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Review

Advancing Power Systems with Renewable Energy and Intelligent Technologies: A Comprehensive Review on Grid Transformation and Integration

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Abstract: The global energy landscape is witnessing a transformational shift brought about by the adoption of renewable energy technologies along with power system modernisation. Distributed generation (DG), smart grids (SGs), microgrids (MGs), and advanced energy storage systems (AESSs) are key enablers of a sustainable and resilient energy future. This review deepens the analysis of the fulminating change in power systems, detailing the growth of power systems, wind and solar integration, and next-generation high-voltage direct current (HVDC) transmission systems. Moreover, we address important aspects such as power system monitoring, protection, and control, the dynamic modelling of transmission and distribution systems, and advanced metering infrastructure (AMI) development. Emphasis is laid on the involvement of artificial intelligence (AI) techniques in optimised grid operation, voltage control, stability, and the system integration of lifetime energy resources such as islanding and hosting capacities. This paper reviews the key aspects of current advancements in grid technologies and their applications, enabling the identification of opportunities and challenges to be addressed toward achieving a modern, intelligent, and efficient power system infrastructure. It wraps up with a perspective on future research paths as well as a discussion of potential hybrid models that integrate AI and machine learning (ML) with distributed energy systems (DESs) to improve the grid's resilience and sustainability.

Keywords: artificial intelligence; distributed generation; high-voltage direct current; smart grid; voltage control

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1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the increasing adoption of renewable energy sources (RESs) and the necessity for modernising power systems. This shift is motivated by growing concerns over climate change, rising energy demands, and the need to enhance energy security. Renewable energy technologies, such as photovoltaic (PV), wind turbine (WT), and hydropower systems, have emerged as pivotal elements in achieving sustainability and resilience in power systems. According to the International Energy Agency (IEA), renewable energy accounted for nearly 30% of global electricity generation in 2023, with a significant increase anticipated in the coming decades [1].

The traditional power grid, originally designed for centralised energy production and a unidirectional power flow, faces challenges in meeting the dynamic demands of modern energy systems. The rise of distributed energy resources (DERs) necessitates transitioning to decentralised and bidirectional energy management. This transformation is enabled by

technological advancements such as smart grids (SGs), microgrids (MGs), and advanced energy storage systems (AESSs). SGs incorporate information and communication technologies (ICTs) to facilitate real-time monitoring, predictive analytics, and optimised energy distribution. MGs, in contrast, offer localised energy solutions that enhance grid reliability and resilience, particularly in remote or disaster-prone regions [2].

A critical aspect of this evolution is the seamless integration of variable RESs into the grid. The intermittent nature of solar and wind energy introduces complexities in maintaining grid stability, frequency control, and voltage regulation. To address these challenges, innovative solutions such as grid-forming inverters, dynamic line rating (DLR), and AESSs have been developed [3]. These technologies not only stabilise the grid but also maximise the utilisation of renewable energy.

Artificial intelligence (AI) has emerged as a transformative tool in the operation and optimisation of power systems. Machine learning (ML) algorithms and predictive models enable accurate demand forecasting, fault detection, and real-time decision-making, enhancing grid efficiency and reliability. Furthermore, AI-driven optimisation techniques are employed to streamline the integration of distributed energy systems (DESs), ensuring a balance between supply and demand [4].

This paper comprehensively reviews the advancements in renewable energy integration and intelligent grid technologies. It explores critical areas such as next-generation high-voltage direct current (HVDC) systems, the dynamic modelling of power systems, and the role of AI in grid optimisation. By identifying current trends, challenges, and opportunities, this review aims to provide valuable insights into the ongoing transformation of power systems and the pathways toward achieving a modern, intelligent, and sustainable energy infrastructure.

1.1. The Contributions of the Paper

This paper presents a comprehensive review of the transformation of power systems by integrating renewable energy and intelligent technologies. The key contributions of this work are outlined as follows:

- Advancements in Grid Technologies: A detailed analysis is provided of modern power system developments, including HVDC transmission systems, advanced metering infrastructure (AMI), and the dynamic modelling of transmission and distribution networks.
- AI Applications: This study highlights the increasing role of AI in grid optimisation, including applications in voltage control, demand forecasting, fault detection, and system stability. Integrating AI and ML with DESs is examined to enhance grid resilience.
- Blockchains for Energy Systems: This paper reviews the use of blockchain technology in securing energy transactions, enabling peer-to-peer (P2P) trading, and ensuring transparency in energy markets.
- Cybersecurity Challenges and Solutions: The vulnerabilities of SGs to cyber threats are analysed, and potential solutions, including federated learning and decentralised security frameworks, are discussed.
- Technical and Regulatory Challenges: This paper identifies key challenges in power system transformation, including regulatory barriers, economic viability concerns, and scalability issues, and discusses policy frameworks that can facilitate this transition.

This work contributes to the ongoing discourse on modernising power systems by bridging the gap between technological advancements and real-world applications. Its findings serve as a reference for researchers, policymakers, and industry stakeholders who aim to develop intelligent, secure, and sustainable energy infrastructures.

1.2. The Organisation of the Paper

The structure of this paper is designed to provide a logical flow of information, guiding the reader through the key aspects of modern power system advancements, challenges, and future prospects.

Section 2 introduces the integration of RESs into modern power grids. It also highlights the role of distributed generation (DG) and energy storage systems (ESSs) in achieving grid stability. Following this, Sections 3 and 4 present a detailed review of advanced grid technologies, such as SGs, MGs, and HVDC transmission. These sections also discuss recent developments in grid-forming inverters, DLR, and demand response (DR) strategies. Section 5 focuses on applying AI and ML in energy management and grid optimisation. It explores AI-driven solutions for demand forecasting, fault detection, and voltage regulation. In addition, Section 6 examines the role of blockchain technology in energy systems, particularly its potential to enhance security, facilitate P2P energy trading, and improve transparency in electricity markets.

Cybersecurity concerns in modern SGs are discussed in Section 7, where various threats and vulnerabilities are identified, along with potential solutions such as federated learning, anomaly detection, and decentralised security frameworks. Section 8 then outlines the key challenges associated with transforming power systems, including regulatory, economic, and technical barriers, while highlighting opportunities for policy-driven solutions and technological advancements.

The paper concludes with Section 9, summarising key findings and providing recommendations for future research and policy development in smart and sustainable power systems. This section discusses future perspectives and research directions, emphasising the potential of hybrid energy models that integrate AI, blockchains, and power electronics for achieving a resilient and intelligent energy infrastructure.

2. Renewable Energy Integration in Modern Power Systems

2.1. Methodology of Literature Selection

This review was conducted by systematically analysing relevant scientific publications to ensure a comprehensive evaluation of advancements in smart grids, renewable energy integration, artificial intelligence applications, and cybersecurity in power systems. Several reputable databases were used to search for the relevant literature, including *IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and Web of Science*. These databases were chosen due to their extensive coverage of engineering, energy systems, and computer science disciplines, ensuring that the selected studies were from peer-reviewed sources.

To refine the search, a combination of specific keywords and Boolean operators was used, focusing on terms such as the following:

- "Smart grids" AND "renewable energy integration";
- "Artificial intelligence in power systems" OR "machine learning for energy optimisation";
- "Cybersecurity in energy grids" AND "blockchain applications";
- "HVDC transmission" OR "dynamic line rating" AND "grid stability".

The selection of publications followed a set of inclusion and exclusion criteria to ensure relevance and reliability. The inclusion criteria encompassed the following:

- Peer-reviewed journal articles and conference papers published in the last 10 years (2015–2025) to ensure up-to-date information.
- Studies focused on grid modernisation, artificial intelligence in energy systems, cybersecurity, and the integration of renewable energy.

- Papers presenting quantitative analyses, experimental results, or systematic evaluations of power system technologies.

The exclusion criteria involved the following:

1. Publications without technical or experimental relevance to smart grids or renewable energy.
2. Non-peer-reviewed sources, including white papers, industry reports, and opinion articles.
3. Studies with a regional focus only, unless they provided significant insights applicable to global energy systems.

By following this approach, the review ensured a balanced and well-structured assessment of the most relevant and impactful research in the field of modern power system transformation.

