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A systematic review of systemic challenges and transition strategies for integrating renewable energy sources into conventional electricity generation in the European Union

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This review investigates the integration of renewable energy sources (RES) into the European Union's electricity system, focusing on the infrastructural, regulatory, and systemic complexities encountered during the transition to a low-carbon model. The rising penetration of intermittent sources such as wind and solar has created operational challenges for grid stability, dispatchability and overall system flexibility. Empirical studies highlight the growing role of energy storage technologies, sector coupling and coordinated planning tools in addressing these challenges. Considerable divergence persists among national strategies because of heterogeneous climatic, geographic and socio economic conditions, which shape the timing and scope of fossil fuel phase out, especially in coal dependent member states such as Germany and Poland. Financial instruments ranging from tax relief to auction based procurement and shared ownership models have been implemented. However, their effectiveness remains constrained by site specific factors, including resource variability and differing levels of public engagement. Regulatory heterogeneity across EU member states, particularly in the application of renewable portfolio standards, continues to impede convergence in integration efforts. Environmental assessments of high RES penetration scenarios indicate substantial emission reduction potential when integration is aligned with local generation patterns and infrastructure capabilities. The review traces the structural interplay between technological development, institutional arrangements and socio economic determinants in shaping the evolving configuration of the EU electricity sector.

KEYWORDS

decarbonization strategies, energy transition policies, European Union electricity system, grid stability and flexibility, renewable energy integration, smart grids, sustainability governance, systematic review

1 Introduction

The integration of renewable energy sources into the European Union electricity system represents a multifaceted transformation driven by decarbonisation commitments, energy security objectives and technological capabilities developed over recent decades. By 2020, renewable sources surpassed fossil fuels for the first time in EU electricity generation, marking a significant milestone in the transition trajectory.

This achievement reflects decades of policy support, technological advancement and substantial investment across member states. However, the deepening penetration of variable renewable energy sources, particularly wind and solar, has simultaneously introduced operational, regulatory and institutional challenges that extend beyond conventional engineering solutions.

The technical dimensions of this transition are substantial and increasingly pressing for system operators and planners. Wind and solar generation, which together account for a growing share of EU electricity capacity, introduce intermittency into systems historically designed around dispatchable, centralized generation. Managing this variability requires coordinated investments in transmission infrastructure modernization, energy storage deployment, demand side flexibility mechanisms and real time operational protocols Technical constraints interact with regulatory fragmentation, market design misalignments and governance structures that differ across member states. Support mechanisms for renewable deployment operate within heterogeneous national policy frameworks. These mechanisms range from feed in tariffs to auction based schemes and contribute to coordination challenges and uneven integration pathways. Beyond regulation and markets, socio economic factors including public acceptance, labor market transitions and distributional equity concerns fundamentally shape both the feasibility and the pace of renewable energy deployment.

Despite the extensive volume of research and policy analysis addressing renewable energy integration, the evidence base remains fragmented across disciplinary and sectoral domains. Technical investigations of grid operation and stability proceed largely independently from analyses of market design or governance arrangements. Economic research on cost trajectories and investment dynamics often develops without engagement with institutional constraints or social acceptance dynamics. Regulatory assessments and policy studies typically focus on individual member states or specific technologies, limiting understanding of how integration challenges and transition responses vary systematically across the Union and how they interact at the system level. This fragmentation reflects the genuine complexity of renewable energy integration but also constrains the emergence of coherent, evidence based strategies that bridge technical requirements with institutional possibilities and social realities.

The objective of this systematic review is to synthesize and critically assess existing evidence on the systemic challenges and transition strategies associated with renewable energy integration into conventional electricity generation systems in the European Union. The review adopts an integrated analytical perspective that treats technical, regulatory, market and socio-economic dimensions not as separate domains but as interconnected elements of a complex transition process. The analysis examines three complementary dimensions. The first encompasses the technical, infrastructural and operational constraints that emerge as variable renewable energy penetrates electricity systems, including grid stability, balancing mechanisms, storage requirements and frequency regulation. The second addresses the regulatory frameworks, market design arrangements and governance structures that either facilitate or impede the management of these technical challenges. The third dimension encompasses the transition strategies and policy instruments proposed or implemented to maintain system reliability and cost-effectiveness while advancing decarbonization objectives. By synthesizing evidence from diverse methodological approaches, technological contexts and geographic settings, the review aims to clarify points of scientific convergence, areas of persistent uncertainty and critical gaps where further investigation is warranted.

The article unfolds in four main movements. First, the methodological choices are described, including database selection, search protocols and classification criteria employed to ensure transparency and reproducibility. Second, evidence from the reviewed literature is presented, organized thematically around systemic challenges and associated transition strategies as they emerge across technical, regulatory and socio-economic domains. Third, these findings are situated within current debates on EU energy policy and regulation, examining how evidence informs or contests policy approaches. Finally, the main limitations of the available evidence base are assessed and priorities for future research and policy development are identified.

The ongoing transformation of the European Union's electricity sector through the integration of renewable energy sources is a complex, multi-dimensional process driven by decarbonization imperatives, energy security concerns, and the pursuit of environmental sustainability (Carallo et al., 2025). This shift has been strongly influenced by the need to reduce pollution and meet emission reduction targets, with the electricity sector playing a pivotal role in the broader energy transition (Almutairi and Alhamed, 2025). Within this evolving landscape, technologies such as solar photovoltaics have expanded significantly. Rooftop PV installations, for instance, currently represent around 66% of the EU's total installed PV capacity, underscoring the impact of targeted deployment programs and cost reductions (Rashid et al., 2024; McGovern and van der Zwaan, 2025).

Despite this growth, integrating variable renewable energy sources, wind and solar continues to generate systemic challenges (Bożek et al., 2024). Their intermittency introduces volatility in generation profiles, which complicates real-time balancing of supply and demand and increases pressure on grid stability and resilience (Che et al., 2025). Traditional grid architectures, based on centralized dispatchable generation, are being strained by these new dynamics, prompting the need for upgrades in infrastructure and control technologies (Powell et al., 2024). The deployment of smart inverters and digital tools has become increasingly relevant in managing the operational unpredictability introduced by VREs (Cheng et al., 2025).

From a regulatory standpoint, the EU has introduced harmonized market access frameworks designed to enable fair participation of RES producers (Carallo et al., 2025). Instruments such as feed-in tariffs (FiT) have contributed to the proliferation of community energy initiatives (Brunoro et al., 2024). However, these mechanisms have also led to forms of policy-induced

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Abbreviations: RES, Renewable energy sources; TSO, Transmission system operator; DSO, Distribution system operator; EU ETS, EU Emissions Trading System; LCA, Life cycle assessment; DSM, Demand-side management; VRE, Variable renewable energy (folosești "VREs"); ESS, Energy storage systems; RPS, Renewable Portfolio Standards; PV, Photovoltaic; EU, European Union; FiT, Feed in tariff.

dependency, where projects become financially exposed to abrupt changes in support schemes (Taromboli et al., 2025). Moreover, while frameworks like renewable energy guarantees of origin have improved transparency and traceability, the implementation of such systems remains uneven across member states (Vishwakarma et al., 2024).

Research has increasingly focused on delineating the conceptual boundaries and multi-level benefits associated with RES integration, particularly through assessments of community energy models, techno-economic trade-offs, and environmental externalities (Teng et al., 2025). The structure and assumptions of life cycle and system modeling exercises have proven decisive in shaping perceptions of sustainability outcomes. Regional coordination strategies and the inclusion of energy storage systems (ESS) have emerged as recurring elements in integration studies, especially for their role in mitigating the operational constraints of VREs (Krishnamurthy et al., 2024; Khan et al., 2025).

Market integration efforts, supported by regulatory alignment and cross-border infrastructure planning, have contributed to a more unified European electricity market (Van Liedekerke et al., 2025). These developments reflect the interaction between technical evolution, institutional adaptation, and policy convergence. The resulting transition, though uneven across the Union, is redefining the operational, economic, and governance foundations of electricity systems, gradually consolidating a model centered on flexibility, decentralization, and carbon neutrality (Gou et al., 2025; Zeitlin and Rangoni, 2025).

2 Materials and methods

2.1 Background and context of renewable energy in the EU

2.1.1 Historical evolution of electricity generation in the EU

The trajectory of electricity generation in the European Union has undergone marked structural transformations from the late 20th century onward. Initially dominated by fossil fuels and, in certain member states, nuclear energy, the energy mix began to diversify following the implementation of environmental regulations and increasing awareness of climate change (Neto et al., 2024).

