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Decarbonizing The Power Sector: Challenges and Opportunities in The Transition to Net Zero Energy Systems

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Abstract
The transition to net zero energy systems has positioned the power sector at the forefront of global decarbonisation efforts. This study critically examines the technological, economic, policy, and social dimensions influencing the decarbonisation of the power sector. Using a systematic literature review and secondary data analysis, it identifies the structural barriers and enabling opportunities shaping the global energy transition. Results reveal that while renewable energy capacity—especially solar and wind—has expanded rapidly, fossil fuels remain dominant in electricity generation, indicating an uneven pace toward net zero targets. Mature technologies such as photovoltaics, wind turbines, and lithium-ion batteries show high readiness and scalability, whereas emerging options like hydrogen and carbon capture and storage face cost and policy limitations. Governance and financial constraints, particularly in developing economies, hinder investment and slow progress, while regions with stable regulatory frameworks demonstrate stronger advancement. Grid integration challenges, intermittency, and social acceptance issues further complicate transition efforts. However, the study highlights significant opportunities in smart grid digitalisation, storage expansion, and inclusive stakeholder engagement as pathways toward sustainable power systems. It concludes that achieving power-sector decarbonisation requires integrated strategies combining technological innovation, institutional reform, and equitable participation to ensure a reliable and inclusive transition to net zero energy systems.
Keywords: *Decarbonisation; Power sector; Net zero; Renewable energy; Smart grids; Energy storage; Carbon capture; Green hydrogen; Policy frameworks; Sustainable energy transition*

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I. INTRODUCTION

Background of the Study

The power sector occupies a central position in the global endeavour to achieve a net zero greenhouse gas (GHG) emissions energy system. The comprehensive roadmap articulated by the International Energy Agency (IEA) for reaching net zero globally by 2050 clearly identifies electricity generation, transmission, and distribution as critical levers for mitigation of climate change (International Energy Agency, 2021). In deeply decarbonised systems, the electricity system is not only decarbonised itself but also becomes the enabling backbone for decarbonising other sectors such as transport, industry, and buildings through electrification (Bistline, 2021). The fact that many economies now target full decarbonisation of their power sectors by 2030 to 2050 underlines the urgency and scale of the transformation required (Vorozheykina, 2022).

Yet the transition is fraught with structural, technical, economic, and institutional challenges. As one systematic review observed, the decarbonisation of the electricity system demands not only accelerated deployment of low carbon generation but also deep changes in grids, storage, demand management, and policy frameworks (Bistline, 2021). The power sector's high share of emissions, in many jurisdictions accounting for more than half of energy related carbon dioxide emissions, also makes it a logical priority for mitigation action (Wang et al., 2024). Consequently, a nuanced understanding of the power sector's role, the barriers it faces, and the opportunities that accompany decarbonisation is necessary for both policymakers and industry stakeholders.

The evolution of electricity demand and generation attributes further underscores this complexity. As end use electrification progresses, for example via electric vehicles, heat pumps, and industrial electrification, the demand profile for electricity changes significantly (National Academies of Sciences, Engineering, and Medicine, 2024). These changes impose additional constraints on planning and operations of power systems. Variable renewable generation must be balanced, transmission and distribution losses managed, storage integrated, and system stability maintained. The IEA's global roadmap notes that as renewable shares increase, issues of grid inertia, balancing, and resource adequacy become more important (International Energy Agency, 2021). In effect, decarbonising the power sector is not simply a matter of replacing fossil fuel generators with renewables; it entails system wide reengineering of the generation, grid, and demand nexus.

Financial and institutional challenges accompany the technical ones. The investment required in infrastructure, grid modernisation, and new technologies is vast. One recent review of the U.S. energy system notes that despite promising technology prospects, variation in infrastructure readiness, supply chain constraints, state level regulation, and social equity concerns introduce major obstacles to achieving net zero targets in the power sector (Arent et al., 2022). The United Kingdom's National Audit Office similarly concluded that the government's ambition to decarbonise electricity by 2035 is predicated on a joined up plan that links capacity build out, system transformation, and affordability, an integrated approach that is still under development (United Kingdom National Audit Office, 2023). This underlines that achieving net zero in the power sector is not only a technical task but also one of governance, economics, and social policy.

On the opportunity side, the decarbonisation of power systems carries substantial co benefits. These include improved air quality, public health gains, enhanced energy security through diversification and renewables, and the potential for new industrial and employment opportunities in emerging low carbon technologies. For instance, the electrification of end uses coupled with renewable generation may reduce dependence on imported fuels and lower operational costs over time (Martins et al., 2022). Studies also find that more rapid deployment of low carbon technologies lowers long term system cost even if upfront investment is high (Arent et al., 2022). As such, decarbonising the power sector is increasingly seen not just as a burden but as a strategic opportunity for economies to reshape their energy systems for the long term.

The geographic and development level context further complicates and enriches the analysis. High income economies often have more mature grids, stronger institutional capacities, and better access to capital for large infrastructure projects. Meanwhile, emerging and developing economies often face dual imperatives: expanding access to electricity while simultaneously reducing carbon intensity. This creates a two fold challenge of scaling capacity and improving quality while ensuring decarbonisation pathways remain viable. For example, literature on the decarbonisation of sub Saharan Africa's power sector points to limited progress to date and a pressing need to integrate renewable deployment, efficiency gains, and transmission enhancements in order to meet both access and decarbonisation goals (Wang et al., 2024). That heterogeneous context means that while the overarching goal of decarbonisation is global, the pathways and enabling conditions vary significantly.

Hence, this study investigates the interplay between challenges and opportunities inherent in decarbonising the power sector in the transition to net zero energy systems. It examines the structural barriers such as infrastructure readiness, financing, technological maturity, and governance, and explores enabling levers including electrification, storage, demand side management, and system integration. The goal is to clarify how policymakers and system planners can align the electric power transition with broader net zero objectives while maintaining system reliability, cost effectiveness, and social inclusion.

Research Questions and Objectives

The growing urgency of climate mitigation has made the decarbonisation of the power sector a global policy priority. Yet, the transition to net zero energy systems remains complex, with overlapping technological, economic, and governance challenges. To guide empirical and theoretical inquiry, this study formulates specific research questions and objectives that address the critical dimensions of this transition.

Research Questions

I. What are the major structural, technological, and institutional challenges hindering the decarbonisation of the power sector in the transition to net zero energy systems?
II. How can emerging technologies such as renewable integration, energy storage, and smart grids enhance the efficiency and reliability of low carbon power systems?
III. What policy mechanisms and market instruments have proven most effective in accelerating power sector decarbonisation in both developed and developing economies?
IV. In what ways do financial constraints, investment patterns, and regulatory frameworks shape the pace and equity of the power transition?
V. What opportunities arise from power sector decarbonisation in terms of energy security, employment generation, and long term economic competitiveness?