2.2. MG Applications

MGs are decentralised energy systems capable of operating independently or in conjunction with the main grid. They provide a highly resilient, flexible, and sustainable energy solution by addressing local energy needs. The importance of MGs is highlighted in Figure 1 through their applications in various scenarios:

- **Remote and off-grid areas:** MGs are pivotal in bringing electricity to remote and underserved regions. Leveraging DERs such as PV panels, WTs, and biomass generators ensures a reliable and sustainable energy supply [5]. These systems reduce the dependency on centralised power plants and facilitate the electrification of off-grid communities. For instance, MGs have been instrumental in rural electrification projects across Africa and South Asia, empowering communities with access to clean energy.
- **Enhancing resilience against natural disasters and cyber-attacks:** MGs' ability to "island" or operate independently from the main grid during emergencies makes them essential for energy security. During natural disasters such as hurricanes or earthquakes, MGs can maintain a continuous power supply to critical facilities, hospitals, emergency response centres, and shelters [6]. Similarly, their ability to mitigate cyber-attack risks by isolating vulnerable sections of the grid enhances the overall system security.
- **Integrating DERs such as rooftop PV panels and small-scale WTs:** Designed to optimise renewable energy utilisation, MGs integrate various DERs efficiently. Advanced energy management systems (EMSs) and smart inverters enable seamless integration and ensure consistent power delivery, even with intermittent RESs [7]. The capability to integrate these sources contributes significantly to achieving decarbonisation goals and reducing the reliance on fossil fuels.
- **Supporting electrification in critical sectors:** MGs have found applications in critical sectors such as healthcare, education, and industries where uninterrupted power is essential. For example, MGs deployed in educational institutions ensure reliable power for e-learning tools, while industrial MGs improve energy efficiency and cost savings.
- **Catalysing smart city development:** MGs are crucial to smart city initiatives in urban environments. By integrating renewable energy, advanced sensors, and ESSs, MGs enhance urban areas' sustainability and energy autonomy. SGs can also efficiently manage electric vehicle (EV) charging networks, reducing strain on the main grid.

As shown in Figure 1, MGs also contribute to grid modernisation by enabling advanced functionalities such as DR, energy storage integration, and localised energy trading. Surplus energy generated by DERs can be sold to nearby consumers or fed back into the main grid,

facilitating a decentralised energy market [8]. Such capabilities promote energy efficiency and decentralised energy ownership, empowering communities to participate in the energy ecosystem actively.

In addition to their technical advantages, MGs offer significant socio-economic benefits. They create opportunities for community-based energy initiatives, fostering local entrepreneurship and energy independence. For example, rural communities equipped with MGs often experience economic growth through energy access, enabling small businesses to thrive. By integrating smart technologies such as the Internet of Things (IoT) and AI, MGs enhance operational efficiency, allowing for real-time monitoring, control, and predictive maintenance [9].

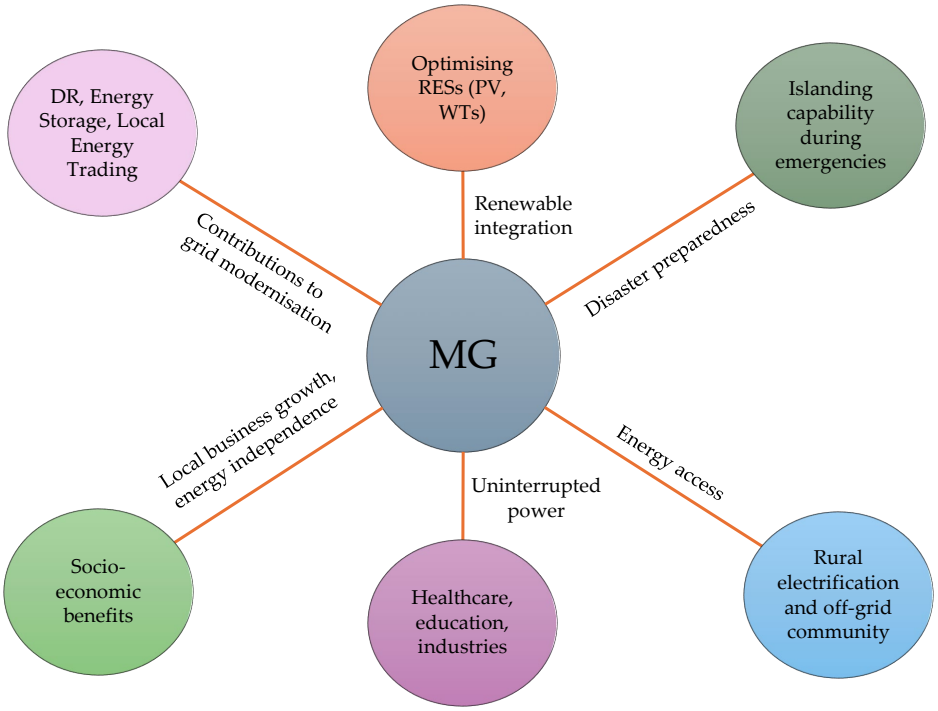


Figure 1. Role of MGs in energy optimisation and socio-economic development.

ESSs, such as lithium-ion batteries and hydrogen fuel cells (FCs), further improve MG reliability and resilience. These systems play a critical role in balancing supply and demand, particularly during variable renewable energy generation periods. For example, batteries store excess energy during peak production hours and release it when high demand requires a consistent power supply [10]. FCs add another layer of reliability by providing backup power during prolonged outages, which is particularly valuable for critical applications like data centres and medical facilities.

Furthermore, MGs support energy justice by addressing energy poverty in marginalised regions. By deploying MGs in areas with limited access to electricity, governments and organisations can bridge the energy gap, promoting equitable energy distribution and improving living standards. MGs also empower local communities to manage their energy systems, fostering autonomy and reducing the dependence on centralised utilities.

Despite their benefits, the widespread adoption of MGs faces challenges related to scalability, interoperability, and cost-effectiveness. High initial investment costs, complex system integration, and regulatory barriers remain significant hurdles. However, ongoing research and development are driving innovations in MG design and operation, such as modular MGs and blockchain-based energy trading platforms, which aim to address these challenges. Collaboration between governments, private sectors, and research institutions is essential to developing policies and funding mechanisms that support MG deployment.

As the global energy transition accelerates, MGs will be crucial in building a sustainable and resilient energy future. Addressing energy access, integrating renewables, and enhancing grid reliability represent a transformative solution for modern energy systems.

2.3. Challenges in Integration

Despite renewable energy's impressive growth, integrating these resources into existing power systems presents several challenges, illustrated in Figure 2. A primary concern is the variability and intermittency of RESs, which depend on weather conditions and the time of day. These fluctuations can lead to significant voltage and frequency deviations within the grid, creating imbalances between supply and demand that pose risks to grid stability and reliability [11]. For instance, during periods of high renewable generation, excess electricity can cause overvoltage conditions, whereas low-generation periods can result in under-frequency situations, potentially disrupting the power supply [12].

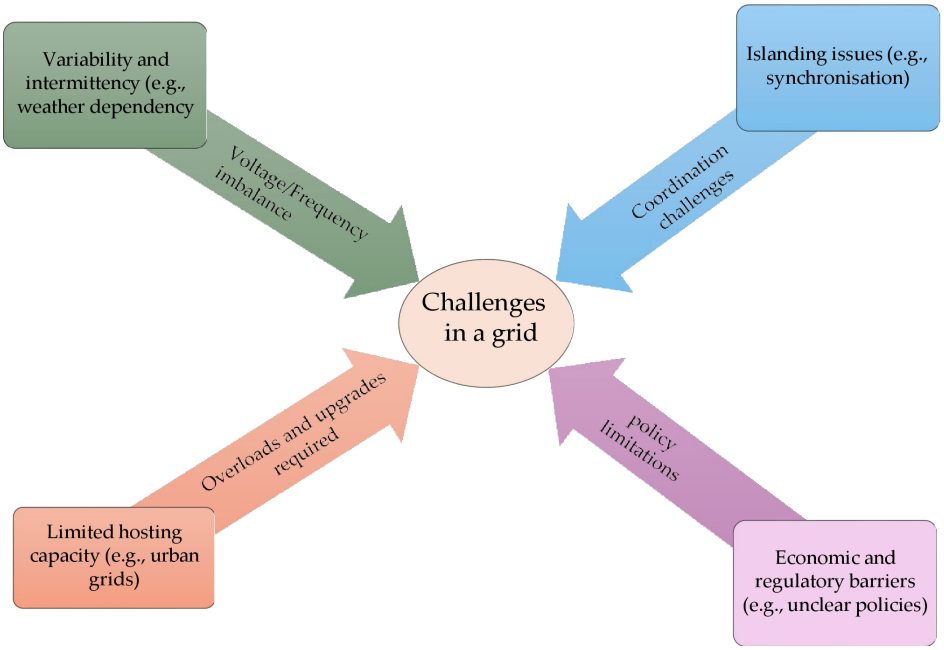


Figure 2. Challenges of utility grids in renewable energy integration.

Another key challenge is the limited hosting capacity of distribution networks. Many existing grids, particularly in urban areas, are not designed to accommodate the additional load from DERs. This limitation can restrict the amount of renewable energy that can be integrated without compromising the system performance [13]. Urban infrastructure, often ageing and congested, exacerbates these constraints, requiring costly upgrades to support higher renewable penetration [14].