Subsequent regulatory milestones, such as the introduction of the EU Emissions Trading System (ETS) in 2003, contributed to accelerating the decarbonization of the electricity sector. In parallel, broader liberalization efforts reshaped market dynamics through the unbundling of national systems and the promotion of cross-border electricity flows (Sitarz et al., 2024). Western European countries advanced rapidly in expanding renewable capacity, driven by financial incentives and supportive institutions, while Eastern member states displayed a slower pace due to legacy infrastructure and energy mix characteristics (Di Foggia and Beccarello, 2024).

By 2010, renewable electricity accounted for 21% of the EU total, a figure that increased in line with policy targets and declining technology costs (Jorge-Vazquez et al., 2024). In 2020, for the first time, renewable electricity generation surpassed fossil-based sources within the EU (Basílio, 2025). Hydropower remained central in Nordic and Baltic regions, whereas Germany, Spain, and the Netherlands focused on large scale solar PV and wind projects (Hao and Dragomir, 2025). Offshore wind deployment experienced substantial growth between 2012 and 2021, signaling the consolidation of this sector within the EU's renewable mix (Pasimeni et al., 2024).

Installed renewable capacity grew significantly between 2014 and 2023, not only in electricity but also across heating and cooling sectors, which saw a rise in renewable penetration from 11.7% in 2004 to 22.9% in 2021 (Rosenow et al., 2025). This expansion, however, introduced operational challenges, particularly regarding the integration of intermittent sources such as wind and solar PV. Addressing these issues required investments in transmission systems, storage, and demand side flexibility tools (Chen et al., 2025; Zheng et al., 2025). The evolution of the EU electricity system thus reflects the convergence of regulatory ambition, technological development, and structural differentiation across member states (Mellot et al., 2025).

2.1.2 Policy drivers for renewable energy adoption

Regulatory and policy frameworks have played a central role in shaping renewable energy deployment across the EU. Instruments such as Renewable Portfolio Standards (RPS), energy efficiency mandates, and emission reduction targets have redefined market structures and influenced investment patterns (Migliavacca, 2025).

The effectiveness of such policies, however, varies across regions due to sub national disparities in implementation and institutional capacity (Anh et al., 2024).

Empirical assessments show that incentive schemes adapted to local resource availability and economic contexts can accelerate renewable uptake (Nsude et al., 2024). Public perception, captured in studies such as Eurobarometer, has also been identified as a significant factor influencing the design and acceptance of energy policies (Kassymbekov and Aitkul, 2024). Public trust and perceived fairness in energy policy are closely linked to social acceptance and system resilience.

Socio political and administrative barriers remain present. Challenges include limited access to financing, bureaucratic complexity, and divergent national priorities (Radtke and Renn, 2024). These factors interact with socio technical conditions. Industrial legacy systems, cultural attitudes, and governance traditions mediate the translation of policy objectives into renewable outcomes (Ferreira and Pereira, 2025).

In Eastern European contexts, lower familiarity with renewable technologies and lower institutional trust levels can reduce policy efficacy. Integration of educational and stakeholder-driven components into policy design has been proposed as a corrective measure (Grecu, 2025). Environmental considerations are also embedded in policy drivers, as renewable deployment aligns with EU climate strategies aimed at pollution mitigation and ecological protection (Dorigoni and Anzalone, 2024).

Regulatory frameworks at the EU level also target system stability by addressing intermittency and integration challenges.

Legislative coherence and standardization, particularly regarding grid codes and energy market rules, remain essential for effective coordination. The interplay between technological progress and governance adaptation continues to shape the regulatory landscape (Rajendran et al., 2025).

2.1.3 Technological advancements in renewable energy

Technological development has been a key enabler of RES expansion in the EU. Improvements in solar PV efficiency, wind turbine design, and control systems have enhanced the reliability and scalability of renewable energy (Alizadeh et al., 2025). These advances support the EU's 2030 and 2050 decarbonization goals and have redefined generation, transmission, and consumption processes.

Grid modernization efforts such as the rollout of smart meters, automation, and advanced control systems have improved integration capacity for variable renewables by enabling real-time balancing and dynamic load management (Kumar et al., 2025). Sector coupling, involving the integration of electricity with heating and mobility sectors, and the deployment of energy storage systems (ESS), further augment system flexibility and efficiency (Ruan et al., 2025).

Adoption of new technologies varies across member states due to differences in GDP, R&D investment, and policy priorities. The maritime sector exemplifies this variation, where technological conservatism and limited incentives have delayed innovation diffusion (Ferrarini et al., 2025). Additionally, emerging decentralized energy models, including prosumer networks, microgrids and local energy communities, are increasingly enabled by digital platforms and recent legislative reforms (Igliński et al., 2024).

The interaction between regulatory reform and innovation ecosystems is critical. Policies that reduce risk and align incentives with grid needs have catalyzed deployment and reduced investment barriers (Das et al., 2025). Initiatives under the European Green Deal have further accelerated clean technology production and positioned the EU competitively in global renewable markets (Areola et al., 2025).

Nevertheless, non technical barriers persist. Resistance from stakeholders, lack of public awareness, and uneven institutional capacity continue to slow adoption, particularly in regions with limited administrative support or lower levels of digitalization (Skrzyzowski et al., 2024). Addressing these gaps requires integration of education, engagement, and adaptive governance into technological deployment strategies. Although Western Europe leads in implementation, substantial potential remains untapped in other regions, underscoring the need for coordinated, cross border innovation strategies (Ndungane et al., 2024).

2.1.4 Societal and economic motivations

The adoption of renewable energy in the EU is influenced by intersecting societal and economic dynamics. Energy policy is embedded in the broader framework of sustainable development, encompassing environmental goals, social inclusion, and economic competitiveness (Almutairi and Alhamed, 2025). Societal expectations for climate action have amplified demands for clean energy solutions that also contribute to employment and energy access (Dayi et al., 2025).

Investments in RES generate employment across multiple sectors, including manufacturing, construction, and operations. These activities have multiplier effects on regional economies and contribute to diversification and resilience (Tegenie et al., 2025). For countries with high energy import dependency, developing domestic renewable industries serves both economic and strategic interests (Hassanein et al., 2024).

Disparities between member states in terms of infrastructure and institutional maturity result in uneven renewable integration progress (Basílio, 2025). EU funding mechanisms aim to reduce these gaps by supporting vulnerable regions and smaller actors. This approach seeks to maintain public support and minimize distributional inequalities (Khalique et al., 2025).

Institutional and cultural factors, including governance styles, public trust and policy coherence, are crucial in shaping both underlying motivations and the results of policy implementation. Stability in policy planning has been linked to higher investment flows and more sustained renewable deployment (Dang et al., 2024). The interplay between long-term economic benefits and immediate social equity concerns defines the scope and pace of renewable integration (Navia Simon and Diaz Anadon, 2025). Moreover, community-based initiatives and energy communities are increasingly recognized as pivotal for fostering local acceptance and accelerating decentralized renewable energy adoption, providing tangible benefits to local populations (Panori, 2024).

The cumulative effect of these factors has positioned societal and economic dimensions as integral components of the EU's energy transition. Renewable energy adoption is not solely a response to environmental imperatives but reflects a broader reconfiguration of industrial and social systems (Adamo et al., 2024; Bizjak et al., 2024).

2.2 Methodology and scope of the review

2.2.1 Criteria for literature selection

The methodology employed in this review rests on a rigorous and clearly delineated literature selection process, designed to ensure both scientific relevance and methodological consistency (Dacre et al., 2025). The applied inclusion and exclusion criteria were tailored to identify research contributions that directly address the integration of renewable energy sources (RES) into the EU electricity system, with specific attention to systemic constraints and transition mechanism (Rahdan et al., 2025).

Sources were screened using a multi stage procedure. The initial stage applied keyword based searches across academic databases, after which full texts were assessed to exclude studies that did not address system level aspects such as grid flexibility, regulatory coherence or infrastructural adequacy (Potts et al., 2024) highlight the relevance of transparent documentation and standardized filtering protocols to ensure replicability and limit bias during selection. Subsequent qualitative screening targeted papers with substantive engagement in issues of market design, interconnectivity, and system operation, as outlined by Boyle et al. (2025). This systematic approach ensured the inclusion of studies that rigorously analyzed the technical, economic, and policy challenges associated with integrating variable renewable energy sources at scale (Oduro et al., 2024). This meticulous selection process facilitates a comprehensive analysis of the existing literature, highlighting both advancements and persistent challenges in fostering a resilient and sustainable energy infrastructure across the European Union (Wehbi, 2024).