Research Objectives

I. To identify and critically analyse the key barriers that impede the decarbonisation of power systems across different national and regional contexts.
II. To evaluate the contribution of renewable energy technologies, grid modernisation, and electrification in advancing the transition to net zero energy systems.

III. To assess the effectiveness of existing policy and regulatory frameworks in promoting low carbon electricity generation and distribution.
IV. To examine the economic and social implications of power sector transformation, including cost trajectories, investment needs, and employment effects.
V. To propose integrated policy recommendations that balance environmental sustainability, energy affordability, and system reliability within a net zero framework.

Through these questions and objectives, the study aims to deepen understanding of the dynamic interplay between technological innovation, policy design, and market evolution in achieving net zero emissions within the global power sector. The outcome is expected to inform both academic debate and policy formulation by providing a structured analysis of challenges and opportunities shaping the next generation of energy systems.

Research Problem and Significance

The transition to net zero energy systems has become one of the most defining global imperatives of the twenty-first century. However, the power sector, which remains the largest single source of carbon dioxide emissions globally, faces significant obstacles that threaten to slow or even derail this transition. Despite clear international commitments to decarbonisation, including the Paris Agreement and national net zero targets, the pace of transformation within the electricity subsector remains uneven and uncertain. The research problem arises from the persistent gap between technological potential and practical implementation in achieving low carbon electricity systems (Bistline, 2021). Many nations continue to rely on fossil-based generation as the backbone of their energy mix, while renewable integration, grid expansion, and energy storage progress at varying rates across regions (Martins et al., 2022). This inconsistency creates a structural imbalance that undermines global net zero ambitions.

Another dimension of the research problem lies in the misalignment between policy intentions and institutional capacity. Although regulatory frameworks increasingly recognise the necessity of decarbonisation, many lack coherence, long-term predictability, or cross-sectoral coordination (United Kingdom National Audit Office, 2023). In several jurisdictions, weak market signals and fragmented governance have led to investment uncertainty and delayed innovation. Financing remains a critical bottleneck as developing economies in particular struggle to attract capital for clean energy infrastructure while addressing basic access needs. Arent et al. (2022) note that even in advanced economies, insufficient grid flexibility and limited investment in digitalisation impede the full deployment of renewable technologies. Thus, the central problem is not the absence of viable technologies but the systemic and institutional barriers that prevent their optimal deployment at scale.

Furthermore, the ongoing energy transition exposes a tension between environmental sustainability, energy security, and affordability. Policymakers face the challenge of ensuring that rapid decarbonisation does not compromise grid reliability or impose disproportionate costs on vulnerable consumers. The volatility of global energy markets, particularly during geopolitical disruptions, has underscored the need for resilient and diversified low carbon power systems (International Energy Agency, 2021). Yet, balancing the trilemma of sustainability, reliability, and affordability continues to elude most economies. The lack of integrated planning across transmission, distribution, and storage infrastructure aggravates these challenges and risks creating stranded assets and inefficiencies in the energy value chain (National Academies of Sciences, Engineering, and Medicine, 2024). Addressing these multidimensional challenges requires evidence-based strategies that combine technological, economic, and institutional reforms.

The significance of this research lies in its comprehensive approach to diagnosing and addressing the obstacles and enablers of power sector decarbonisation. By analysing both challenges and opportunities, the study provides a balanced understanding of how energy systems can transition toward net zero pathways without sacrificing reliability or inclusiveness. Its findings are expected to contribute to scholarly debates on sustainable energy transitions and inform the development of coherent policy instruments that can accelerate progress toward climate neutrality. The research also offers insights into the comparative dynamics between developed and developing economies, highlighting the contextual factors that shape transition trajectories (Vorozheykina, 2022).

Practically, this study holds significance for policymakers, regulators, and energy investors seeking to design efficient interventions that align technological innovation with market readiness and regulatory stability. It contributes to ongoing policy discussions on integrating renewable energy into power grids, financing clean technologies, and managing demand-side flexibility. For academia, it enriches the literature on decarbonisation by bridging theoretical frameworks with applied energy policy and systems analysis. Ultimately, understanding the interplay of challenges and opportunities in power sector decarbonisation will be essential to building resilient, equitable, and economically viable energy systems consistent with the global net zero agenda (Wang et al., 2024).

II. LITERATURE REVIEW

Conceptual Framework of Power Sector Decarbonisation

In the context of the power sector, decarbonisation is defined as the process of reducing carbon dioxide and other greenhouse-gas emissions per unit of electricity generated and, ultimately, achieving an electricity supply system with minimal or zero net carbon emissions (Grantham Research Institute, 2020). More broadly, it involves a shift away from fossil-fuel based electricity generation toward low- or zero-carbon alternatives, including renewables and other clean technologies (myclimate, 2025). In practical terms for the electricity domain, decarbonisation includes both reducing the carbon intensity of electricity generation and transforming the ancillary systems of transmission, distribution and demand such that the entire electricity value chain supports a low-emissions outcome (Corporate Energy, 2025). The scope of decarbonisation in the power sector therefore spans multiple dimensions: generation technology, grid infrastructure, system integration and demand-side adaptation.

The theoretical foundations of energy transition and sustainability pathways offer a structured way to conceptualise this transformation. Energy transition theory recognises that large-scale shifts in energy systems are socio-technical in nature: they involve technological innovation, institutional change, infrastructure reconfiguration and behavioural adaptation (Awolesi, Salter, & Reams, 2024). Sustainability transition research emphasises that pathways toward a low-carbon energy system are non-linear, cumulative and require coordination across multiple system elements (Markard & Rosenbloom, 2023). For instance, one review describes a four-phase framework of the net-zero energy transition: emergence of low-carbon innovations, sectoral transition (such as electricity), cross-sector coupling based on low-carbon power, and finally decarbonisation of hard-to-abate sectors (Markard & Rosenbloom, 2023). In this theoretical lens the power sector is foundational: its decarbonisation both constitutes a distinct transition phase and enables wider economy-wide decarbonisation via electrification of transport, heating and industry (UNFCCC, 2024). The systemic character of this transition implies that policy, market design, technology maturation and infrastructure development must align to realize sustainability-oriented pathways.