Moreover, islanding—a condition where a portion of the grid becomes electrically isolated—poses synchronisation challenges when reconnecting MGs and distributed systems with the central grid. Ensuring proper coordination during re-synchronisation is essential to avoid power quality issues, equipment damage, or outages [15].

Other challenges include the economic and regulatory barriers associated with renewable energy integration. Uncertainties in energy markets and a lack of clear policies for incentivising renewable adoption can deter investments in grid modernisation and renewable projects. Additionally, operational complexities such as maintaining grid inertia in systems dominated by renewables and managing real-time grid balancing further complicate integration efforts.

2.4. Role of MGs and Distributed Generation in Energy Resilience

MGs and distributed generation (DG) technologies are critical in enhancing energy resilience by decentralising power generation, reducing the dependence on centralised grids, and integrating renewable energy sources. These systems are particularly valuable in regions prone to extreme weather events, natural disasters, and grid instability, as they provide localised energy solutions that can operate independently when the main grid fails. By incorporating solar photovoltaic (PV) panels, wind turbines, energy storage systems (ESSs), and combined heat and power (CHP) units, MGs and DG ensure a continuous and reliable power supply, making them essential for critical infrastructure such as hospitals, emergency response centres, and industrial facilities. The ability of MGs to operate in an islanded mode during grid failures allows communities to maintain essential services, preventing large-scale blackouts and economic disruptions [14].

In addition to their role in energy resilience, MGs and DG technologies support the integration of renewable energy into the power sector, reducing the reliance on fossil fuels and lowering carbon emissions. Unlike traditional power grids, which rely on large, centralised generation plants that require extensive transmission infrastructure, MGs enable energy to be generated closer to the point of consumption, minimising transmission losses and improving the overall efficiency. This decentralised approach is particularly beneficial in rural and off-grid areas in developing countries, where electrification rates are often low due to the high costs of extending national grids. By leveraging local energy resources, such as biomass and small-scale hydroelectric systems, MGs help improve energy access while fostering economic development and energy independence [11].

Despite their advantages, the widespread adoption of MGs and DG faces several challenges, particularly in terms of technical, economic, regulatory, and infrastructural barriers. In developed countries, one of the primary barriers is the integration of MGs with existing grid infrastructure. Traditional power grids were designed for a centralised, one-way power flow, making accommodating bidirectional energy exchanges and distributed energy resources difficult. Upgrading these grids to support MG deployment requires significant investment in smart grid technologies, advanced metering infrastructure (AMI), and real-time control systems. Additionally, regulatory uncertainty and market structures in many developed nations hinder MG adoption, as electricity pricing mechanisms and grid interconnection policies are often designed to favour large utilities rather than decentralised energy producers. Permitting and compliance requirements also create bureaucratic obstacles, delaying project development and increasing costs [15].

The challenges to MG and DG adoption are even more pronounced in developing countries. One of the most significant barriers is the high investment cost of deploying MG infrastructure, including solar panels, battery storage, and control systems. Many communities in developing regions lack access to financing and government support, making implementing and scaling MG projects difficult. In addition, technical expertise and workforce development remain key challenges, as operating and maintaining MGs require specialised skills often lacking in underdeveloped energy markets. Grid stability concerns also arise in countries with weak and outdated transmission networks, where integrating DG sources can lead to voltage fluctuations and reliability issues [11]. Furthermore, political and regulatory instability often prevents long-term investment in decentralised energy projects, with inconsistent energy policies and a lack of clear incentives discouraging private sector participation. Another major obstacle in both developed and developing countries is public and utility resistance to decentralised energy models. In many cases, large utility companies view MGs and DG as threats to their business model, as increased self-generation by consumers reduces the demand for electricity from central grids. This has led to disputes over tariff structures, grid access fees, and revenue-sharing mechanisms,

making it challenging for MG operators to achieve financial viability. In some cases, subsidies for fossil fuel-based electricity generation create an uneven playing field, where renewables and DG projects struggle to compete with conventional energy sources [13].

Despite these challenges, several policy and technological advancements can drive the expansion of MGs and DG. Governments can play a crucial role by introducing supportive policies, such as feed-in tariffs, net metering, and financial incentives for distributed energy resources. Innovations in battery storage technology and AI-driven energy management systems are also improving the feasibility of MGs by enhancing their ability to store excess renewable energy and optimise load balancing. Additionally, the rise of peer-to-peer (P2P) energy trading platforms and blockchain-based decentralised markets enables greater consumer participation in local energy exchanges, further promoting the adoption of MGs [13].

2.5. Advanced Solutions

To address these challenges, several advanced technological solutions and strategies have been developed, fostering the smoother integration of renewable energy into the grid, as demonstrated in Figure 3:

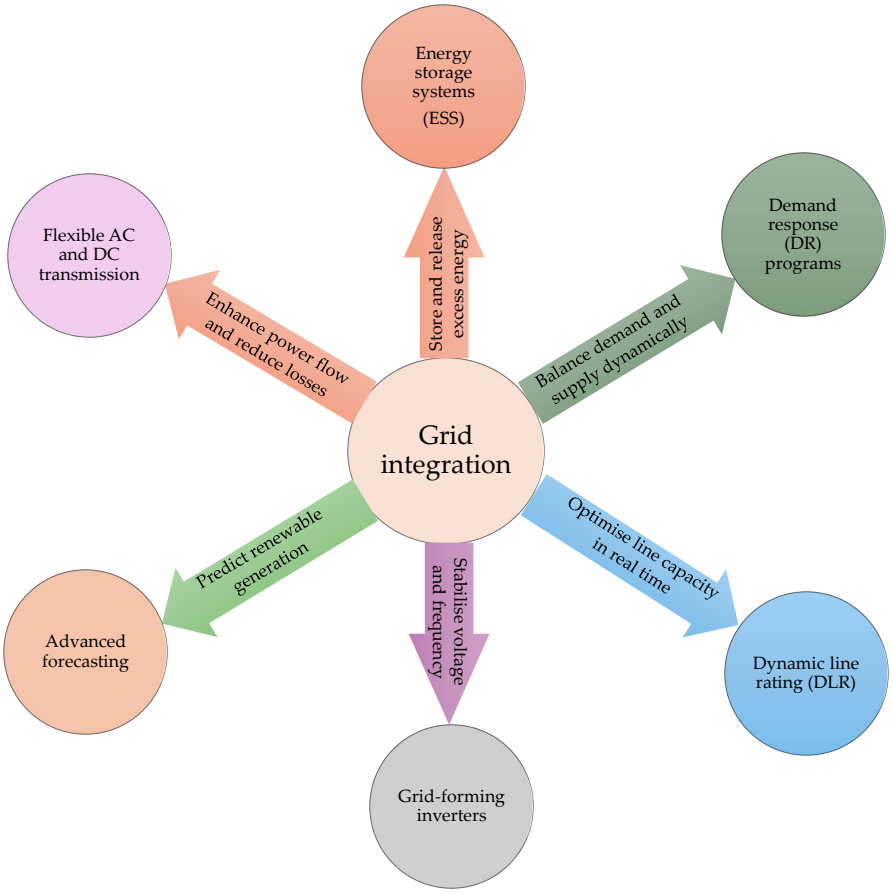


Figure 3. Key technologies for enhancing grid integration and stability.

- **ESSs:** Energy storage, particularly battery storage systems, plays a critical role in mitigating the variability of RESs. ESSs can store excess energy generated during peak production and release it during periods of low generation, ensuring a stable energy supply. Lithium-ion batteries are especially popular due to their high energy density, scalability, and decreasing costs, making them a viable solution for grid-scale applications [16]. In addition, newer storage technologies, such as flow batteries and hydrogen storage, are gaining traction for their long-duration capabilities.

- **Grid-Forming Inverters:** These innovative devices enable renewable energy systems to provide a stable voltage and frequency, even without a traditional synchronous generator. Grid-forming inverters facilitate the seamless integration of DERs, improving the overall grid stability and resilience. They also allow MGs to operate autonomously and re-synchronise with the central grid without compromising the system performance [17,18].
- **DLR Technologies:** DLR technology enables the real-time monitoring and optimisation of the transmission line capacity by adapting to changing environmental conditions and load demands. Unlike traditional static ratings that assume conservative worst-case conditions, DLR adjusts line ratings based on real-time meteorological factors such as the ambient temperature, wind speed and direction, and solar radiation, significantly influencing the conductor's ability to dissipate heat. Studies have shown that higher wind speeds and lower ambient temperatures can substantially increase the transmission line capacity, reducing the risk of overheating and improving grid flexibility [19–21]. By leveraging sensor-based monitoring and AI-driven forecasting, utilities can maximise the efficiency of existing infrastructure, enhancing grid resilience and reducing the need for costly transmission upgrades while accommodating higher renewable energy penetration [22,23]. Several studies have extensively analysed the role of DLR in optimising power line performance under varying climatic conditions, demonstrating its effectiveness in improving grid reliability and enabling the better integration of variable renewable energy sources [24].
- **Demand Response Programmes:** Advanced DR mechanisms help balance supply and demand by incentivising consumers to adjust their energy usage based on grid requirements. For example, smart appliances and IoT devices can respond to real-time price signals or grid conditions, reducing the peak demand and enabling the more effective integration of intermittent renewables.
- **Advanced Forecasting Techniques:** Leveraging ML and AI, advanced forecasting tools provide accurate predictions of renewable energy generation and demand patterns. These insights enable grid operators to plan and allocate resources more effectively, minimising the impact of renewable variability.
- **Flexible AC and DC Transmission Systems:** Flexible Alternating Current Transmission Systems (FACTSs) and HVDC systems enhance the ability of grids to accommodate variable renewable energy by improving power flow control, reducing losses, and enabling long-distance energy transmission from remote renewable sources.