Selection further incorporated variables such as temporal scope, geographical coverage, and analytical approach. Studies were prioritized when they reported empirical metrics and demonstrated strong methodological rigor, for example through scenario modeling, techno economic evaluations or life cycle assessment frameworks. Evaluative matrices facilitated the comparison of publications across criteria such as impact factor, methodological rigor, and thematic coherence (Hemmati et al., 2024).

Particular weight was assigned to research integrating system oriented perspectives. Literature was categorized thematically thereby allowing targeted analysis of each domain (De Carne et al., 2024). This stratification served both to organize the review content and to emphasize interrelations among technological, economic, and regulatory variables.

To preserve analytical consistency, systematic reviews and meta-analyses were included selectively, with priority given to those incorporating transparent methodologies and reproducible datasets (Getahun et al., 2024). The scope of selected studies was further verified using taxonomies adapted from, ensuring alignment with the review's focus on electricity system integration rather than broader sustainability narratives (Losada-Agudelo and Souyris, 2024).

In sum, the literature selection procedure employed here integrates quantitative screening techniques with qualitative relevance assessment. This dual approach enables the identification of contributions with both analytical depth and high utility in understanding the operational and strategic dimensions of RES integration within the EU context (Bankins et al., 2024).

2.2.2 Solar energy technologies

Solar energy technologies occupy a central position in the taxonomy of renewable energy systems, comprising both photovoltaic (PV) and solar thermal applications. PV systems convert solar radiation directly into electricity using semiconductor materials, primarily crystalline silicon and emerging thin-film technologies. Their modularity permits deployment across scales, from decentralized rooftop installations to centralized utility-scale facilities, thereby introducing a broad spectrum of integration challenges and opportunities (Ahmed et al., 2024).

Distributed PV generation contributes to reducing transmission losses and diversifying electricity supply but complicates grid operation due to its variability and spatial dispersion. Grid operators must account for localized production surges and forecast errors, particularly in high penetration scenarios (Meister et al., 2025). Cost reductions in module manufacturing and gains in conversion efficiency have accelerated deployment across EU member states, with contemporary PV systems exhibiting improved capacity factors and economic performance (Szabo et al., 2024).

In parallel, solar thermal technologies capture solar energy in the form of heat, enabling its conversion to electricity via thermodynamic cycles, or direct use in heating networks. Configurations such as parabolic troughs, solar towers, and dish systems are typically deployed in regions with high solar irradiance and ample available land. The geographic heterogeneity in solar potential across Europe influences the technical design and spatial allocation of thermal solar capacity (Pargmann et al., 2024).

Thermal storage systems integrated into solar thermal plants extend the dispatchability of solar output and mitigate intra day variability. These storage capacities are instrumental in offsetting the intermittency observed in PV dominated installations, especially where battery systems remain limited in scale or cost effective deployment (Ren et al., 2025). The strategic placement of storage enhances supply-demand balancing and supports system stability under fluctuating input conditions. Moreover, advancements in solar technology have led to significant improvements in both efficiency and cost effectiveness, with photoelectric conversion efficiency nearing theoretical limits and new materials enhancing reliability and durability (Afre and Pugliese, 2024).

Technological development in the solar sector is driven not only by regulatory incentives but also by capital allocation to research and innovation (Ogundipe et al., 2024). Investment in R&D has contributed to performance gains, while policy support frameworks have enabled scaling through feed-in tariffs, net metering schemes, and auction based procurement. These policy mechanisms vary by country, reflecting national energy strategies and market maturity levels (Chai et al., 2025).

Integration complexity increases with growing penetration of solar technologies into the grid, requiring sophisticated forecasting tools, demand-side response mechanisms, and grid reconfiguration strategies. Smart grid infrastructure, AI enabled dispatch optimization, and advanced inverter technologies are progressively incorporated to manage high volumes of variable generation (Hafez et al., 2025). Energy storage with multiple time horizons from batteries to seasonal thermal storage remains a pivotal component in ensuring stable system operation (Khan et al., 2025).

The spatial distribution of solar resources reinforces regional differentiation in deployment strategies, with southern European countries demonstrating a higher solar yield and favorable economics for large-scale systems (Zwickl-Bernhard et al., 2025). These geographical patterns, coupled with falling technology costs and improved system integration tools, position solar energy as a key contributor to the decarbonization of the EU power system.

However, high levels of solar deployment necessitate concurrent development of enabling infrastructures, including flexible generation assets, robust transmission networks, and digital control systems, to maintain overall system reliability (Ramos et al., 2024; Mellot et al., 2025).

2.2.3 Hydropower and marine energy

Hydropower and marine energy constitute key segments within renewable electricity generation, characterized by their origin in continuous hydrological and geophysical cycles. Hydropower, with its mature technological base and high installed capacity across the EU, plays a stabilizing role in the power system through its dispatchability and fast response capabilities. This allows it to function both as baseload and peaking power, offsetting the operational variability introduced by wind and solar resources (Khan et al., 2024).

The integration of hydropower into national grids is supported by established infrastructure, regulatory frameworks, and market mechanisms. Its contribution to system inertia and frequency regulation is critical in maintaining grid stability, especially under conditions of high renewable penetration (Ullah et al., 2024). However, the deployment of new large scale hydropower installations is constrained by environmental regulations and limited site availability, leading to a focus on modernization and efficiency upgrades of existing facilities (Turner et al., 2024).

Marine energy technologies, by contrast, are at earlier stages of development. They encompass a broad range of systems that convert kinetic and thermal energy from oceanic sources including tidal currents, waves, salinity gradients, and ocean thermal differentials into electricity (Cheng et al., 2025). Despite their lower global installed capacity compared to hydropower, pilot projects and commercial demonstrations are expanding in countries such as the UK, France, and Germany (Zhang et al., 2025).

Progress in marine energy deployment is hindered by unresolved regulatory and financial challenges. Disputes over intellectual property rights, uneven national commitment, and fragmented policy instruments slow the scale-up of marine energy projects (Zhao et al., 2025). In contrast to hydropower, which benefits from clear regulatory pathways and grid integration protocols, marine technologies remain dependent on targeted subsidies, innovation funding, and demonstration programs to reach commercial viability (Cao et al., 2025).

The capital intensity of both hydropower and marine energy remains a central constraint. While hydropower projects offer long asset lifetimes and low operational costs, initial investments are substantial and project timelines extended. Marine energy faces additional uncertainty due to limited standardization and technological risk, further affecting bankability and investor confidence (Yu, 2024).

From a systems perspective, hydropower's operational flexibility makes it a critical enabler for high shares of variable renewable energy, offering balancing, reserve, and ancillary services. Its role in frequency response and ramping support remains unmatched among current renewable technologies (Jaffal et al., 2024). Marine energy, though not yet deployed at scale, has the potential to contribute to supply diversification, particularly in coastal regions with favorable resource profiles.

Review methodologies assessing hydropower and marine energy integration combine technical, regulatory, and economic lenses. Comparative analyses of policy frameworks, project economics, and environmental constraints are used to map barriers and progress across EU jurisdictions (Santhakumar et al., 2024). The segmentation of literature by resource type and maturity level facilitates targeted evaluation of technology readiness, policy alignment, and investment risk. Furthermore, the Iberian Peninsula, comprising Spain and Portugal, presents a unique case study for marine energy due to its extensive coastlines and significant oceanic resources, yet it faces specific challenges in grid integration and infrastructure development (Vieira et al., 2024). Further extensive integration of these technologies at system level hinges on addressing cross-border governance barriers, strengthening coordination in research and development, and aligning deployment pathways with overarching EU climate and energy targets. Structured policy roadmaps and funding mechanisms play a crucial role in accelerating deployment, particularly in the marine sector. Pilot advances in tidal and wave energy, if supported by clear investment signals and regulatory harmonization, may enhance the overall resilience and flexibility of the renewable energy portfolio (Chen and Wu, 2024).