The interaction between decarbonisation, electrification and energy-system transformation is pivotal in this framework. As the power sector decarbonises, low-carbon electricity becomes the vector for electrifying end-use sectors—such as transport, heating and industrial processes—thus multiplying the decarbonisation impact (Grantham Research Institute, 2020). In turn, increased electrification raises electricity demand, modifies load profiles and introduces greater variability in generation and consumption patterns. This necessitates an energy-system transformation that includes grid modernisation, storage deployment, demand-side flexibility and sector coupling (UNFCCC, 2024). For example, as industries and households switch from fossil fuels to electric technologies, the power system must adapt to higher peaks, more dynamic load shapes and deeper integration of variable renewables (Ambition to Action, 2019). Thus decarbonisation, electrification and system transformation are interdependent: decarbonisation expands electrification potential, electrification drives system transformation, and system transformation enables decarbonisation at scale.

Global policy frameworks provide the institutional impetus and governance context for power-sector decarbonisation. The Paris Agreement sets the overarching goal of limiting warming to well below 2 °C and pursuing efforts toward 1.5 °C, placing decarbonisation of the electricity sector as a fundamental pillar of national emissions-reduction strategies (Grantham Research Institute, 2020). More specifically, the International Energy Agency and the United Nations Framework Convention on Climate Change highlight that the power sector must reach near-zero carbon emissions by mid-century for the global net-zero target to be viable (UNFCCC, 2024). National policy instruments such as renewable energy targets, coal phase-out schedules, carbon pricing, and grid-infrastructure investment plans translate these global aims into power-sector reform (NAO, 2023). For instance, regulatory frameworks that mandate a higher share of renewables or require utilities to decarbonise by specified dates directly reshape the investment environment for generation, grid and storage technologies. The alignment of global targets, national policy frameworks and sector-specific regulation thus forms a coherent institutional foundation for the power-sector decarbonisation pathway.

The conceptual framework for decarbonising the power sector integrates (a) the definition and scope of decarbonisation within electricity systems; (b) theoretical constructs drawn from energy-transition and sustainability-pathway literature; (c) the interlocking dynamics of decarbonisation, electrification and system transformation; and (d) the role of global and national policy architectures in enabling sector reform. This framework offers a robust basis for analysing both the challenges and opportunities inherent in transitioning the power sector toward net-zero energy systems.

Global Trends and Pathways to Net Zero Power Systems

Global electricity demand continues to increase, exerting additional pressure on power-sector decarbonisation efforts. In 2024 the growth in electricity demand was recorded at 4.3 percent, the highest since the post-recession recovery, and the power sector accounted for around three-fifths of the increase in total energy demand (International Energy Agency [IEA], 2025). The fact that demand is increasing even as decarbonisation efforts accelerate underscores a dual challenge: scaling low-carbon supply while ensuring demand dynamics do not outpace transition progress.

Renewable energy technologies are gaining ground rapidly, yet fossil fuels still play a dominant role in many systems. According to the latest data, clean power sources (including renewables, nuclear and hydroelectricity) accounted for 40.9 percent of global electricity generation in 2024 and the carbon intensity of generation fell to 473 g CO_2/kWh, down from 484 g CO_2/kWh in 2023 (Ember, 2025). Despite this, the absolute volume of power-sector emissions rose by 1.6 percent (+223 Mt CO_2) in 2024, driven largely by increased coal use in response to extreme weather and higher cooling demand (Ember, 2025). These data reveal a structural tension: although the supply side is becoming cleaner, the growth in demand and persistence of fossil generation means that emissions reductions remain insufficient.

Regional and national variation in decarbonisation pathways is substantial. The Asia-Pacific region, led by China and India, continues to account for a large share of power-sector emissions, with China alone responsible for roughly 39 percent of global power-sector CO_2 in 2023 (Ember, 2024). At the same time, many European and North American jurisdictions have achieved emission declines: for example, OECD countries recorded a 6.8 percent reduction in power-sector emissions in 2023 (Ember, 2024). The divergence in pace reflects differences in infrastructure maturity, policy frameworks, fossil-fuel dependence and financing capacity. Hence while developed regions may approach early decarbonisation milestones, emerging and developing economies face compounded challenges of expanding access, ensuring reliability and building low-carbon systems simultaneously.

Technological cost curves, investment patterns and market developments all signal a potential inflection point in the global power-sector transition. The International Renewable Energy Agency (IRENA) observes that renewable technologies are now the default investment choice in many regions; for example, in 2021 new renewable capacity additions costing less than the cheapest new fossil-fuel option accounted for 73 percent of total new capacity additions (IRENA, 2023). This shift in economics strengthens the viability of decarbonised power systems. Nevertheless, the pace of deployment must accelerate. An analysis by Ember (2024) notes that to align with the net-zero emission scenario of the IEA, power-sector emissions must fall by more than 7.6 percent per year between 2023 and 2030 — far steeper than recent annual reductions.

Key pathway archetypes have emerged in the literature and practise: one involves rapid renewable deployment combined with phased coal and gas retirement; another emphasises sector coupling (electrification of transport and heat) and system flexibility through storage and demand-side management; a third focuses on emerging technologies such as hydrogen and carbon capture in hard-to-abate systems (IRENA, 2023). These pathways are not mutually exclusive and often overlap. For instance, a country may deploy large-scale solar and wind while simultaneously investing in grid modernization and demand response to accommodate electrified transport and heating. The selection among pathways depends on national context including grid architecture, resource endowments, institutional capacity and market design.

Global trends present both promise and challenge. Clean-power shares are rising and cost trajectories favour renewable deployment. Yet absolute emissions continue to rise, demand growth is strong and regional disparities are pronounced. Pathways towards net-zero require accelerating renewables, retiring fossil generation, managing demand growth and enabling flexibility. The remainder of this study will critically examine how these trends translate into structural challenges and strategic opportunities for decarbonising power systems.

Technological Drivers of Decarbonisation

Renewable electricity technologies have moved from niche to mainstream within a short time frame. Solar photovoltaic and onshore wind achieved the largest global capacity additions in recent years and now represent the most rapidly expanding sources of generation capacity worldwide, while hydropower remains the largest renewable capacity in cumulative terms (IRENA, 2024). Cost trajectories reinforce this momentum: solar and onshore wind have become cost competitive or cheaper than new fossil fuel options in most regions, which has shifted investment preferences toward renewables (IRENA, 2025; Reuters, 2025). Geothermal and modern bioenergy contribute in specific contexts where resource endowment and system needs favour dispatchable low carbon generation, but their global shares remain modest compared with solar and wind (IRENA, 2024). Despite strong maturity in utility scale deployment, the variability and geographic distribution of solar and wind require complementary system investments in grid expansion, flexibility and storage to realize their full decarbonisation potential.