Beyond technological advancements, addressing integration challenges requires supportive policy frameworks and collaboration among stakeholders. Governments, utilities, and private enterprises must work together to establish clear regulations, provide financial incentives, and promote research and development. Efforts to streamline permitting processes and reduce barriers to renewable projects are equally important to accelerate deployment.

As renewable energy expands its share of global electricity generation, adopting these advanced solutions will create a sustainable, reliable, and resilient energy system capable of meeting future demands.

2.6. Role of Dynamic Line Rating in Renewable Energy Integration

DLR technologies play a crucial role in optimising energy transmission and supporting the integration of variable renewable energy sources (RESs) by allowing for real-time adjustments to the transmission capacity based on environmental conditions. Unlike conventional static line ratings, which use conservative assumptions about the weather and temperature, DLR systems continuously monitor factors such as the ambient temperature,

wind speed, and conductor sag to determine the actual transmission capacity of power lines. This enables grid operators to maximise the utilisation of existing infrastructure, reducing the need for costly transmission upgrades and enhancing grid flexibility. For renewable energy integration, DLR helps manage solar and wind generation variability by dynamically increasing the transmission capacity when the renewable output is high. For instance, strong winds that increase wind farm generation also cool transmission lines, allowing them to carry more electricity without overheating. This ensures more renewable energy can be transmitted to demand centres, reducing curtailment and improving the overall grid efficiency. Additionally, DLR facilitates faster congestion management, enabling grids to handle fluctuations in renewable generation without significant losses or instability.

Despite its benefits, the large-scale implementation of DLR faces several challenges. One major issue is the requirement for real-time data collection and advanced grid-monitoring infrastructure, which involves installing specialised sensors, communication networks, and AI-driven control systems. Many existing grids lack the necessary digital infrastructure to support DLR, making upgrades costly and time-consuming. Regulatory and operational challenges also hinder adoption, as utilities must adapt their grid management practices and comply with evolving industry standards. Additionally, integrating DLR into current grid-planning models requires improved coordination between grid operators, renewable energy developers, and policymakers to ensure seamless deployment. While DLR presents a cost-effective and scalable solution for optimising transmission and integrating renewables, overcoming technical, regulatory, and infrastructural barriers remains essential for widespread adoption in modern power systems.

3. SG Developments

3.1. SG Technologies

SGs transform traditional energy systems into highly responsive, automated, and efficient infrastructures. By integrating AMI, supervisory control and data acquisition (SCADA) systems, and DR mechanisms, SGs enable the following:

- Real-time data acquisition and analytics: AMI allows utilities to monitor energy consumption in real time, enabling operators to detect inefficiencies and optimise grid operations. SCADA systems further enhance this by providing the centralised control and monitoring of grid components [25]. Predictive analytics powered by these technologies are crucial in anticipating demand fluctuations and ensuring a stable energy supply.
- Predictive maintenance and fault detection: Predictive maintenance technologies rely on SCADA system and AMI data to identify and mitigate potential equipment failures. This capability not only minimises downtime but also reduces repair costs and enhances grid reliability [26].
- Enhanced customer engagement through dynamic pricing and consumption insights: Smart meters, a key component of AMI, empower consumers by providing detailed insights into their energy usage. This facilitates the adoption of dynamic pricing models, enabling customers to adjust their consumption patterns and reduce costs [27].

Integrating IoT technologies and AI further augments the capabilities of SGs. IoT devices enhance communication between grid components, while AI algorithms analyse vast amounts of data to optimise grid performance and resilience [28]. Cybersecurity remains a critical concern in SG development, with advanced encryption and intrusion detection systems implemented to safeguard data integrity and prevent cyber-attacks [29].

Moreover, the transition to RESs necessitates innovative solutions for grid management. ESSs and smart inverters are being deployed to stabilise the grid and accommodate

fluctuations in renewable energy generation [30]. These advancements underscore the importance of the continued research and development of SG technologies.

3.2. AI-Driven Predictive Maintenance in SGs

AI-driven predictive maintenance strategies significantly enhance the reliability and efficiency of smart grids by proactively identifying potential equipment failures before they occur. Traditional maintenance approaches rely on scheduled inspections or reactive repairs, often leading to unexpected outages, high operational costs, and inefficient resource allocation. In contrast, AI-based predictive maintenance leverages ML, DL, and data analytics to monitor grid components in real time, detect anomalies, and accurately predict faults [28].

By analysing vast amounts of data from sensors, smart meters, SCADA systems, and IoT devices, AI algorithms can identify patterns indicating early signs of wear, overheating, or electrical faults in transformers, circuit breakers, and transmission lines. This allows grid operators to schedule maintenance only when necessary, optimising repair costs and reducing downtime. AI-driven fault diagnosis also enables faster response times, as the system can automatically isolate faulty sections and reroute power, ensuring continuous service with minimal disruptions [29].

Despite these benefits, several challenges remain in implementing AI-based fault detection and diagnosis in real-world power systems. One of the key obstacles is the availability and quality of data. Predictive models require extensive historical and real-time datasets to train effectively, but many existing grids lack standardised data collection frameworks or have incomplete datasets. Additionally, AI models must be adaptable to diverse grid infrastructures, as different regions use varied grid designs, components, and operational strategies.

Another major challenge is cybersecurity and data privacy. Since AI-driven maintenance relies on continuous data exchange between sensors, cloud servers, and control centres, it becomes vulnerable to cyber-attacks and data breaches. Ensuring secure communication protocols and robust encryption prevents system manipulation or unauthorised access. Moreover, integrating AI into legacy power grids requires significant investment in digital infrastructure and workforce training. Many grid operators still rely on conventional monitoring techniques and lack the expertise to interpret AI-generated insights effectively. There is also resistance to automation, as utilities may hesitate to replace human-based decision-making processes with AI-driven systems [30].

While AI-based predictive maintenance offers unprecedented advantages in improving grid reliability and efficiency, overcoming challenges related to data availability, cybersecurity, integration costs, and workforce adaptation is essential for its widespread adoption. As power systems become increasingly complex with high renewable energy penetration, AI will ensure smarter, more resilient, and self-healing grids.

4. Role of HVDC Systems

HVDC systems are pivotal in modern power transmission, particularly in integrating RESs into the electrical grid. The increasing demand for efficient power transmission over long distances, coupled with the need for enhanced grid stability and reliability, has led to a significant rise in the adoption of HVDC technology. This section discusses the advantages of HVDC systems, their applications in renewable energy integration, and the challenges associated with their implementation.

4.1. Advantages of HVDC Systems

HVDC systems offer several advantages over traditional High-Voltage Alternating Current (HVAC) systems. One of the primary benefits is the reduced power loss during transmission. HVDC technology allows electricity to be transmitted over long distances with minimal losses, making it particularly suitable for connecting remote RESs, such as offshore wind farms, to urban centres [31,32]. The ability to transmit power efficiently over long distances is crucial for integrating renewable energy into the grid, as many renewable resources are located far from consumption centres [33].

Another significant advantage of HVDC systems is their ability to interconnect asynchronous power systems. This capability allows different grids to operate independently while still exchanging power, enhancing the overall grid reliability and flexibility [34]. HVDC systems also provide better control over the power flow, enabling grid operators to manage congestion and maintain stability more effectively [35]. Furthermore, HVDC technology facilitates the integration of large amounts of renewable energy, essential for achieving global climate goals [36].

4.2. Applications in Renewable Energy Integration

HVDC systems have become indispensable in integrating RESs. As the share of renewables in the global energy mix continues to grow, HVDC technology has emerged as a critical enabler for connecting these resources to the grid. For instance, offshore wind farms often require HVDC transmission due to the long distances involved and the need to minimize energy losses [32]. HVDC systems efficiently transmit the generated electricity from these remote locations to the onshore grid for consumer distribution [33].