2.2.4 Bioenergy and biomass conversion

Bioenergy originates from biomass, encompassing a wide range of organic materials, including wood, energy crops, and agricultural residues, capable of storing solar energy via photosynthesis (Rivaldi et al., 2025). The conversion of biomass into usable energy carriers (electricity, heat, or liquid fuels) follows distinct technological generations, classified by feedstock type and process maturity. First generation technologies typically utilize edible crops and direct combustion, while second and third generation systems focus on non-food feedstocks, aquatic biomass and advanced thermochemical or biochemical pathways (Raman et al., 2025).

By 2022, global installed capacity for biomass-based power exceeded 150 GW, with a recorded 5% increase in biopower capacity that year. Within the European Union, bioenergy constitutes a central pillar of the renewable energy mix, accounting for approximately 60% of renewable energy in final consumption in 2021. Solid biofuels, including wood and pellets, represent nearly 70% of this share, with the remainder comprising liquid biofuels, biogas, and biodegradable waste primarily deployed in the heating and transport sectors (Ali et al., 2024).

The integration of bioenergy into the EU electricity system offers operational flexibility. It is applicable not only to base-load and dispatchable power generation, but also as a stabilizing complement to variable renewable energy (VRE) sources such as wind and solar. Scenario based analyses indicate that, under conditions of modest efficiency gains and partial electrification, bioenergy demand could increase by up to a factor of five compared to 2015 baselines. In such configurations, biomass is extensively used for heating, including in applications where electric technologies might otherwise be viable (Millinger et al., 2025). This underscores the importance of aligning biomass deployment with system-wide decarbonization strategies and efficiency objectives.

In addition to its technical advantages, bioenergy offers significant socio economic benefits. The entire bioenergy supply chain, from growing biomass to its conversion and transport, creates jobs, with estimates suggesting around 1.63 jobs for every kilotonne of oil equivalent processed (García-Mateos et al., 2025). This employment aspect strengthens bioenergy's contribution to energy diversity and the reduction of foreign energy dependency.

Despite the rapid growth of solar and wind capacity, bioenergy maintains a substantial share within the renewable mix due to its storage potential and dispatchability. Comparative analyses confirm its continued relevance for balancing intermittent generation and supporting grid stability (Malik et al., 2025).

Within the transport sector, bioethanol derived from biomass is positioned as a principal candidate for displacing gasoline. Projections suggest that bioethanol could replace up to 85% of gasoline demand by 2050, with synthetic renewable fuels covering the remainder (Estevez et al., 2024). This projection is grounded in ongoing advances in biomass processing technologies, including enzymatic hydrolysis, fermentation optimization, and integrated biorefining.

The strategic deployment of bioenergy within the EU's decarbonization framework increasingly involves hybridized system models. In the heating and cooling sectors, bioenergy can complement electrified technologies such as large-scale heat pumps and thermal energy storage systems, enabling the system to absorb fluctuations in VRE generation (Hyvönen et al., 2024). The systemic value of biomass therefore arises not only from its potential carbon neutrality but also from its ability to underpin integrated, flexible and cost efficient renewable energy systems (Yaseen and Alawi, 2025).

2.2.5 Geothermal energy applications

Geothermal energy, sourced from the Earth's internal thermal gradients, constitutes a reliable and dispatchable component of the renewable energy portfolio. Its applications span power generation, district heating, and industrial process heat, with deployment feasibility determined by subsurface temperature profiles and geological conditions (Nkinyam et al., 2025). Geothermal systems are commonly grouped into high enthalpy and low enthalpy resources, according to the depth and temperature of the underlying reservoir. High enthalpy resources, concentrated in tectonically active areas, are predominantly used for electricity production via steam turbine technologies and provide a nearly continuous output with very low variability. This characteristic distinguishes geothermal from intermittent sources such as wind and solar (Memon et al., 2024).

Low enthalpy geothermal systems, on the other hand, are utilized for direct applications, including district heating networks, greenhouse climate control, and industrial heating processes. These systems enhance local energy autonomy and support the decarbonization of thermal demand in both residential and industrial sectors (Brown et al., 2024). Direct use geothermal applications typically incur lower conversion losses and contribute to efficiency gains in regional energy systems.

From an environmental perspective, geothermal technologies exhibit low emissions of greenhouse gases and air pollutants, due to the absence of combustion processes (Abir Ahsan et al., 2025). Life cycle analyses consistently classify geothermal energy as among the lowest-emission renewable technologies, provided that appropriate reinjection and site management practices are observed (Elshehabi and Alfehaid, 2025). However, subsurface risks such as induced seismicity, reservoir depletion, and mineral scaling require continuous monitoring and technological mitigation strategies.

The expansion of geothermal energy within the EU electricity mix is contingent on sustained investment in drilling technologies, reservoir modeling, and binary cycle power plant development (Horne et al., 2025). Innovations in enhanced geothermal systems (EGS) are particularly relevant for increasing the geographic scope of geothermal deployment beyond naturally hydrothermal areas. In this context, cross-border cooperation and shared research initiatives within the EU have been instrumental in supporting pilot projects and improving access to high-resolution geological data (Ramos et al., 2025).

Methodologically, geothermal energy assessments are embedded within broader energy systems modeling and policy analysis. These models emphasize geothermal role in diversifying the generation mix, reducing import dependency, and enhancing system reliability through its baseload characteristics (Nkinyam et al., 2025). Geothermal is consistently positioned alongside hydropower and bioenergy in long-term planning scenarios as a stabilizing force within high-renewable penetration systems (Ricks et al., 2025).

Hybrid energy system configurations increasingly incorporate geothermal as a complement to variable renewable energy. In such models, geothermal serves as a foundation load provider, enabling higher integration of solar and wind resources without compromising grid stability. This synergy is particularly effective in balancing temporal mismatches in generation and demand, especially in decarbonized heating-dominated regions (Islam et al., 2025).

Overall, the integration of geothermal energy into the EU electricity mix is determined by site specific resource potential, prevailing policy frameworks and the readiness of supporting infrastructure. Although geothermal still accounts for a relatively small share of total installed capacity, its system level contribution is amplified by its dispatchability, favorable environmental profile and its ability to displace fossil based thermal generation. Effective large scale deployment therefore requires strategies that bring together technological innovation, targeted investment incentives and clear, stable regulation in order to fully unlock geothermal energy's role in the European context (Nkinyam et al., 2025).

2.2.6 Scope and limitations of the review

This review focuses on the systemic challenges and transition pathways associated with the integration of RES into the European Union's electricity system. Its scope is defined by sectoral, methodological, and temporal parameters, with an emphasis on grid stability, policy design, and the interaction between technical and institutional variables (Saleh et al., 2025). The analysis deliberately excludes certain peripheral topics to maintain coherence with the central objective: to examine integration mechanisms of RES and their implications for the operation and evolution of electricity systems in the EU.

One primary scope constraint is the selective treatment of modeling approaches. The review does not aim to catalog all available energy system models, which vary significantly in spatial granularity, temporal resolution, and analytical scope (Barani et al., 2026). Instead, it concentrates on those modeling frameworks that directly inform strategic planning, RES integration, and regulatory assessment. Such a focus reflects the divergence between models tailored for long-term capacity expansion and those optimized for real-time operational forecasting (Mundu et al., 2024).

A further limitation arises from the technological and regional specificity of many reviewed studies. While these sources provide granular insights, their findings are not uniformly transferable across the EU due to divergences in national infrastructure, policy maturity, and resource endowment. Moreover, the attribution of macro level outcomes as emission reductions or improvements in energy security exclusively to RES deployment often disregards confounding variables related to economic structure, market design, and social acceptance (Dang et al., 2024; Wang et al., 2025).

The review also operates within temporal boundaries. Many regulatory documents and policy analyses predate recent legislative changes, particularly those introduced after 2020. As a result, some emerging technologies, regulatory instruments, or market signals may not be fully reflected in the literature examined. The reliance on pre 2020 studies limits the scope of interpretation regarding current policy dynamics and technological frontiers (Wesche et al., 2024).

In addition, several data constraints impact the review's comprehensiveness. A significant portion of scenario, based projections rely on proprietary datasets or closed-source models, reducing transparency and hindering replicability. This epistemic opacity complicates the critical appraisal of methodologies and may mask underlying assumptions that influence projected outcomes (Mundu et al., 2024). The inclusion of gray literature, minor national reports, and region-specific assessments is limited by their absence in standardized databases or lack of peer-reviewed validation.