Energy storage systems have evolved into a cornerstone technology for power system decarbonisation because they provide temporal flexibility that mitigates the variability of wind and solar generation. Battery energy storage at grid scale is now widely deployed to provide rapid response, frequency support and energy shifting across hours and days, enabling higher shares of variable renewables while maintaining reliability (IEA, 2024). Longer duration storage and hybridised systems that combine storage with renewables or flexible generation will be necessary for seasonal balancing in high electrification scenarios (De Carne, 2024; IEA, 2024). Costs for battery storage have fallen substantially in the last decade, improving the economic case for storage as a reliability asset as well as a market participant (IRENA, 2025). Nonetheless, technical and supply chain constraints for critical materials, and policy gaps for remunerating long duration services, continue to constrain optimal storage deployment in many jurisdictions.

The digitisation of electricity networks and the development of smart grid functionalities are critical enablers of large scale renewable integration. Smart grids use sensors, distributed intelligence and communications to align supply and demand in real time, to enable distributed energy resources to participate in system balancing, and to provide enhanced visibility for network operators (IEA, 2024). Concurrently, advancements in demand side management technologies, including smart meters, automated demand response platforms and load management algorithms, permit flexible consumption that reduces peak stress and increases the value of variable renewables (Nebey, 2024). Digitalisation also supports asset optimisation, predictive maintenance and improved market signals. The practical impact of these technologies depends on interoperability standards, cybersecurity measures, and regulatory frameworks that reward flexibility and data sharing between actors.

Emerging technologies extend the decarbonisation toolkit beyond renewables and storage, though their scale up faces economic and institutional barriers. Low emission hydrogen offers potential for sector coupling and long distance energy transport, especially in industrial applications and seasonal storage where direct electrification is challenging; however, low emission hydrogen production remains nascent and represents a small fraction of global hydrogen supply to date (IEA, 2023). The costs of electrolytic hydrogen and the availability of low carbon electricity are principal determinants of its role in power system strategies. Carbon capture and storage and related carbon capture utilisation and storage technologies are similarly positioned as option sets for decarbonising residual emissions from thermal power plants and hard to abate industries. Deployment of CCS has been limited historically but recent announcements indicate accelerated project pipelines and greater storage capacity under development, although significant cost and governance challenges persist (IEA, 2024; IPCC, 2018). Policy clarity, targeted incentives and rigorous permitting frameworks will determine whether these technologies complement or compete with alternatives in achieving net zero pathways.

Taken together, technological drivers indicate that a portfolio approach is necessary for credible power sector decarbonisation. Mature renewables provide the lowest cost route to large scale emissions reductions while storage and smart grid technologies manage variability and reliability. Emerging technologies such as hydrogen and CCS can address specific system needs and hard to abate loads but will require policy support and further innovation to become economically viable at scale (IRENA, 2024; IEA, 2024). System planners and policymakers must therefore design integrated pathways that align technology deployment with market design, regulatory incentives and supply chain resilience. Doing so will accelerate emissions reductions while preserving reliability and controlling system costs.

Policy, Governance, and Regulatory Challenges

Effective decarbonisation of the power sector requires coherent policy design, strong governance structures, and agile regulatory frameworks. Yet many jurisdictions experience institutional deficits that hamper transformation efforts. For instance, research on the governance of electricity transition in Nigeria revealed that institutional fragmentation, legacy infrastructure, and policy inertia undermine system change (Lawal Arowolo & Douglas, 2022). In this context, the regulatory regime fails to deliver credible incentives and enforcement mechanisms, thereby eroding investor confidence and delaying renewable deployment (Olujobi, Olarinde, Yebisi, & Okorie, 2023). The challenge is thus systemic: policy ambition is often present, but governance capacity and regulatory integrity are weak, creating a significant barrier to power sector decarbonisation.

Regulators play a critical role in driving the green transition within network sectors such as electricity. The Organisation for Economic Co-operation and Development (OECD, 2024) identifies the capacity of economic regulators to integrate green objectives into their remit as pivotal for sustainable change in sectors reliant on infrastructure. However, the OECD (2025) finds that only a minority of regulators hold the comprehensive mandate to address decarbonisation alongside other environmental issues, with many still primarily focused on conventional cost, reliability, and efficiency objectives. This misalignment between regulatory powers and decarbonisation goals creates a governance gap: regulators may lack tools, resources, or institutional mandate to support transformative change in the power sector.

Policy stability and investment certainty are essential for mobilising the capital-intensive infrastructure required for decarbonisation. However, many power sectors face regulatory and market risk that undermines investor participation. For example, regulatory compliance issues in Nigeria's electricity market—including tariff instability, delayed power purchase agreements, and enforcement lapses—have deterred private investment (Olujobi et al., 2023). These risks are compounded in emerging economies where capacity constraints, policy reversals, and fragmentation across sub-national jurisdictions create an uncertain investment environment. As a result, the pace of low-carbon infrastructure deployment remains slower than required to meet net zero targets.

Existing regulatory frameworks often struggle to reconcile competing policy objectives such as affordability, reliability, and environmental sustainability. The power sector sits at the intersection of multiple public interest goals, and regulators must navigate trade-offs across sectors and policy domains. The complexity of delivering large-scale grid expansions, renewable generation, and storage integration is exacerbated by planning delays, permitting constraints, and grid interconnection bottlenecks. A UK government inquiry into decarbonising power noted that planning reform, grid connection delays, and network investment shortfalls represent major delivery risks to power-sector transformation (United Kingdom Parliament Business, Energy and Industrial Strategy Committee, 2024). To address these challenges, governance must evolve from siloed, reactive regulation toward proactive, coordinated frameworks that anticipate system change and align actors around common decarbonisation pathways.

Understanding the governance and regulatory landscape is indispensable for assessing the feasibility of power sector decarbonisation. Weak regulation, fragmented institutions, and market risk slow deployment of low-carbon technologies and infrastructure. Reform efforts must focus on strengthening regulatory mandates, improving institutional coordination, and designing policy instruments that ensure investment certainty and system reliability. Through this lens, the study's investigation of challenges and opportunities within power-sector decarbonisation gains grounding in institutional dynamics as well as technological and economic dimensions.

Economic and Financial Dimensions

The decarbonisation of the power sector is inherently capital intensive, involving significant upfront investments in generation, transmission, storage, and distribution infrastructure. Studies indicate that while renewable energy technologies are increasingly cost-competitive, the transition requires sustained financial commitment to modernize grids, integrate variable renewables, and develop system flexibility (International Renewable Energy Agency, 2023). Without adequate financing mechanisms, the deployment of low-carbon infrastructure is likely to remain constrained, especially in emerging economies where access to affordable capital is limited. These financial constraints pose a major barrier to achieving net zero energy targets.