Additionally, HVDC technology is instrumental in facilitating the development of super grids, which are large-scale interconnected networks capable of transporting electricity across vast distances [34]. These super grids enhance the stability and reliability of power systems by allowing for the sharing of resources and balancing supply and demand across regions. The energy sector can build a more resilient and sustainable future by connecting diverse energy sources through HVDC systems, including solar power, wind power, and hydropower [36].

4.3. Challenges in Implementation

Despite their numerous advantages, HVDC systems face several challenges that must be addressed to enable their widespread adoption, as demonstrated in Table 1:

1. High capital costs: The initial investment required for HVDC technology is substantial, which may deter some utilities from implementing it [37]. The cost of HVDC converters, transmission lines, and installation significantly exceeds that of HVAC systems, creating a financial barrier.
2. Complexity and expertise: HVDC systems require specialised design, operation, and maintenance knowledge. Their complexity can complicate deployment and necessitate extensive personnel training [38].
3. Integration with existing infrastructure: Integrating HVDC systems with HVAC infrastructure poses technical challenges. The transition requires the installation of converters, control systems, and grid upgrades, which can be time-consuming and costly [39,40].
4. Regulatory and policy barriers: Regulatory frameworks must evolve to accommodate the deployment of HVDC technology. Policymakers need to align HVDC implementation with broader energy transition goals, ensuring supportive legislation and incentives [41].

Table 1. Role of HVDC systems in power transmission.

Category	Details	Benefits	References
Advantages	Reduced transmission losses	Efficient energy transfer over long distances	[42,43]
	Interconnection of asynchronous grids	Enhanced grid stability and flexibility	[44,45]
	Better power flow control	Improved congestion management	[37]
Applications in RESs	Offshore wind farms	Reliable transfer of electricity to urban centres	[46,47]
	Super grids	Balancing supply and demand across regions	[48,49]
	Integration of diverse renewable sources	Enables interconnection of solar power, wind power, and hydropower	[50]
Challenges	High capital costs	Financial barriers to implementation	[51]
	Technical complexity	Requires specialized expertise for operation	[52,53]
	Integration with existing HVAC infrastructure	Requires new converters and upgrades	[37]
Future Perspectives	Technological advancements	Improved reliability and efficiency of converters	[54]
	Cost reduction efforts	Decrease in initial and operational expenses	[55]

HVDC systems are transformative in integrating RESs, particularly in regions with high offshore wind potential. As the demand for clean energy grows, HVDC technology is becoming increasingly vital for long-distance power transmission, efficient grid integration, and the interconnection of asynchronous power networks. HVDC transmission offers superior efficiency, scalability, and reliability compared to traditional HVAC systems, making it the preferred choice for modern power grids transitioning towards sustainable energy solutions.

One of the primary challenges in integrating offshore wind farms, solar farms, and other DERs into national grids is the geographical separation between generation sites and urban consumption centres. Offshore wind farms are often far from coastal cities, requiring transmission technology that minimises energy losses over long distances. HVDC provides an ideal solution due to its ability to transmit electricity with minimal losses efficiently.

The key advantages of HVDC in renewable energy integration include the following:

1. Long-Distance Transmission Efficiency: Unlike HVAC systems, where transmission losses increase significantly with distance, HVDC systems can transfer large amounts of power over hundreds of kilometres with lower resistive losses. This makes it particularly well suited for connecting offshore wind farms, remote solar farms, and hydroelectric plants to urban centres.
2. Integration of Offshore Wind Power: Offshore wind power presents a unique challenge due to variable generation patterns and the need to connect turbines spread over vast sea areas. HVDC technology allows multiple offshore wind farms to be integrated into a single high-voltage link, delivering power to the mainland grid. This reduces infrastructure costs and enhances grid reliability.
3. Asynchronous Grid Interconnection: HVDC technology enables the interconnection of different power networks that operate at varying frequencies. This is crucial for cross-border electricity trading and international power exchange, allowing surplus renewable energy from one region to be exported to another with high demand.
4. Grid Stability and Blackout Prevention: The rapid growth of renewables has introduced challenges in frequency stability due to the intermittent nature of wind and solar power. HVDC technology provides better frequency control, reactive power support, and dynamic stability, reducing the risk of grid disruptions.
5. Scalability for Future Energy Demand: With the global transition towards carbon neutrality and higher renewable penetration, HVDC technology can accommodate

increasing energy demands without requiring major infrastructure overhauls. The modular nature of HVDC substations allows for easy expansion and adaptation to future grid needs.

4.4. HVDC vs. Traditional AC Systems: Efficiency and Scalability

While HVAC technology has been the dominant transmission technology for over a century, it faces significant limitations when integrating modern renewable energy systems. The efficiency and scalability of HVDC transmission compared to traditional AC transmission can be assessed in several key aspects. One of the most crucial differences lies in energy losses and transmission efficiency. HVAC systems experience higher transmission losses due to capacitance, inductance, and the skin effect, particularly over long distances. In contrast, HVDC transmission eliminates reactive power flow and enables direct power transmission with lower resistance, reducing overall energy losses. Studies have indicated that over distances greater than 500 km, HVDC transmission can be 30–50% more efficient than HVAC transmission, making it a more viable option for long-distance energy transfer. Another major advantage of HVDC transmission is voltage control and grid stability. In AC systems, power flow control is inherently complex due to reactive power variations and frequency mismatches, leading to inefficiencies and grid instability. HVDC transmission, however, provides precise power control, allowing grid operators to efficiently balance fluctuations in renewable energy generation and maintain stability in weak or isolated grids. This particularly benefits power networks incorporating a high share of variable energy sources, such as wind and solar power.

HVDC transmission also enables the interconnection of different power networks that operate at varying frequencies. Traditional HVAC networks require a shared frequency for seamless interconnection, significantly limiting cross-border energy exchange and international power trading. HVDC transmission overcomes this limitation by converting AC to DC and then back to AC, effectively linking asynchronous grids. This capability enhances energy security and market flexibility, making international electricity trading more feasible and efficient. Regarding infrastructure costs and scalability, HVAC systems are typically more affordable for short-distance transmission due to their more straightforward converter station requirements. However, HVDC transmission proves to be more cost-effective when it comes to long-distance and high-power transmission. Advances in voltage source converter (VSC) technology have further improved HVDC transmission's feasibility, as they enable a reduction in the substation footprint and operational costs, making it easier to scale HVDC networks as the energy demand grows. Lastly, HVDC transmission offers significant advantages in subsea and underground transmission. HVAC transmission through undersea cables suffers from excessive capacitive losses, making offshore wind farm integration and long-distance submarine connections inefficient. HVDC transmission, on the other hand, is better suited for subsea and underground applications due to its lower cable losses and higher reliability. This makes it the preferred choice for offshore wind integration and for linking remote renewable energy sources to urban centres.

4.5. Future Perspectives

The role of HVDC systems in power transmission is expected to grow as the demand for renewable energy integration increases. Several key factors will shape the future of HVDC technology:

- Technological advancements: Improvements in converter efficiency, reliability, and scalability will enhance the feasibility of deploying HVDC systems on a larger scale. Innovations in materials and power electronics are expected to reduce costs and improve system performance [32].

- Cost reduction efforts: Ongoing research and development aimed at lowering the capital and operational costs of HVDC systems will be crucial for overcoming financial barriers. Collaborative efforts among industry stakeholders can reduce costs and facilitate wider adoption [37].
- Collaboration and innovation: Cooperation among policymakers, researchers, and the private sector will be essential for addressing implementation challenges. By fostering innovation and promoting best practices, the energy sector can leverage HVDC technology to create a more sustainable and resilient power grid [40].

As the world transitions toward a low-carbon energy future, HVDC systems will play a vital role in integrating RESs and ensuring grid stability. Their ability to enhance transmission efficiency, connect diverse energy resources, and improve grid reliability makes them a cornerstone of modern power infrastructure.

5. AI in Grid Optimisation

AI is increasingly recognised as a transformative force in power system optimisation, particularly within SGs. Integrating AI techniques such as ML, deep learning (DL), and optimisation algorithms is reshaping various operational aspects of electrical grids. Table 2 explores key applications of AI in grid optimisation, focusing on voltage control and stability, fault detection and diagnosis, and demand forecasting.

Voltage control and stability are critical components of power system operations, as they directly influence the reliability and efficiency of electricity distribution. AI algorithms have been developed to optimise voltage profiles, thereby minimising power losses across the grid, as seen in Table 2. Marques highlights that AI technologies can enhance the management of electrical grids by enabling predictive analytics and real-time monitoring, which are essential for maintaining voltage stability and reducing operational costs [56]. Furthermore, the application of AI in voltage optimisation can lead to improved grid performance, as it allows for dynamic adjustments based on real-time data inputs, thus ensuring that voltage levels remain within acceptable limits [57]. Integrating AI-driven solutions in voltage control enhances stability and contributes to the power system's overall resilience against fluctuations and disturbances [58,59].