Sectoral coupling and multi-vector system integration as electricity-gas interactions or links with the transport and heating sectors are acknowledged but not treated in depth (Brennenstuhl et al., 2025). These interconnections are important for long term decarbonization pathways, but their complexity lies beyond the analytical boundaries of this review. Similarly, maritime transitions and selected non electrical renewable options are considered only to the extent that they help to illustrate broader integration challenges (Che et al., 2025).

Certain definitional inconsistencies across Member States also restrict comparability. For instance, large hydropower is excluded from RES classification in some EU state aid regulations, affecting how its contribution is framed within national strategies (Bensadi, 2024). Additionally, heterogeneous reporting standards and administrative definitions influence the availability and comparability of key indicators, such as RES share in final consumption or storage capacity deployment (Du Toit, 2024).

Methodologically, the review relies on structured keyword searches, expert consultation, and thematic clustering rather than full bibliometric mapping or citation network analysis. Although this approach allows for depth and focus, it may omit marginal or emerging voices not captured by standard indexing mechanisms. Validation is carried out by triangulating findings against legal texts and cross checking them with multi author review studies, but this process may not fully capture all domains, especially those examined through LCA tools or system dynamics models with wide uncertainty ranges (Ferdous et al., 2024; Zhu et al., 2024).

For environmental assessments, only a relatively small set of life cycle or full system impact studies is included, reflecting both data limitations and the often narrow scope of available analyses. Consequently, system-wide rebound effects, indirect emissions, and environmental trade-offs may be underrepresented (Gaffey et al., 2024). The same applies to socio-economic dimensions, where employment effects or equity considerations are treated where directly linked to technological deployment but not explored in systemic depth.

The review identifies several domains where evidence remains fragmented or inconclusive. These gaps include long term interactions between renewable deployment and electricity market design, cross border infrastructure adequacy in the context of growing decentralization, and the institutional inertia that slows regulatory harmonization across Member States. Taken together, these omissions highlight the dynamic, multi scalar character of the European energy transition and point to the need for iterative evidence building based on transparent, multidisciplinary methods (Gumber et al., 2024).

3 Results of the review

3.1 Systemic challenges in integrating renewable energy

3.1.1 Technical and infrastructural challenges

The incorporation of renewable energy sources (RES) into the EU's electricity system has introduced significant technical and infrastructural complexities. The intermittent nature of solar and wind generation alters the dynamics of grid operation, generating variability in voltage and frequency that requires enhanced system flexibility. The shift from synchronous generators to inverter based technologies has reduced available system inertia, creating a need for more sophisticated control architectures, predictive control algorithms and demand response schemes supported by digitalisation and artificial intelligence (Blaabjerg et al., 2023; Krasniqi, 2024).

The increasing penetration of RES in the EU's energy mix highlights the need for robust grid infrastructure to manage variability and ensure stability. Insights from China's energy system, where smart grid technologies are extensively deployed, provide valuable lessons for the EU. The chart below illustrates the average values of key variables influencing energy efficiency in China's smart grid systems in 2023, offering a comparative perspective on the scale of smart grid deployment and its implications for grid reliability and efficiency in the EU context (Zaman and Bibi, 2025).

The variables include Energy Efficiency (EEF, 9.75 energy units per GDP, indicating energy efficiency level), Demand-Side Management Implementation (DSMI, 97.84% of population with electricity access), Renewable Energy Integration (REI, 24.89% of total final energy consumption), Grid Reliability Metrics (GRM, 6.77% transmission and distribution losses), Technical Infrastructure Investment (TI, 1.12% of investments in smart grid projects), and Energy Consumption Patterns (ECP, 78.82, reflecting consumption patterns). Notably, the Smart Grid Penetration Rate (SGPR) is excluded due to its significantly larger scale (6.558×10^{10}), which would distort the visualization. These data highlight the extensive deployment of smart grid technologies and demand-side management in China, offering insights for the EU's efforts to enhance grid reliability and energy efficiency through targeted infrastructure upgrades and renewable energy integration.

Grid flexibility is further supported by demand-side response programs, interregional power exchanges, and dynamic load-shifting strategies (Chiva, 2024), though their effectiveness depends on regulatory coordination and infrastructure readiness.

The legacy transmission and distribution (T&D) infrastructure originally configured for centralized, unidirectional power flow is misaligned with the requirements of decentralized generation. Bidirectional energy flows, locally variable generation patterns and reverse power injections make grid reinforcement, continuous real time monitoring and adaptive operational protocols indispensable. The integration of RES is frequently hindered by congestion, curtailment, and localized instability, particularly in regions with high renewable penetration and insufficient grid upgrades (Blaabjerg et al., 2023).

Cross border interconnection is essential for optimizing the geographic dispersion of RES and balancing regional surpluses and deficits. Despite the technical viability of such integration, progress is constrained by inconsistent planning procedures, regulatory fragmentation, and divergent national investment priorities. High capital costs and the absence of harmonized standards further delay infrastructural modernization and interconnectivity.

3.1.2 Regulatory and market challenges

The evolving structure of the EU electricity market is increasingly misaligned with traditional regulatory and pricing arrangements. The marginal cost pricing model, originally developed for fully dispatchable generation, is ill suited to technologies with near zero operating costs such as wind and solar. This transformation reshapes the merit order, depresses average wholesale prices and increases price volatility, including more frequent negative price episodes during periods of high renewable output, so that market prices no longer signal the true system value of flexibility and reserve capacity (Göke et al., 2025).

Support schemes like feed in tariffs and feed in premiums played a central role in the early diffusion of renewables by providing revenue certainty. However, tariff based models can unintentionally detach producer behavior from market conditions, whereas premium schemes expose generators only partially to real time price dynamics. Distortions can arise when such mechanisms are poorly coordinated between countries or maintained after technologies have matured, prompting reforms that extend market design to include remuneration for ancillary services, capacity mechanisms and increasingly granular locational price signals that better reflect system level costs and benefits of renewable integration (Balzer and Watts, 2024).

Persistent divergence in national regulatory frameworks, grid codes and incentive structures continues to hamper cross border coordination and long term infrastructure investment. Even though umbrella strategies such as the European Green Deal and REPowerEU articulate common decarbonisation goals, their on the ground implementation remains uneven, with inconsistencies in technical standards and planning approaches limiting coherent scenario building and constraining the realization of cross border projects of common interest (Taromboli et al., 2025).

Financial instruments including subsidies, guarantees of origin, carbon pricing schemes and green bond standards underpin the mobilization of private capital for renewable deployment. Yet differences in design, eligibility rules and administrative accessibility across Member States influence perceived risk, shape investor confidence and generate disparities in project bankability, while emerging actors such as collective prosumers and energy communities often struggle to access mainstream financing channels, especially in less developed markets. A tighter monetary environment, characterized by higher interest rates and global macroeconomic uncertainty, further challenges the economics of renewable projects that rely heavily on debt finance (Jadidi et al., 2025).

Regulatory stability and coherent fiscal signaling at EU level are therefore essential to reduce investment risk, sustain long term capital flows and create more equal competitive conditions across jurisdictions. Ongoing market fragmentation and policy divergence remain structural barriers to establishing a truly integrated and resilient European electricity market.

3.1.3 Environmental and social considerations

Renewable energy technologies, while instrumental in reducing carbon emissions, also introduce specific environmental and social impacts. Wind and solar installations require substantial land areas, which may lead to habitat fragmentation, biodiversity loss, and competition with agricultural or conservation land uses. Biomass use raises additional concerns regarding resource depletion, deforestation, and lifecycle emissions associated with supply chain logistics (Chowdhury et al., 2025).

Environmental impacts are not uniform across technologies or geographies and are mediated by site selection, project scale, and local ecological sensitivity. Lifecycle assessments (LCA) serve as critical tools for quantifying emissions, energy return on investment (EROI), and environmental externalities across all stages from raw material extraction to decommissioning and recycling.

Public perception significantly influences the deployment trajectory of RES projects. Acceptance levels are shaped by procedural transparency, spatial justice, and the distribution of benefits and burdens. Resistance may arise in communities where perceived environmental or aesthetic costs outweigh socio-economic gains. Local engagement and participatory planning can influence siting decisions and mitigate conflict, although structural trust deficits in certain regions remain a challenge (Elshehabi and Alfehaid, 2025).