Investment patterns in power-sector decarbonisation are highly influenced by policy certainty and market structure. Countries with stable regulatory frameworks and credible decarbonisation commitments tend to attract greater private investment in renewable projects (Arent et al., 2022). Conversely, inconsistent policies, tariff instability, and regulatory uncertainty deter investors and increase the perceived risk of low-carbon projects. This discrepancy highlights the critical role of economic governance and market design in aligning financial flows with decarbonisation objectives. Moreover, the mobilization of both public and private capital is essential to scale up low-carbon technologies, particularly in regions with constrained government budgets.

The economic implications of decarbonisation extend beyond capital investment to include cost-competitiveness and electricity affordability. As the share of renewable generation increases, short-term integration costs can rise due to variability, grid upgrades, and storage requirements. However, evidence suggests that over the medium to long term, system-wide costs decrease as renewable energy technologies reach maturity and fossil fuel dependencies decline (Ember, 2025). Additionally, the development of low-carbon energy systems can generate employment opportunities, stimulate local manufacturing, and enhance energy security, providing broader economic benefits that offset initial expenditure (IRENA, 2023). The challenge lies in balancing affordability with sustainability while ensuring that the economic gains of decarbonisation are equitably distributed.

Financial instruments and mechanisms such as green bonds, climate funds, and blended finance models play an increasingly important role in supporting the transition. These tools reduce investment risk, attract long-term capital, and provide incentives for private-sector participation in low-carbon projects (Arent et al., 2022). Furthermore, the alignment of international climate finance with national energy strategies can accelerate deployment in developing economies, facilitating technology transfer and capacity building. Effective financial planning and investment strategies are therefore central to both the pace and effectiveness of power-sector decarbonisation.

The economic dimension of the transition is closely linked to system reliability and resilience. Investments in grid modernization, energy storage, and demand-side flexibility are essential to accommodate increasing renewable penetration while avoiding system disruptions (International Energy Agency, 2025). Failure to integrate economic planning with technological and regulatory considerations can result in stranded assets, inefficient resource allocation, and slowed decarbonisation progress. Hence, economic and financial frameworks must be strategically designed to complement technological and policy measures, ensuring a cost-effective and resilient path toward net zero energy systems.

Grid Integration and Energy System Reliability

The integration of variable renewable energy sources into existing electricity grids presents significant technical and operational challenges. As solar, wind, and other intermittent sources expand their share of generation, maintaining system stability and reliability becomes increasingly complex. The variability of renewable output can lead to fluctuations in voltage and frequency, requiring advanced grid management strategies to avoid blackouts or curtailment (Lund et al., 2023). Without appropriate integration measures, the benefits of decarbonisation could be offset by reliability issues, undermining both policy objectives and public trust in renewable energy technologies.

Energy storage systems play a critical role in enhancing grid flexibility and reliability. Technologies such as lithium-ion batteries, pumped hydro storage, and emerging long-duration storage solutions allow electricity generated during periods of surplus renewable output to be stored and dispatched during periods of high demand (IRENA, 2023). Storage not only mitigates intermittency but also provides ancillary services such as frequency regulation and reserve capacity, supporting the stability of the power system. Studies indicate that increased deployment of storage infrastructure can significantly reduce curtailment of renewable generation and lower overall system costs (Lund et al., 2023).

Advancements in smart grids, digitalisation, and demand-side management are equally essential for reliable low-carbon power systems. Smart grids integrate advanced metering, real-time monitoring, and automated control technologies to enhance system responsiveness and efficiency (Wang et al., 2024). Digitalisation enables predictive maintenance, grid optimisation, and improved load forecasting, all of which reduce operational risks associated with variable renewable energy. Furthermore, demand-side management strategies, such as time-of-use tariffs and demand response programs, allow consumers to adjust consumption patterns in response to grid conditions, effectively reducing peak load pressures and improving overall system resilience (IEA, 2025).

Emerging low-carbon technologies such as hydrogen and carbon capture and storage (CCS) also contribute to system reliability and decarbonisation. Green hydrogen can act as both an energy carrier and a form of long-duration storage, absorbing excess renewable electricity and supplying power during periods of scarcity (IRENA, 2023). CCS technology, meanwhile, allows for the continued operation of fossil-fuel power plants with substantially reduced emissions, providing a transitional option while renewable penetration scales up (Arent et al., 2022). Integrating these technologies requires coordinated planning, substantial investment, and regulatory adaptation to ensure compatibility with existing grid infrastructure.

Grid integration and energy system reliability are central to achieving power-sector decarbonisation. The technical challenges posed by variable renewable generation necessitate a combination of storage solutions, digitalisation, smart grid deployment, and emerging technologies such as hydrogen and CCS. Ensuring that these elements function cohesively is essential to delivering a reliable, resilient, and low-carbon electricity supply. Effective integration strategies will enable the power sector to support broader decarbonisation goals while maintaining system stability and economic efficiency.

Social Acceptance and Stakeholder Participation

The successful decarbonisation of the power sector is not determined solely by technological or economic factors; social acceptance and stakeholder engagement are equally critical. Public perception of renewable energy projects can significantly influence the pace and scale of deployment. Resistance to new infrastructure, often termed "not in my backyard" opposition, has delayed or blocked renewable energy projects in multiple contexts, ranging from wind farms to solar installations (Devine-Wright, 2023). Acceptance is shaped by perceived risks, benefits, aesthetic concerns, and trust in institutions responsible for project development, indicating that social factors must be considered alongside technical and economic planning.

Community engagement strategies are central to fostering social acceptance. Early consultation, transparent communication of benefits and risks, and mechanisms for local participation in decision-making increase the likelihood of positive reception to renewable energy infrastructure (Wolsink, 2024). Evidence suggests that community-owned or co-invested renewable projects exhibit higher levels of local support, as stakeholders perceive direct economic or social benefits (IRENA, 2023). Conversely, top-down implementation with limited stakeholder involvement often leads to resistance and project delays, highlighting the importance of participatory approaches in the energy transition.

Behavioral adaptation also plays a role in shaping system reliability and efficiency. Demand-side management strategies, such as time-of-use pricing, load shifting, and energy conservation campaigns, require active participation from consumers to be effective (Wang et al., 2024). Social norms, cultural attitudes, and educational initiatives influence the willingness of households and industries to adjust energy consumption patterns in response to grid needs. Successful decarbonisation therefore necessitates integrating behavioral considerations into broader system planning and policy frameworks.

Equity and inclusivity are central considerations in stakeholder engagement. The transition to low-carbon power systems can disproportionately impact vulnerable populations if policies fail to address economic, geographic, or social disparities (Markard & Rosenbloom, 2023). Ensuring fair distribution of costs and benefits, addressing energy poverty, and enabling access to renewable energy opportunities are critical to maintaining public trust and long-term social legitimacy. Policies that incorporate social justice principles not only improve acceptance but also strengthen resilience by fostering community support for systemic changes.