Table 2. Applications of AI in grid optimisation.

AI Technique	Application Area	Key Advantages	References
ML	Demand forecasting and load prediction	Accurate prediction of energy patterns, enabling enhanced resource planning	[60,61]
	Equipment failure prediction	Prevents outages through timely maintenance	[62]
DL	Fault detection and anomaly prevention	Real-time detection of system failures, improving reliability and minimising downtime	[63,64]
	Grid security monitoring	Identifies cyber threats and data irregularities	[65]
Reinforcement Learning (RL)	Energy storage management	Optimal utilisation of DERs	[66,67]
	MG operation	Minimisation of operational costs and peak load demand	[68]
NLP	User interface for SGs	Enhanced customer interaction through intelligent query handling	[69]
	Smart meter data processing	Provides insights into consumption patterns and for demand-side management (DSM)	[70]

Table 2. *Cont.*

AI Technique	Application Area	Key Advantages	References
Genetic Algorithms (GAs)	Integration of RESs	Optimise resource allocation for solar, wind, and hybrid systems	[71,72]
	Transmission network design	Efficient routing and minimisation of power losses	[73]
Swarm Intelligence (SI)	Voltage regulation	Stabilises decentralised grids using distributed control	[74]
	Fault localisation	Quick identification of system failures	[75]
Hybrid AI Models	Comprehensive grid optimisation	Combine multiple AI methods to handle complex challenges	[76,77]
	Renewable integration analysis	Improve energy forecasting and distribution	[78]
Predictive Analytics	Equipment lifecycle management	Extend asset lifespan through preventive maintenance	[79]
	Energy demand analysis	Accurate forecasting for grid stability	[80]
Fuzzy Logic (FL)	DSM	Adaptive resource distribution under uncertain demand conditions	[81]
	Grid reliability enhancement	Provides flexibility in system operations	[82]

In addition to voltage management, AI plays a pivotal role in fault detection and diagnosis within power systems. The complexity of modern electrical grids, characterised by the integration of RESs and DG, necessitates advanced fault detection mechanisms. ML models have been employed to identify and predict faults in grid components, significantly improving the speed and accuracy of fault diagnosis. For example, Wang et al. presented a deep RL-based method for diagnosing power system faults, which demonstrates the effectiveness of AI in managing the increasingly complex fault scenarios encountered in contemporary grids [83]. This capability is crucial for minimising downtime and enhancing the reliability of the power supply, as rapid fault detection allows for quicker response times and targeted maintenance efforts [84]. Moreover, using AI in fault diagnosis can streamline operations by automating the identification of problematic areas, thus reducing the burden on human operators [84].

Demand forecasting is another area where AI has made significant strides, enabling utilities to predict the electricity demand more accurately. Accurate demand forecasting is essential for effective resource allocation and planning within power systems. AI techniques, particularly those involving ML and DL, have been shown to enhance the accuracy of demand predictions by analysing historical data and identifying patterns that may not be readily apparent using traditional forecasting methods [85,86]. For instance, the research conducted by Kuponiyi emphasises the importance of real-time load forecasting in optimising MG performance, which is directly applicable to broader grid management strategies [87]. The ability to predict demand fluctuations allows utilities to manage supply and demand better, ensuring that resources are allocated efficiently and reducing the risk of outages or overloading [88].

Integrating AI into SGs not only facilitates improved voltage control, fault detection, and demand forecasting but also enhances the overall efficiency and sustainability of power systems. As the energy landscape evolves with the increasing incorporation of RESs, AI technologies provide innovative solutions to manage these resources' inherent variability and uncertainty. For example, the use of AI in optimising the operation of PV systems has been explored, highlighting the potential for AI to enhance energy generation forecasts and improve grid stability [89]. This is particularly relevant as transitioning to a more

decentralised energy model necessitates advanced management strategies that can adapt to changing conditions in real time [90].

Moreover, the application of AI in SG ecosystems extends beyond operational efficiency to encompass broader sustainability goals. The development of intelligent dispatching systems, as noted by Zhang et al., illustrates how AI can be leveraged to optimise energy distribution and reduce safety risks within power grids [91]. Utilities can enhance their operational capabilities by employing AI-driven analytics, leading to a more reliable and sustainable energy infrastructure that aligns with global carbon reduction targets [92]. The ability to optimise energy flows and manage resources effectively is increasingly vital in the context of climate change and the push for greener energy solutions.

Integrating AI in grid optimisation is pivotal in developing resilient and sustainable power systems, particularly in managing RESs and enhancing grid stability. AI-driven technologies address the inherent challenges associated with renewable energy, such as intermittency and unpredictability, while also improving modern power grids' efficiency, security, and adaptability. One of the most significant contributions of AI is its ability to predict the energy demand and dynamically balance the supply. For accurate demand forecasts, ML algorithms analyse historical consumption data, weather patterns, and grid conditions [93,94]. By anticipating fluctuations in renewable energy generation, AI enables grid operators to optimise power distribution, thereby preventing overloads or energy shortages. RL further enhances real-time grid management by continuously adjusting system parameters in response to changes in supply and demand. AI also plays a crucial role in ensuring grid stability and voltage regulation. RESs introduce variability into the grid, leading to voltage and frequency fluctuations. AI-driven voltage control systems analyse the real-time grid conditions and automatically adjust transformers, capacitor banks, and flexible AC transmission systems to stabilise the power supply. Swarm intelligence, a decentralised AI approach, facilitates the adaptive control of distributed energy resources, allowing microgrids to operate autonomously and maintain stability even without a centralised control system [95–97].

Another key application of AI in grid optimisation is fault detection and predictive maintenance. AI-powered sensors and DL models analyse grid infrastructure data to identify anomalies and potential failures before they lead to major disruptions. AI can detect irregularities by processing data from power lines, transformers, and substations and schedule preventive maintenance, reducing downtime and operational costs. This capability is significant for managing ageing grid infrastructure, where unexpected failures can have severe consequences. Energy storage optimisation is another area where AI significantly enhances grid resilience. With the increasing adoption of BESSs, AI-driven management algorithms optimise charging and discharging cycles based on energy demand forecasts and grid conditions. This ensures that surplus energy generated from renewables is stored efficiently and released when needed, reducing the reliance on fossil fuel-based backup systems. AI-driven grid-forming inverters further support energy storage integration by autonomously stabilising the voltage and frequency in MGs [98,99].

AI also facilitates decentralising power generation and consumption through peer-to-peer energy trading. By leveraging blockchain technology, AI enables efficient and transparent energy transactions between consumers and producers. This decentralised approach allows households and businesses with solar panels to sell excess energy directly to other consumers, reducing the dependence on centralised power plants and promoting the use of renewable energy. In addition to operational optimisation, AI enhances cybersecurity in SGs. As power grids increasingly become digitalised, they become more vulnerable to cyber threats. AI-driven intrusion detection systems monitor network activity and detect potential security breaches in real time. Federated learning techniques enhance

data privacy and security by allowing distributed energy management systems to analyse data locally without exposing sensitive information to external threats [100–103]. Overall, AI is transforming power grids into intelligent, adaptive, and resilient energy systems. By improving demand forecasting, grid stability, fault detection, energy storage management, decentralised trading, and cybersecurity, AI enables the seamless integration of RESs while ensuring a reliable and efficient power supply. As the global energy transition accelerates, AI will continue to be a driving force in building sustainable, resilient, and intelligent power infrastructures.

6. Role of Blockchains in Energy Systems

The role of blockchain technology in energy systems is increasingly recognised as a transformative force, particularly in the context of P2P energy trading, enhancing security and transparency and addressing various challenges and opportunities associated with its integration, as seen in Figure 4. This synthesis will explore these aspects in detail, drawing on the relevant literature to substantiate the claims.

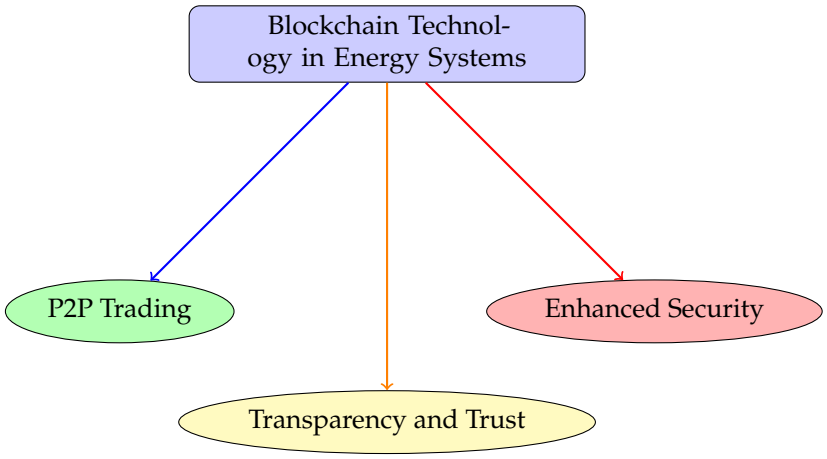


Figure 4. Applications of blockchain technology in energy systems.