Socioeconomic disparities further complicate the distributional outcomes of renewable expansion. Low income households may experience disproportionate energy cost burdens or be excluded from accessing benefits such as self-generation or energy community participation. Regional inequalities in grid infrastructure, administrative capacity, and funding availability intensify these effects (Forrester et al., 2024).

Institutional mechanisms for addressing these concerns rely on transparent governance, inclusive policy instruments, and spatially targeted support measures. The effectiveness of environmental and social safeguards depends on the quality of regulatory enforcement, the availability of technical expertise, and the coordination across environmental, energy, and planning authorities. The integration of environmental and social dimensions into energy system governance is essential for maintaining system legitimacy and avoiding backlash in the transition process.

3.2 Impacts of renewable energy sources on conventional electricity generation

3.2.1 Displacement of fossil fuel-based generation

The progressive integration of renewable energy sources (RES) within the EU electricity sector has directly contributed to the reduction of fossil fuel-based electricity generation. In 2023, fossil fuels accounted for 42% of the EU electricity mix, with a continued downward trend as wind and solar expanded their presence. Countries such as Denmark and Austria exemplify this shift, relying heavily on wind and hydropower, respectively (Simoglou et al., 2025). The zero marginal cost nature of RES has disrupted the merit order, reducing the operating hours and profitability of fossil-fuel generators and creating downward pressure on market prices (Moore et al., 2025).

This displacement effect is reinforced by policy targets aligned with EU climate goals and economic trends favoring low cost renewables over traditional technologies. Long term forecasts support this trajectory, highlighting declining capacity factors and increasing decommissioning of coal and gas assets (Igliński et al., 2024). However, limitations in RES capacity to provide baseload and ancillary services underline the continued, albeit reduced, need for flexible fossil generation (An et al., 2025). The transition involves systemic implications for labor markets, infrastructure, and energy-intensive sectors reliant on electricity (Pati et al., 2025).

3.2.2 Impacts on grid operations and reliability

RES integration alters grid dynamics due to the inherent variability and intermittency of wind and solar. Reduced inertia from inverter based generation complicates frequency regulation and voltage control, while weather dependency introduces new patterns of unpredictability. This necessitates greater reliance on forecasting tools, automation, and ICT infrastructure to stabilize the system (Aouidad and Bouhelal, 2024).

Thermal plants experience more frequent cycling to accommodate RES, degrading efficiency and increasing maintenance requirements (Hu et al., 2024). Grid congestion and redispatch become prevalent where renewable generation exceeds local demand or exceeds transmission capacity. The demand for system flexibility grows, requiring not only enhanced storage capacity but also dynamic demand response and supportive regulatory mechanisms (Singh et al., 2024).

3.2.3 Flexibility requirements for conventional plants

The operational paradigm of conventional generation has shifted from baseload to flexibility focused services. Frequent ramping and shorter start-up times are now critical to maintain grid balance. This operational shift, while essential, results in technical strain, efficiency losses, and increased costs (Karekezi et al., 2025).

The reduced runtime and uncertain dispatch schedules complicate investment and maintenance planning. While gas turbines adapt more easily to flexible demands, coal-fired plants face steeper challenges. Consequently, flexible retrofitting and capacity market mechanisms are required to sustain these assets during the transition.

3.2.4 Economic implications for conventional generators

RES integration erodes the economic stability of conventional generators by lowering wholesale electricity prices and reducing operating hours. These dynamics push conventional assets into reserve or balancing roles with limited remuneration. Policy driven pressures, such as emissions reduction targets and subsidy structures for RES, further constrain their viability (Ergun et al., 2025).

The requirement for flexibility and quick response increases operating costs, creating a mismatch between technical needs and market compensation. Investment uncertainty, particularly in response to shifting regulatory frameworks and geopolitical disruptions, limits capital flows toward modernizing legacy infrastructure (Göke et al., 2025). The lack of consistent capacity remuneration mechanisms contributes to concerns over resource adequacy in high-RES systems.

3.2.5 Sector coupling and hybrid systems

Sector coupling emerges as a key enabler for system flexibility. By connecting electricity with heating, transport, and industry, power to heat, power to gas, and electrification pathways help manage RES variability and reduce emissions. These synergies depend heavily on a clean electricity mix and well-developed infrastructures (Zhou et al., 2025).

Electric vehicles and heat pumps exemplify this interaction, offering both increased demand and controllable loads for system balancing. Hybrid systems comprising RES, conventional generation, and storage provide inertia and grid stability in low-inertia environments. Their deployment must be aligned with market reforms, enabling them to provide ancillary services and demand side flexibility (Manamperi et al., 2024).

Digital platforms and energy management technologies further enhance the potential of sector coupling, supporting real time coordination and adaptive consumption. Integrated planning and regulatory support are necessary to scale these approaches and ensure their contribution to system resilience (Abdelkader et al., 2024).

3.3 Impacts of renewable energy sources on conventional electricity generation

3.3.1 Technological innovations and digitalization

The transformation of the European Union's electricity system is deeply dependent on the integration of technological innovation and digital tools to manage the challenges posed by high shares of variable renewable energy sources (RES). The migration from centralized generation models to distributed energy systems necessitates smart grid deployment and advanced digital infrastructure.

Smart grids enable real time monitoring, control, and communication across the grid, facilitating efficient energy balancing and system stability. Integration of Supervisory Control and Data Acquisition (SCADA) systems, Internet of Things (IoT) devices, and artificial intelligence allows operators to optimize grid operations while managing the intermittency of RES. These systems support predictive maintenance and automated dispatch, particularly when combined with decentralized energy resources and energy storage systems (Hafez et al., 2025).

The emergence of prosumers consumers who also generate energy—has been enabled by the diffusion of distributed energy resources (DERs), smart metering, and responsive pricing. Households equipped with rooftop solar and battery storage systems contribute to grid flexibility and resilience, especially when aggregated within microgrids. Optimization tools such as EnergyPlus and machine learning controllers facilitate forecasting, load management, and the integration of net-zero energy buildings (Wang and Shi, 2025).

Digitalization enhances system transparency, energy equity, and consumer participation. However, its full deployment depends on policies that ensure cybersecurity, interoperability, and data access. Investments in digital infrastructure and regulatory adaptation remain critical to enabling these emerging configurations (Radtke and Renn, 2024).

3.3.2 Policy and regulatory frameworks

The EU's transition to a decarbonized electricity sector is underpinned by a combination of legally binding targets and market-oriented reforms. The 2030 Climate and Energy Framework establishes ambitious goals for RES deployment, requiring alignment among Member States and consistent implementation.

To meet these objectives, the EU relies on a spectrum of instruments such as feed-in tariffs, tax reliefs, and mandatory RES quotas. While these reduce financial barriers and stimulate private investment, their effectiveness is contingent upon regulatory alignment and flexibility to accommodate technical realities like RES intermittency and storage requirements (Azhgaliyeva et al., 2024).

The decentralization of energy supply has complicated coordination across national energy systems. Harmonized grid codes, transparent cost allocation schemes, and joint infrastructure planning are needed to overcome the current fragmentation. Market coupling, exemplified by Germany and Denmark, underscores the value of cross-border electricity exchange and shared balancing services (Chakrabarty et al., 2021).

Political and regulatory inertia, alongside divergent national strategies, continues to obstruct integration. The volatility in wholesale energy markets during recent geopolitical tensions further illustrates the importance of shared infrastructure and responsive policy mechanisms.

3.3.3 Socio-economic transition mechanisms

A sustainable transition depends on socio-economic inclusivity and strategic support for regions historically reliant on fossil fuels. The Just Transition Mechanism (JTM) provides structural assistance to regions undergoing industrial decline, supporting reskilling, economic diversification, and community engagement.

Skills development is critical as the renewable sector demands expertise in digital systems, grid operation, and smart infrastructure. However, funding limitations and uneven distribution of JTM resources risk excluding vulnerable communities. Empirical cases such as Denmark's wind cooperatives demonstrate how local participation can reinforce policy effectiveness and enhance project legitimacy (Weisdorf et al., 2025).

Renewable projects stimulate local employment and attract investment but may exacerbate inequalities in under resourced regions. Tailored support mechanisms and participatory governance are essential to balancing national climate goals with regional socio economic realities (Mendes et al., 2025).

3.3.4 Role of research and development in transition

Research and development (R&D) remains pivotal in overcoming systemic and technological barriers associated with the integration of renewables. The evolution of grid models, energy storage systems, and control technologies is largely contingent on continued investment in applied and fundamental research.