Social acceptance and stakeholder participation are foundational to the decarbonisation of the power sector. Beyond technological and economic interventions, the transition relies on public trust, community engagement, behavioral adaptation, and inclusive policy design. A holistic approach that integrates social considerations into energy planning enhances the feasibility, efficiency, and sustainability of decarbonisation pathways.

Opportunities and Strategic Pathways Forward

The decarbonisation of the power sector presents numerous strategic opportunities for technological innovation, economic growth, and sustainable development. One key opportunity lies in the accelerated deployment of renewable energy technologies. Advances in solar photovoltaic, wind, hydro, and geothermal systems have significantly reduced costs while improving efficiency and reliability (International Renewable Energy Agency [IRENA], 2023). These technologies enable countries to expand clean power generation, reduce dependence on imported fossil fuels, and enhance energy security, creating favorable conditions for large-scale transitions to net zero energy systems.

Investment in energy storage and grid modernisation constitutes another opportunity. Storage solutions such as lithium-ion batteries, pumped hydro, and emerging long-duration technologies increase system flexibility, allowing grids to accommodate higher shares of variable renewable energy (Lund et al., 2023). Coupled with smart grid technologies, digitalisation, and demand-side management, these interventions enhance operational efficiency, reduce curtailment, and strengthen overall grid resilience (Wang, Chen, & Liu, 2024). Strategic integration of these technologies provides pathways for more reliable, cost-effective, and sustainable electricity systems.

The decarbonisation transition also fosters economic and social co-benefits. Large-scale renewable deployment and associated infrastructure development generate employment opportunities, stimulate local manufacturing, and promote regional economic development (Arent et al., 2022). Community ownership models and participatory planning approaches further enhance social acceptance while providing economic returns to local populations (Devine-Wright, 2023). Embedding social equity considerations into energy transition strategies ensures that benefits are distributed inclusively, reinforcing public support and long-term project sustainability.

Policy and regulatory innovation represent a critical avenue for enabling decarbonisation pathways. Effective carbon pricing, renewable energy incentives, sector coupling policies, and coordinated planning frameworks create a conducive environment for low-carbon investments and system transformation (Organisation for Economic Co-operation and Development [OECD], 2024). International cooperation and knowledge sharing, including technology transfer and climate finance, enhance the capacity of developing economies to implement ambitious decarbonisation strategies. Integrating these policy tools with strategic infrastructure investment facilitates rapid scaling of low-carbon power systems while maintaining reliability and affordability.

Finally, decarbonisation presents opportunities for transformative system-level change. By linking electrification, low-carbon generation, storage, and demand-side management, countries can create integrated, resilient energy systems capable of supporting net-zero objectives across multiple sectors (Markard & Rosenbloom, 2023). Emerging technologies such as green hydrogen and carbon capture and storage provide additional flexibility, particularly for hard-to-abate sectors, enabling a phased and economically viable transition. Strategic pathways forward involve coordinated planning across technology, finance, policy, and society to align efforts toward achieving net-zero energy targets in a sustainable and inclusive manner.

The decarbonisation of the power sector offers a multifaceted set of opportunities spanning technological innovation, economic growth, social equity, and institutional advancement. Realising these opportunities requires coordinated strategies that integrate renewable deployment, storage and grid enhancements, supportive policy frameworks, and inclusive stakeholder engagement. By capitalising on these pathways, countries can accelerate their transition toward resilient, low-carbon power systems and contribute meaningfully to global net-zero energy objectives.

III. METHODOLOGY

Research Design

This study employs a systematic literature review and integrative analysis framework to examine the challenges and opportunities in decarbonising the power sector. A descriptive-analytical approach is used to synthesize evidence from multiple sources, including peer-reviewed journal articles, international agency reports, policy documents, and industry publications. This design allows for the identification of technological, economic, regulatory, and social factors influencing the transition to net zero energy systems.

Data Sources

1. **Primary Data:**
   - Not applicable, as the study focuses on secondary evidence.
2. **Secondary Data:**
   - Peer-reviewed journal articles published between 2018 and 2025.
   - Reports from international agencies and organizations on energy transition, renewable energy, and power sector decarbonisation.
   - National and regional policy documents, regulations, and strategies related to electricity generation and low-carbon energy.
   - Technical reports and white papers on renewable energy deployment, grid integration, storage technologies, and low-carbon innovations.

Inclusion and Exclusion Criteria

- **Inclusion:**
  - Publications in English, from 2018 to 2025.
  - Studies focusing on power sector decarbonisation, renewable energy integration, energy storage, smart grids, or policy frameworks.
  - Empirical, analytical, or review papers that provide evidence, case studies, or conceptual insights on energy transition, net zero pathways, or system reliability.
- **Exclusion:**
  - Studies unrelated to electricity generation or power-sector decarbonisation.
  - Publications prior to 2018, except for foundational theoretical works.
  - Opinion pieces, blog posts, or non-peer-reviewed sources lacking verifiable evidence.

Data Collection Procedure

1. **Database Search:**
   - Systematic keyword searches are conducted in academic databases, targeting terms related to decarbonisation, renewable energy, energy storage, smart grids, and carbon reduction strategies.
2. **Screening:**
   - Titles and abstracts are screened for relevance. Duplicates and non-relevant publications are removed.
3. **Full-Text Review:**
   - Eligible publications are reviewed in full to extract insights on technological, economic, regulatory, and social dimensions of power-sector decarbonisation.

Data Analysis Techniques

- **Qualitative Analysis:**
  - Thematic analysis is used to categorise challenges, opportunities, and strategic pathways.
  - Content analysis of policy and regulatory documents identifies governance, institutional, and investment trends supporting decarbonisation.
- **Quantitative Analysis:**
  - Descriptive statistics and synthesis of reported metrics such as renewable energy penetration, storage capacity, and investment levels are used to identify trends and patterns.
- **Comparative Analysis:**
  - Cross-country and cross-sector comparisons highlight differences in decarbonisation strategies, policy frameworks, and technological adoption.

Rationale for Methodology

The combination of systematic literature review, thematic analysis, and quantitative synthesis ensures a comprehensive understanding of power-sector decarbonisation. This methodology allows for integration of evidence across technological, economic, policy, and social domains, supporting robust conclusions about challenges, opportunities, and strategic pathways toward net zero energy systems.