6.1. P2P Energy Trading Using Blockchains

P2P energy trading represents a paradigm shift in distributing and consuming energy. By leveraging blockchain technology, individuals can engage in direct energy transactions without intermediaries, thereby promoting decentralised energy markets. According to Alladi et al., blockchain technology facilitates efficient data aggregation and enables real-time energy consumption monitoring, which is crucial for P2P trading systems [104]. This decentralised approach not only empowers consumers to trade excess energy generated from RESs but also enhances the overall efficiency of energy distribution networks.

The transparency inherent in blockchain technology is another significant advantage for P2P energy trading. As noted by Negro-Calduch et al., the immutable nature of blockchain records ensures that all transactions are securely documented, providing a reliable audit trail that can be accessed by all participants in the network [105]. This transparency fosters trust among users, which is essential for successfully implementing P2P energy trading systems. Furthermore, tracking energy transactions in real time can help mitigate disputes and enhance user confidence in the trading process.

Moreover, integrating smart contracts within blockchain frameworks can automate trading, reducing transaction times and costs. Smart contracts can execute trades based on predefined conditions, ensuring that transactions are conducted seamlessly and efficiently. This automation not only streamlines operations but also minimises the potential for human error, as highlighted by Jafar et al. in their exploration of blockchain applications across

various domains [106]. The combination of P2P trading and smart contracts thus presents a compelling case for adopting blockchains in energy systems.

6.2. Blockchains for Energy System Security and Transparency

The security of energy systems is paramount, especially as they become increasingly interconnected and reliant on digital technologies. Blockchain technology offers a robust solution to enhance the security of energy systems by providing a decentralised framework that reduces the risks associated with centralised data storage, as seen in Table 3. As Das et al. discussed, blockchain technology's distributed nature ensures that no single point of failure exists, making it significantly more resilient to cyber-attacks [107]. This characteristic is particularly important in energy systems, where a successful cyber-attack could have catastrophic consequences.

Table 3. Comparison of traditional vs. blockchain-based energy systems.

Feature	Traditional Sys.	Blockchain-Based Sys.	Ref.
Data Storage	Centralised	Decentralised	[108]
Security	Vulnerable to Single Point of Failure	Highly Resilient	[109]
Transparency	Limited	Immutable Audit Trail	[110]
Automation	Manual Processes	Smart Contracts	[111]

Blockchain technology enhances transparency, crucial for regulatory compliance and fostering trust among consumers and energy providers. According to Ellahi et al., its application in energy systems facilitates improved data sharing and validation, leading to better decision-making processes [112]. However, as illustrated in Figure 5, the scalability of blockchain networks remains a challenge, particularly in handling high transaction volumes efficiently. The figure demonstrates how increasing transactions can impact the processing time, revealing potential bottlenecks in consensus mechanisms such as Proof of Work (PoW) or Proof of Stake (PoS). These limitations can affect the responsiveness of energy trading platforms and the reliability of decentralised grid management. To address these concerns, emerging solutions such as layer-2 scaling techniques, sharding, and more efficient consensus protocols are being explored to ensure blockchain technology remains viable for large-scale energy applications. By providing all participants access to the same immutable transaction history, blockchain technology enhances transparency and contributes to the security and efficiency of decentralised energy markets.

Furthermore, integrating blockchain technology can improve the traceability of energy sources, particularly in the context of renewable energy. Consumers increasingly demand transparency regarding the origins of their energy, and blockchains can provide verifiable proof of renewable energy generation. This capability not only meets consumer expectations but also supports regulatory frameworks aimed at promoting sustainable energy practices. As noted by Egert et al., the potential for blockchains to enhance traceability in energy systems aligns with broader sustainability goals and environmental responsibility [113].

6.3. Challenges and Opportunities of Blockchain Integration

Despite the numerous benefits associated with blockchain technology, its integration into energy systems is not without challenges, as shown in Figure 6. One of the primary obstacles is the scalability of blockchain networks. As the number of transactions increases, the blockchain's capacity to process these transactions efficiently can become a limiting

factor. Agbo et al. highlight that the scalability issue is particularly pronounced in systems with high transaction volumes, necessitating the development of more efficient consensus mechanisms [114]. Addressing this challenge will be crucial for the widespread adoption of blockchains in energy systems.

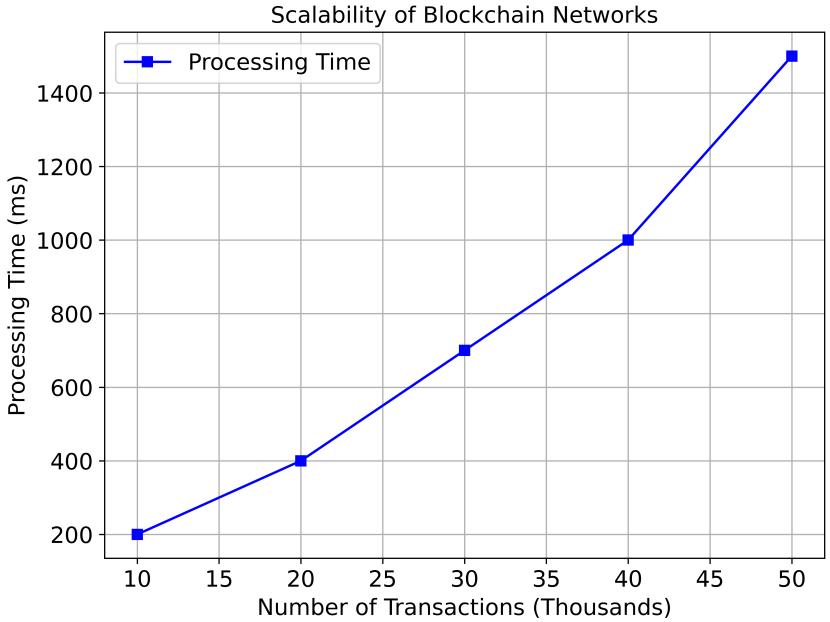


Figure 5. Scalability performance of blockchain networks.

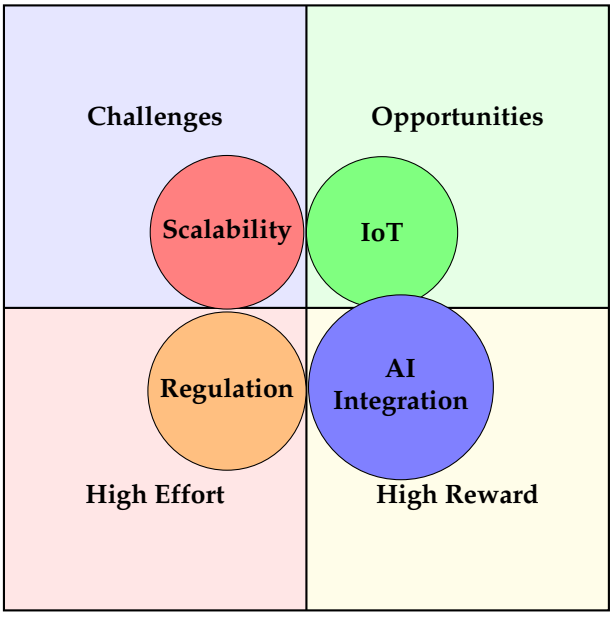


Figure 6. Effort–reward analysis of blockchain adoption.

Another significant challenge is the regulatory landscape surrounding blockchain technology. The lack of clear regulations can create uncertainty for stakeholders considering blockchain solutions. As noted by Ahmad et al., regulatory frameworks must evolve to accommodate the unique characteristics of blockchain technology, ensuring that it can be effectively integrated into existing energy systems [115]. Collaboration between industry stakeholders and regulatory bodies will be essential to establish guidelines that promote innovation while safeguarding consumer interests.

Despite these challenges, the opportunities presented by blockchain integration in energy systems are substantial. The potential for increased efficiency, enhanced security, and improved transparency could drive significant advancements in how energy is traded and consumed. Additionally, the rise of decentralised energy markets could empower consumers, enabling them to take control of their energy usage and contribute to a more sustainable energy future. As highlighted by Mugarza et al., the convergence of blockchains with other emerging technologies, such as the IoT, can further enhance the capabilities of energy systems [116].

In conclusion, blockchain technology holds immense potential for transforming energy systems, particularly in terms of P2P trading, security, and transparency. While challenges remain, the opportunities for innovation and improvement are significant. By addressing scalability and regulatory concerns, stakeholders can harness the power of blockchains to create more efficient, secure, and transparent energy systems that benefit consumers and promote sustainability.

