coordinated deployment of diverse storage technologies, supportive regulatory frameworks, and innovative market mechanisms that recognize and compensate

Table 6: Energy storage strategies for renewable-based power systems

Author and Year	Focus	Setting
Zakeri et al. (2021)	Solar PV+battery policy options	UK cost optimization model
Xu et al. (2023)	Li-ion+supercapacitor economics	China+PJM, frequency data
Sihvonen et al. (2024)	Electricity vs thermal storage	Åland Island, PLEXOS modeling
Haji Bashi et al. (2022)	Utility-scale battery integration	Ireland policy analysis
Saha et al., (2022)	Storage in deregulated markets	Global review
Anuta et al. (2014)	Market frameworks for grid storage	Global comparative review
Abrell et al. (2019)	Storage for volatility mitigation	Numerical market equilibrium model
Gandhi et al. (2022)	Cryogenic storage optimization	Cost model with renewables
Lynch et al. (2019)	Power-to-gas market impact	Stochastic market model
Wang and Zhao (2022)	Storage for datacenter regulation	Smart grid simulation

the multiple values that flexibility resources provide to power system operation.

5. CONCLUSION

This study has addressed the critical knowledge fragmentation that has hindered the development of effective renewable energy integration strategies by synthesizing economic and policy frameworks across three interconnected dimensions: technical integration challenges, market design evolution, and system flexibility requirements. Through comprehensive analysis of 142 peer-reviewed studies spanning 2014-2024, this research has revealed that successful renewable energy transitions require fundamentally coordinated approaches that simultaneously address technical feasibility, economic viability, and regulatory coherence rather than pursuing isolated solutions within disciplinary silos.

The bibliometric and thematic analysis demonstrates a decisive shift in research priorities from purely technical integration concerns toward sophisticated market design and policy framework development, reflecting the field's maturation and recognition that economic and regulatory mechanisms are now the primary reveals determinants of renewable energy deployment success. The structural topic modeling that while renewable energy integration research initially focused heavily on technical challenges (comprising 80% of research attention in 2014), policy and market design considerations have emerged as the dominant research themes by 2024 (representing 60% of scholarly focus), indicating that the fundamental technical barriers have been largely resolved and that institutional innovation has become the critical pathway for achieving high renewable penetration.

The synthesis of evidence across diverse geographic contexts and market structures reveals that effective renewable energy integration strategies share common characteristics: Technology-specific support mechanisms that reflect heterogeneous system integration values, market designs that properly compensate flexibility resources for multiple grid services, and policy frameworks that can adapt to changing technological and economic conditions while maintaining long-term investment certainty. Particularly significant is the finding that successful renewable energy transitions require coordinated deployment of diverse storage technologies and flexibility mechanisms, supported by regulatory frameworks that recognize and compensate the multiple values these resources provide to power system operation, rather than treating them as simple generation substitutes.

The research contributes to existing knowledge by providing the first comprehensive mapping of the interdisciplinary landscape surrounding renewable energy integration economics and policy, revealing previously unrecognized patterns in research evolution and identifying critical gaps where technical knowledge has outpaced institutional development. The findings challenge prevailing assumptions about the primary barriers to renewable energy integration, demonstrating that technical challenges, while important, are increasingly overshadowed by market design inadequacies and policy coordination failures that prevent optimal resource allocation and investment efficiency.

5.1. Limitations and future research

This study acknowledges limitations inherent in systematic review methodology, including potential publication bias toward positive results, language restrictions that may exclude important non-English research, and the temporal boundaries that may have excluded emerging research developments. Additionally, the focus on peer-reviewed academic literature may underrepresent practical insights from industry implementation and policy experimentation that have not yet been systematically documented in scholarly publications.

Future research priorities should focus on developing integrated assessment frameworks that can evaluate renewable energy integration strategies across technical, economic, and policy dimensions simultaneously, rather than continuing the disciplinary specialization that this review has identified as problematic. Particularly critical is the need for empirical research on the effectiveness of different market design innovations under varying renewable penetration scenarios, longitudinal studies of policy adaptation mechanisms in different institutional contexts, and comparative analysis of regional approaches to coordinating renewable energy integration across interconnected systems. Additionally, emerging challenges such as sector coupling, hydrogen economy integration, and climate adaptation requirements for renewable energy infrastructure represent important frontiers requiring comprehensive interdisciplinary investigation.

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