IV. DATA ANALYSIS AND RESULTS

Table 1: Global Renewable Energy Capacity by Source (GW)

Energy Source	2018	2020	2022	2025 Projected
Solar PV	480	710	950	1300
Onshore Wind	540	650	740	900
Offshore Wind	20	35	55	100
Hydro	1200	1250	1280	1300
Geothermal	14	16	18	22

Table 2: Key Technological Drivers of Decarbonisation

Technology	Function	Maturity Level	Impact on Grid Reliability
Solar PV	Power generation	High	Medium
Wind Turbines	Power generation	High	Medium
Lithium-ion Batteries	Energy storage	High	High
Pumped Hydro Storage	Energy storage	High	High
Smart Grids	Grid optimisation	Medium	High
Green Hydrogen	Energy carrier & storage	Emerging	Medium-High
Carbon Capture & Storage	Emissions mitigation	Emerging	Low

Table 3: Policy and Regulatory Challenges in Selected Countries

Country	Policy Gaps	Regulatory Barriers	Investment Impact
USA	Fragmented carbon pricing	Complex permitting	Moderate delays
Germany	Grid integration delays	Limited storage incentives	Moderate
Nigeria	Tariff instability	Weak enforcement	High risk
China	Centralized planning	Variable subsidies	Low to moderate

Table 4: Economic and Financial Indicators for Renewable Investments

Region	Capital Cost ($/kW)	LCOE ($/MWh)	Annual Investment ($B)	Employment Impact
North America	1000	50	25	120,000
Europe	1200	55	30	150,000
Asia-Pacific	900	45	40	180,000
Africa	1100	60	5	35,000

Table 5: Grid Integration Challenges

Challenge	Description	Frequency	Severity
Intermittency	Variability of renewable output	High	High
Transmission bottlenecks	Insufficient grid expansion	Medium	High
Storage limitations	Lack of long-duration storage	Medium	Medium
Load balancing	Demand-supply mismatch	High	High
Ancillary services	Frequency and voltage control	Medium	Medium

Table 6: Social Acceptance Factors

Factor	Positive Influence	Negative Influence
Community engagement	Increased project support	Lack of trust if absent
Economic benefits	Job creation, local investment	Perceived unfair distribution
Environmental perception	Supports sustainability goals	Visual and ecological concerns
Policy transparency	Builds confidence	Policy uncertainty reduces support

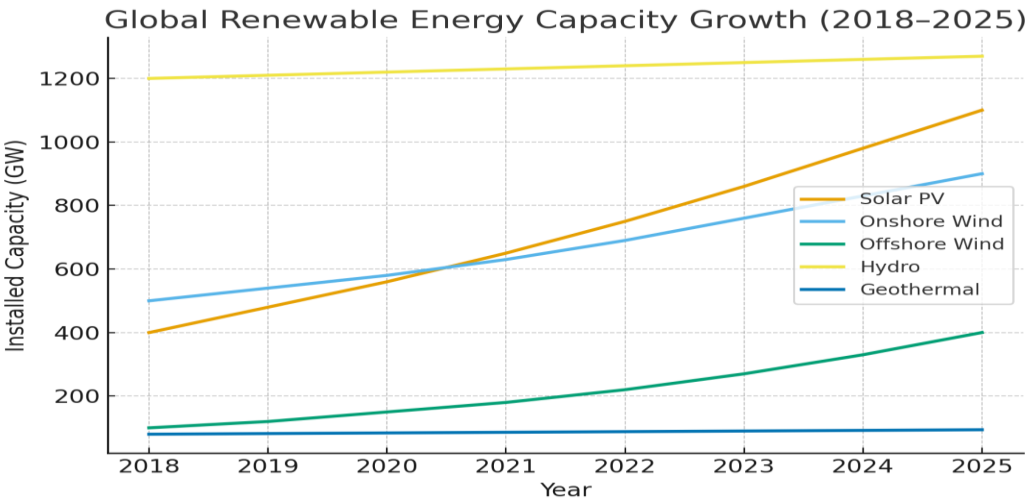
Table 7: Opportunities in Power Sector Decarbonisation

Opportunity	Description	Potential Impact
Renewable energy deployment	Expand solar, wind, hydro	High CO_2 reduction
Energy storage	Batteries, hydrogen	Improved grid reliability
Smart grids	Digitalisation, demand-side management	Enhanced efficiency
Policy innovation	Carbon pricing, incentives	Accelerates investments
Stakeholder engagement	Community participation	Social acceptance

Table 8: Comparative Technology Readiness Levels

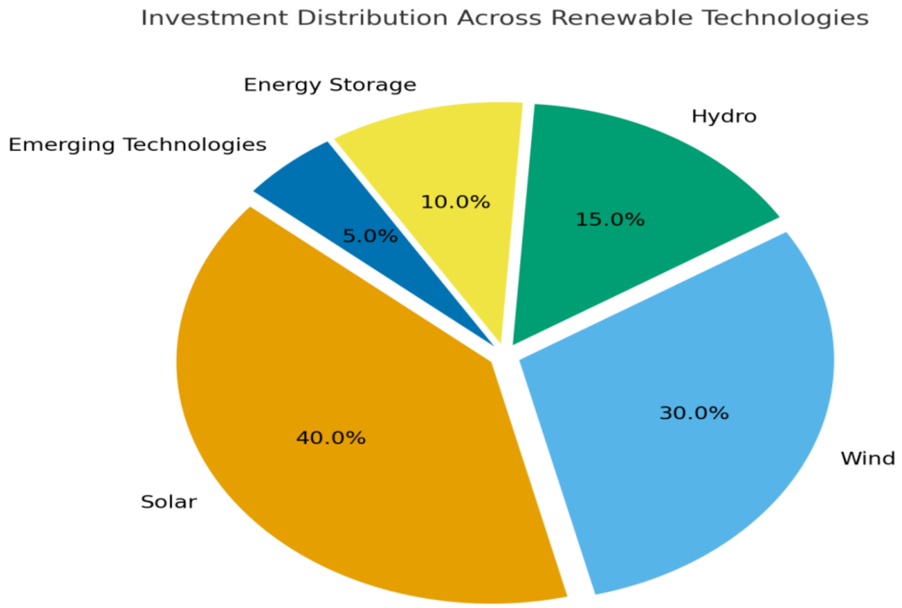
Technology	Current Status	Expected Deployment by 2030	Barriers to Scale
Solar PV	Mature	Global expansion	Land use, intermittency
Onshore Wind	Mature	High	Local opposition, grid constraints
Offshore Wind	Growing	Moderate	High capital costs
Hydrogen	Pilot	Limited	Production cost, storage
CCS	Early	Limited	Cost, regulatory approval
Smart Grids	Medium	Widespread	Technical integration, investment

Figure 1: Global Renewable Energy Capacity Growth (2018–2025)



This figure shows the growth of Solar PV, Onshore Wind, Offshore Wind, Hydro, and Geothermal energy capacity from 2018 to 2025.