The cost reductions in photovoltaic and wind technologies have been driven by technological learning, supported by iterative R&D cycles encompassing laboratory studies, pilot programs, and deployment. Scenario modeling tools informed by R&D enable accurate forecasting of system performance and guide adaptive regulatory design (Höffner and Glombik, 2024).

Beyond engineering solutions, interdisciplinary R&D informs institutional innovation, governance reforms, and economic modeling. It supports the design of equitable and efficient transition pathways that balance decarbonization, supply reliability, and affordability (Das et al., 2025).

The role of R&D is increasingly shifting from incremental improvements to transformative solutions in digital energy systems, long-duration storage, and system architecture. This transformation aligns with broader strategic objectives under the European Green Deal, demanding continued public and private investment in cross-sectoral innovation (Nicoli et al., 2024).

In conclusion, R&D is both a facilitator of present reforms and a driver of future electricity system architectures, embedding flexibility, reliability, and sustainability into the core of Europe's energy transformation.

3.4 Future perspectives and cross-sectoral opportunities

3.4.1 Sector integration and energy system flexibility

Sector integration has emerged as a critical technical pathway for enhancing flexibility and stability in the EU's evolving electricity system. The increasing penetration of variable renewable energy sources (RES) necessitates coordinated strategies across transport, industry, and energy storage to ensure reliable and efficient operation.

Electrification of transport facilitates emissions reduction while enabling interaction with grid dynamics. The deployment of electric vehicles (EVs), along with smart charging and vehicle to grid (V2G) technologies, positions mobile storage as an ancillary resource for load balancing and frequency regulation. These mechanisms contribute to mitigating the variability introduced by RES (Davoudkhani et al., 2024).

In the industrial sector, direct electrification is applicable primarily to low and medium temperature processes. Coupling electrified production with heat storage and combined heat and power (CHP) systems enhances the capacity of industrial actors to align their energy usage with renewable availability. However, high temperature processes remain largely dependent on fossil fuels, reflecting current technological constraints.

Complementing electrification, Power to X (PtX) technologies convert surplus electricity into storable energy carriers such as hydrogen or synthetic fuels. These technologies enable long-duration energy storage and facilitate decarbonization of hard-to-electrify sectors, while also contributing to reduced curtailment of excess renewable generation.

The operationalization of PtX and advanced storage technologies requires integrated planning frameworks, dynamic market mechanisms, and infrastructure investment. Initiatives like the European Battery Alliance aim to consolidate supply chains and technological development in this domain (Nicoli et al., 2024).

3.4.2 Emerging trends in renewable energy deployment

Renewable energy deployment in the EU reflects a multidimensional shift, encompassing systemic, technological, and regulatory transformations. There is an increasing focus on interdisciplinary approaches that embed circular economy principles, digitalization, and sector coupling within energy system design.

Electromobility and enhanced energy storage are reshaping consumption profiles and expanding renewable uptake, particularly through coordinated integration of EVs into grid infrastructure. Despite these advancements, intermittency and storage gaps remain persistent barriers. National disparities in deployment trajectories are becoming more pronounced. While some Member States have accelerated solar and wind integration, others continue to rely on legacy resources such as biomass. These divergences generate concerns over cohesion in meeting EU wide decarbonization targets and underline the need for a harmonized but context sensitive policy landscape (Hyvönen et al., 2024).

Historical data indicate that stable long term targets and clear financial incentives have been effective in driving renewable investment. However, evolving policy frameworks now emphasize transnational grid integration, cross border energy trade, and interoperability, creating a broader platform for renewable balancing and infrastructure optimization.

Modernization of the grid through digital solutions advanced metering, demand side management, and automation enhances flexibility. These developments are reinforced by increasing empirical research, which validates and calibrates theoretical integration models, exposing data and implementation gaps (Monaco et al., 2024).

International cooperation is expanding in both research and infrastructure, enabling shared investment strategies and technology transfer. The complexity of the transition, however, is compounded by year on year variability in hydro and nuclear generation, which necessitates improved disaggregation in energy accounting and trend analysis.

The current trajectory indicates a progressive shift from isolated RES expansion to holistic system transformation. This involves simultaneous advancements in technology, market structure, and sectoral integration, supported by real-world validation and strategic management tools (Zahid et al., 2025).

3.4.3 Potential for innovation in grid management

The increasing share of RES in the EU electricity mix imposes significant challenges on grid management, particularly due to the variability and non-dispatchability of wind and solar generation. This dynamic has accelerated innovation in smart grid technologies, energy storage, and digital control systems.

Modern grid architectures incorporate ICT, power electronics, and decentralized control to manage energy flows in real time. These components collectively enhance the grid's capacity to adapt to rapid fluctuations in supply and demand, thus supporting the operational integration of RES (Kumar et al., 2025).

Legacy infrastructure must undergo structural and control-level transformations to support decentralized generation and storage. Smart grid systems provide granular coordination capabilities across voltage levels, enabling stable frequency and voltage even under volatile input conditions.

Demand-side response and grid-scale storage act as primary levers for flexibility, while advanced control algorithms allow proactive grid stabilization. However, the pace of innovation has been constrained in some Member States due to insufficient collaboration between academic and industrial actors (Micari and Napoli, 2024).

Enabling innovation also depends on regulatory agility. The rise of aggregators and distributed market participants necessitates legal frameworks that accommodate dynamic adjustment and the scaling of novel business models. Periodic reviews and sandbox environments have proven effective in facilitating experimental deployment.

The electrification of a majority share of energy demand and the concurrent rise of RES and nuclear generation elevate the strategic role of grid stability. This has intensified efforts to synchronize infrastructure investments, market integration, and transnational balancing (Saleh et al., 2025).

Sector coupling extends the scope of innovation by allowing excess electricity to be redirected to heating or transport, unlocking system-wide efficiency gains. Yet this remains underexplored in terms of real-time operation and regulatory synchronization.

Cross-border energy trade enabled by market coupling and the EU internal energy market adds further complexity but also opportunities. Coordinated infrastructure planning allows balancing resources to be shared across Member States, mitigating national scale supply fluctuations (Dobos et al., 2025).

Maintaining power quality, interoperability, and cyber security across increasingly digitalized grid environments requires continued R&D. The convergence of RES integration, system resilience, and policy driven innovation places grid management at the nexus of technical and institutional evolution.

Ongoing support for research and ecosystem development, alongside sustained policy alignment, is essential to ensuring that grid infrastructures evolve in parallel with the accelerating pace of renewable integration.

4 Discussion

4.1 Synthesis of key findings

A synthesis of the reviewed literature reveals a set of interconnected factors shaping the integration of renewable energy sources (RES) into the European Union's electricity system. Economic instruments, such as tax exemptions, grants, and low interest loans, have proven effective in attracting investments in RES infrastructure across EU Member States (Di Foggia and Beccarello, 2024). These tools lower initial capital barriers and foster competitive market conditions for renewable technologies.

Economic prosperity is positively correlated with RES deployment. Vasa et al. indicate that higher economic development expands technical capacity and aligns policies more effectively, accelerating emissions mitigation and structural market shifts (Moore et al., 2025). Conversely, countries heavily reliant on fossil fuels with high per capita CO_2 emissions experience slower transitions due to limited incentives and structural inertia (Huterski et al., 2021).

From a technological standpoint, literature points to pressing challenges in grid stability and variability management associated with wind and solar integration, particularly in the electricity and transport sectors (Che et al., 2025). Future energy transition scenarios prioritize scalable storage solutions, flexible grid management, and the adoption of hydrogen and other emerging technologies. Cost reductions in renewable technologies are driven by technological advancements and economies of scale, reinforcing their competitiveness and stabilizing energy markets (Asim et al., 2025).

Policy coherence and regulatory reform are critical to overcoming market fragmentation. EU-wide policy harmonization is identified as essential for synchronized and cost effective RES deployment. Governance quality is equally influential, with digital integration and robust administrative frameworks linked to improved environmental performance and strategic policy implementation (Maczka et al., 2025).

National case studies reveal heterogeneous transition paths, influenced by historical energy mixes, political commitment, and institutional capabilities. Countries like France and the Netherlands illustrate how legacy systems and capacity constraints delay RES uptake. Additionally, the global depletion of conventional energy carriers adds urgency to the transition and highlights ethical and strategic dimensions concerning access equity and sustainability (Munonye, 2025).