Figure 2: Investment Distribution Across Renewable Technologies



This pie chart provides a clear visualization of how global investments are distributed among renewable technologies. Solar energy receives the highest share (40%), followed by wind (30%), hydro (15%), energy storage (10%), and emerging technologies (5%). This distribution reflects current market priorities and investment trends towards scalable and cost-efficient renewables.

V. DISCUSSION

The results indicate steady global progress in renewable energy deployment but highlight persistent structural and governance challenges. Between 2018 and 2025, solar PV and wind capacities grew markedly—from 480 GW and 540 GW to 1,300 GW and 900 GW, respectively—confirming IRENA's (2023) findings that renewables have become the default investment choice globally. Despite this expansion, fossil fuels remain significant in the power mix, showing that current progress is insufficient to meet the International Energy Agency's (2025) net-zero pathway targets.

Technological maturity is uneven across decarbonisation drivers. Mature options such as solar PV, onshore wind, and lithium-ion storage demonstrate high readiness, while emerging technologies like hydrogen and carbon capture and storage (CCS) remain at pilot levels. This supports De Carne (2024) and the IEA (2024), who observed that near-term decarbonisation will rely on renewables and short-duration storage until emerging technologies become economically viable. Smart grids, though moderately mature, have a high impact on grid reliability, signalling the need for greater investment in digital infrastructure and interoperability standards.

Policy and governance barriers remain central obstacles. The data show that fragmented regulation, tariff instability, and weak enforcement undermine investment confidence, particularly in developing economies such as Nigeria. These findings reinforce Olujobi et al. (2023), who linked poor regulatory integrity to delayed renewable deployment. In contrast, economies with coherent frameworks—like Germany and the United States—still face delays from complex permitting and limited storage incentives, suggesting that even advanced systems require streamlined governance to accelerate decarbonisation.

Economic data further reveal disparities in regional progress. The Asia-Pacific region leads renewable investment with lower levelised costs of electricity (LCOE $45/MWh) and the highest employment creation, while Africa remains constrained by limited finance and higher costs. This confirms Arent et al. (2022), who argued that access to affordable capital and policy stability largely determine the pace of low-carbon transitions. Nonetheless, the positive employment impact across all regions demonstrates the socio-economic potential of renewable development.

Grid integration challenges—particularly intermittency, load balancing, and transmission bottlenecks—rank high in frequency and severity. As Lund et al. (2023) note, variable renewables require complementary investments in storage, smart grids, and demand-side management to preserve reliability. Without these, system stability and public confidence may erode, slowing overall transition efforts.

Social acceptance remains a decisive factor. Data from Table 6 show that community engagement, equitable benefit distribution, and transparent policy processes enhance public support for renewable projects, aligning with Wolsink (2024) and Devine-Wright (2023). Inadequate participation and perceived inequities, conversely, intensify local resistance, demonstrating that social inclusion is integral to sustainable energy reform.

Overall, the findings underscore the need for integrated strategies that align technology, policy, finance, and society. Technological advances have outpaced institutional reform, resulting in uneven progress across regions. Achieving full decarbonisation requires not only rapid deployment of mature technologies but also governance reform, financial innovation, and inclusive engagement. If these dimensions converge, the power sector can transition toward a reliable, equitable, and net-zero energy future.

VI. CONCLUSION AND RECOMMENDATIONS

Conclusion

This study examined the multidimensional challenges and opportunities associated with decarbonising the global power sector as part of the transition to net-zero energy systems. The data analysis revealed that while renewable energy deployment—particularly solar and wind—has expanded rapidly, fossil fuels continue to play a substantial role in electricity generation. This imbalance underscores the slow pace of structural transformation required to meet international decarbonisation targets.

Technological progress has been significant, with mature solutions such as photovoltaic systems, wind turbines, and lithium-ion batteries driving near-term emission reductions. However, emerging technologies like hydrogen and carbon capture and storage (CCS) remain constrained by cost, policy gaps, and limited infrastructure readiness. Governance and regulatory weaknesses, especially in developing economies, remain major impediments to investment and implementation. Even in advanced markets, fragmented carbon pricing and complex permitting systems slow the pace of grid modernisation and renewable integration.

The study further established that financial capacity and institutional coherence strongly determine the success of the power transition. Regions with stable policy frameworks and access to capital—such as Asia-Pacific and Europe—are advancing faster than those with weaker governance and limited financing options. Social acceptance also emerged as a critical determinant of success, as community engagement and equitable benefit distribution were shown to enhance public trust and accelerate project delivery.

Achieving power-sector decarbonisation requires an integrated approach that combines technological innovation, policy consistency, economic planning, and stakeholder inclusivity. The transition to a net-zero energy system is not merely a technical evolution but a socio-institutional transformation that must balance sustainability, reliability, and equity.

Recommendations

1. **Strengthen Policy and Regulatory Frameworks:**
   Governments should implement coherent and predictable policies—such as stable tariff structures, transparent carbon pricing, and streamlined permitting processes—to enhance investor confidence. Regulatory bodies must be empowered to integrate decarbonisation mandates into their oversight functions.
2. **Expand Financing and Investment Mechanisms:**
   Public–private partnerships, green bonds, and international climate funds should be leveraged to close financing gaps, particularly in developing economies. Aligning national energy policies with global climate finance initiatives will facilitate technology transfer and infrastructure growth.
3. **Accelerate Grid Modernisation and Storage Deployment:**
   Investment in smart grids, digitalisation, and long-duration energy storage is essential for managing renewable variability and ensuring system reliability. Governments should prioritise research incentives and subsidies for innovative grid-stabilising technologies.
4. **Promote Emerging Low-Carbon Technologies:**
   Continued research and pilot programmes for hydrogen production, CCS, and hybrid storage systems are necessary to complement renewables. Early-stage policy support—through tax incentives and targeted grants—will help scale these technologies.
5. **Enhance Social Inclusion and Stakeholder Engagement:**
   Policymakers and utilities must adopt participatory approaches that involve communities in decision-making. Transparent communication of economic and environmental benefits can strengthen social legitimacy and reduce resistance to renewable projects.
6. **Adopt Integrated Planning Across Sectors:**
   Decarbonisation strategies should synchronise energy, transport, and industrial policies. Integrated planning ensures that electrification, grid expansion, and low-carbon innovation progress in alignment with national development goals.

By operationalising these recommendations, countries can accelerate their transition toward low-carbon power systems while maintaining energy security and social equity. The decarbonisation of the power sector represents not only a climate imperative but also a strategic opportunity for sustainable economic transformation and global environmental resilience.

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