Overall, the reviewed literature underscores that a comprehensive approach combining economic incentives, technological innovation, policy alignment, and good governance is necessary to enable a resilient, low carbon electricity system across the EU.

4.2 Limitations of current research

Despite extensive research on RES integration in the EU, several limitations hinder analytical robustness and policy relevance. A recurring issue is the reliance on static datasets and cross-sectional analyses, which fail to capture temporal dynamics and system responses to shocks or policy changes. Advanced econometric techniques like panel dynamic ordinary least squares (PDOLS) remain underutilized, leaving time-based causal inferences underdeveloped (Sengupta et al., 2025).

Data granularity and regional differentiation are also lacking. Aggregating diverse countries with varying energy dependencies, socio economic contexts, and technological baselines often obscures critical patterns. While Northern European states exhibit strong RES performance, Central and Eastern regions lag due to fossil fuel dependence and slower modernization (Adamo et al., 2024). Insufficient disaggregation by country group, sector, or technology limits the development of targeted policy interventions.

Grid level challenges, although acknowledged, are inadequately quantified. Studies frequently reference intermittency and transmission needs but seldom provide detailed models on congestion, thermal constraints, or voltage and frequency regulation in high RES scenarios (Sun et al., 2025). This reduces the applicability of findings for transmission operators and energy planners.

Regulatory and policy-related analyses tend to generalize barriers without offering empirical evaluations of specific reforms. The effects of policy instruments such as permitting procedures or tariff structures on market integration, investor behavior, or grid compatibility are rarely assessed with precision. Additionally, studies often overlook the interplay between national energy security policies and geopolitical events, including the implications of EU Russia tensions (Huang et al., 2024).

Socio economic dimensions remain underexplored in empirical terms. While literature discusses energy justice, job creation, and fuel poverty, these are typically examined through case studies or limited samples. Broader evaluations of distributive effects and long-term impacts remain fragmented (Mendes et al., 2025).

Technology centered research frequently omits behavioral, institutional, and market feedback loops. For instance, the persistence of fossil fuel infrastructure is seldom interrogated for its economic or political drivers. Moreover, scenario building practices often rely on outdated or simplistic assumptions, underestimating the scale of transformation required for climate neutrality targets (van der Zwaan et al., 2025).

There is also limited integration between RES deployment studies and broader sustainability frameworks, such as the UN Sustainable Development Goals. While RES contributions to decarbonization are acknowledged, linkages to environmental and social metrics are rarely systematized (Migliavacca, 2025).

Lastly, meta analytical overviews of the literature remain scarce. Mapping the academic, industrial, and governmental drivers of RES deployment across EU states is not yet comprehensive, resulting in policy guidance that often lacks precision, relevance, or scalability.

4.3 Implications for policy and practice

Effective policy frameworks are essential to support the EU's shift to a RES based electricity system. Long term, stable climate policies are needed to enable investment planning and sectoral coordination. These policies must be integrated across domains economic, labor, trade, finance, and innovation to ensure systemic alignment and minimize social disruptions (Bistline et al., 2025).

Legal and regulatory instruments must ensure market certainty and support innovation uptake. Clear operational rules are necessary to manage grid flexibility and enable the incorporation of intermittent sources, storage, and demand side response. Predictable regulatory environments enhance investor confidence and facilitate deployment of emerging technologies such as green hydrogen.

Transparent and standardized data collection is fundamental for policy monitoring. Reliable statistics underpin evidence based decisions and cross border comparisons. This becomes increasingly relevant as EU targets project electricity to constitute over 50% of total energy consumption by 2050, largely from RES sources (Trivedi et al., 2024).

Social implications require parallel attention. The transition involves labor displacement, re-skilling, and evolving job profiles. Policies addressing upskilling and just transition measures are essential to maintain inclusivity and public support, particularly in post crisis contexts (Shvetsova, 2025).

Technical integration challenges such as grid stability and market adaptation necessitate investment in smart grids, interconnectors, and flexible pricing mechanisms. These tools help align consumption patterns with generation variability while maintaining system reliability. However, market interventions must avoid distorting investment signals.

Scientific research and innovation play a pivotal role in technology deployment. However, overly complex legislation or inefficient policy execution can hinder the translation of research into applied energy solutions. Enhancing knowledge transfer and simplifying procedures within the European Research Area would accelerate technological diffusion (Sánchez-García et al., 2025).

Regional disparities require policy differentiation. Countries with high energy import dependency or underdeveloped RES capacity demand tailored support mechanisms (Kaya and Kaya, 2025). Uniform policies risk exacerbating transition asymmetries within the EU.

The integration of circular economy principles into energy strategies also presents policy challenges. Synergies between resource efficiency and RES deployment could enhance both environmental and economic outcomes, provided strategies are cross sectorally coordinated.

Energy efficiency and productivity must be incorporated as primary objectives. Policies focusing solely on technology deployment may miss broader opportunities for systemic sustainability and cost effectiveness. Finally, stakeholder engagement is essential. Incorporating citizen preferences and social insights improves policy design and implementation feasibility. Building legitimacy and fostering acceptance are necessary conditions for a successful, inclusive transition to a low carbon electricity system in the EU (Boyle et al., 2025).

5 Conclusion

The transition of the European Union's electricity system toward a renewable energy dominated configuration necessitates a multidimensional and systemic approach that integrates environmental, technical, economic, regulatory, and social considerations. The body of research reviewed throughout this study highlights the pivotal role of innovation and empirical validation in operationalizing theoretical models and informing policy design. In particular, the variable and non dispatchable nature of solar and wind power calls for deeper system integration, facilitated by sector coupling, digital infrastructure, and coordinated energy governance across multiple levels (Koirala et al., 2024).

Addressing technical constraints such as grid instability and supply intermittency demands the deployment of advanced grid management technologies. Smart grids, energy storage systems, demand-side flexibility, and automated control mechanisms are essential to maintaining system resilience in the face of increasing RES penetration (Silva et al., 2024). However, their effective implementation hinges on enhanced cross-sector collaboration, dynamic regulatory frameworks, and supportive market conditions. Regional innovation clusters and public-private partnerships offer promising avenues to accelerate technological diffusion and cost efficient deployment.

Environmental sustainability is intrinsically linked to the energy transition. The expansion of renewable capacity must be accompanied by rigorous life cycle analysis and integrated spatial planning to mitigate adverse effects such as biodiversity degradation, land-use conflicts, and disruptions to food systems. Incorporating environmental externalities into planning decisions and ensuring transparent stakeholder engagement are prerequisites for maintaining ecological integrity and fostering public trust (Hassan et al., 2025).

The social dimension of the transition is equally critical. Ensuring equitable access to clean energy, minimizing distributional disparities, and supporting workforce adaptation through reskilling programs are necessary to deliver a just transition. Policies that facilitate community participation and localized benefit-sharing will strengthen social acceptance and anchor the energy transition in democratic legitimacy.

Policy design must remain adaptive and responsive to dynamic technological progress, market developments, and geopolitical conditions. At the same time, it must provide long term stability to attract capital and guide infrastructural investment. The heterogeneity of resource endowments and economic conditions across EU Member States requires a dual governance strategy: localized policy flexibility complemented by EU-level harmonization. This approach can address regional disparities, promote infrastructure convergence, and ensure energy solidarity.

In sum, the successful realization of the EU's energy transition will depend on the sustained integration of scientific research, technological innovation, and inclusive policymaking. Embedding these principles into cross sectoral governance and maintaining a continuous feedback loop between empirical findings and regulatory action will be essential. By aligning environmental responsibility, social equity, and economic resilience, the European Union can chart a pathway toward a low-carbon electricity system that is robust, inclusive, and sustainable.

Author contributions

G-AB: Investigation, Software, Project administration, Writing – original draft, Data curation, Formal analysis. B-GV: Formal analysis, Writing – original draft, Software, Investigation, Conceptualization, Methodology. GN: Validation, Data curation, Visualization, Methodology, Writing – original draft, Supervision, Software. M-BT: Data curation, Formal analysis, Writing – original draft. GD: Conceptualization, Writing – original draft, Software, Project administration. A-IB: Writing – original draft, Data curation, Software. S-IC: Methodology, Conceptualization, Writing – original draft.

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Conflict of interest

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Generative AI statement

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