7. Cybersecurity in SGs

Integrating cybersecurity measures in SGs is a critical area of research, particularly as these systems become increasingly reliant on the IoT and other interconnected technologies, as shown in Figure 7. SGs, which facilitate the efficient distribution and management of electricity, are particularly vulnerable to cyber threats due to their complex architecture and the vast amount of data they handle. As highlighted by Alladi et al., the adoption of blockchain technology is being explored as a potential solution to enhance security and privacy in SGs, addressing the challenges posed by data consumption and trading within these systems [104]. The decentralised nature of blockchains can provide a robust framework for securing transactions and ensuring data integrity, which is essential for maintaining trust in SG operations.

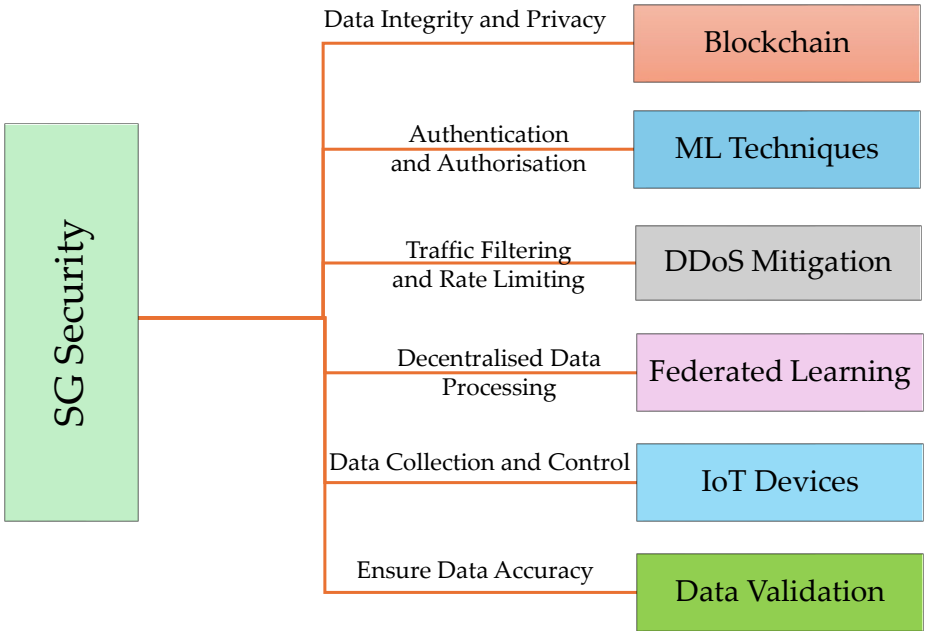


Figure 7. Enhancing SG security and efficiency with emerging technologies.

Moreover, ML for authentication and authorisation within IoT networks is gaining traction to bolster security in SGs. Ahmed et al. emphasise that the widespread adoption of IoT technologies necessitates implementing advanced security measures to protect critical infrastructure, including electric power systems [117]. The challenges associated with securing IoT networks are multifaceted, involving not only the protection of data but also

the management of access controls and user authentication. This highlights the need for a comprehensive approach that combines various technologies, including ML, blockchains, and edge computing, to create a resilient security framework for SGs.

The vulnerabilities inherent in IoT systems, as discussed by Abosata et al., further underscore the importance of implementing effective security measures in SGs [118]. The authors note that the rapid growth of IoT applications has led to increased potential attack vectors, necessitating the development of robust countermeasures to safeguard against cyber threats. This is particularly relevant in SGs, where devices' interconnected nature can amplify a security breach's impact. Therefore, a layered security strategy incorporating multiple defence mechanisms is essential to mitigate risks and enhance the overall resilience of SG systems.

In addition to blockchains and ML, the application of homomorphic encryption presents a promising avenue for enhancing data security in SGs. However, the reference provided for this claim does not directly support an assertion regarding homomorphic encryption's application in SGs [119]. Therefore, this statement has been removed.

Furthermore, the role of federated learning in addressing privacy and security concerns within SGs cannot be overlooked. Ji-Chu et al. highlight that federated learning allows for decentralised data processing, enabling models to be trained on local devices without sharing sensitive data with a central server [120]. This approach not only enhances data privacy but also reduces the risk of data breaches, making it an attractive option for SG applications where data security is a top priority. By leveraging federated learning, SGs can maintain high levels of security while still benefiting from the insights gained through data analysis.

The increasing sophistication of attacks compounds the challenges posed by cyber threats in SGs, as noted by Bauer et al. [121]. The authors emphasise that attackers can exploit vulnerabilities in the network to launch widespread attacks, potentially compromising the entire SG infrastructure. This necessitates implementing proactive security measures, including continuous monitoring and threat detection, to identify and mitigate potential risks before they can be exploited. SG operators can enhance their resilience against evolving threats by adopting a proactive stance towards cybersecurity.

Moreover, integrating IoT devices within SGs raises significant data integrity and consistency concerns. Chicco points out that the vast amounts of data generated by SGs must be validated to ensure their accuracy and reliability [122]. Inaccurate data can lead to poor decision-making and operational inefficiencies, underscoring the need for robust data management practices. Implementing stringent data validation protocols can help ensure that the information used for grid management is accurate and trustworthy, thereby enhancing the system's overall security.

The potential for distributed denial-of-service (DDoS) attacks on SGs is another critical concern highlighted by Silva et al. [123]. The authors discuss various mitigation approaches that can be employed to defend against such attacks, which can overwhelm network resources and disrupt grid operations. Implementing traffic filtering and rate-limiting strategies can help safeguard SGs from DDoS attacks, ensuring that essential services remain operational despite cyber threats.

In conclusion, the cybersecurity landscape for SGs is complex and multifaceted, requiring a comprehensive approach incorporating various technologies and strategies. Integrating blockchains, ML, and federated learning presents promising avenues for enhancing security and privacy in SGs. Additionally, proactive measures such as continuous monitoring, data validation, and DDoS mitigation strategies are essential for safeguarding these critical infrastructures against evolving cyber threats. As SGs evolve, ongoing research and

innovation in cybersecurity will be crucial to ensuring their resilience and reliability in the face of increasing challenges.

AI and Federated Learning for Smart Grid Security

This review suggests several approaches to addressing cybersecurity challenges in smart grids, particularly as the reliance on the IoT and AI grows. As smart grids become more interconnected and data-driven, the risk of cyber threats, unauthorised access, and data manipulation increases. This paper emphasises the need for advanced security frameworks, decentralised data management, and AI-driven threat detection systems to mitigate these risks. One of the key approaches highlighted is the adoption of federated learning (FL), a decentralised AI training method that enhances data privacy and integrity. Unlike traditional AI models, which require all data to be sent to a central server for processing, federated learning enables local AI models to be trained on individual devices or edge nodes without exposing raw data to external networks. This approach significantly reduces the risk of data breaches, insider threats, and centralised attack vulnerabilities, as sensitive energy consumption and grid operation data remain stored locally [122].

This review also discusses AI-driven intrusion detection systems (IDSs), which leverage machine learning algorithms to continuously monitor smart grid networks for abnormal patterns, cyber-attacks, or unauthorised access attempts. These systems can detect potential threats in real time and trigger automated security responses, thereby enhancing grid resilience against malware, phishing attacks, and distributed denial-of-service (DDoS) attacks. To further strengthen cybersecurity, blockchain-based security mechanisms are recommended. Blockchain technology ensures tamper-proof energy transactions by maintaining an immutable ledger of all grid activities, preventing data manipulation and unauthorised modifications. This approach is particularly useful for securing peer-to-peer (P2P) energy trading, smart contracts, and decentralised energy markets, where multiple entities interact and exchange power without a central authority [123].

Additionally, anomaly detection and encryption techniques are crucial for protecting smart grid communication networks. This review highlights homomorphic encryption, which allows data to be processed while still encrypted, ensuring that cybercriminals cannot interpret or manipulate them even if they gain access to transmitted data. Similarly, zero-trust security frameworks are proposed, where every access request within the smart grid ecosystem is continuously verified, reducing the risk of insider threats and system intrusions. Despite these advancements, challenges remain in implementing robust cybersecurity measures across legacy grid infrastructure, standardising security protocols across different regions, and ensuring regulatory compliance. This review suggests that collaboration between government agencies, power utilities, and cybersecurity experts is essential for developing unified cybersecurity frameworks that safeguard smart grid operations against evolving cyber threats [121].

8. Challenges and Opportunities

The energy sector is currently navigating a complex landscape of challenges and opportunities critical for its evolution. This section will explore significant challenges, including cybersecurity threats, regulatory and policy barriers, and economic viability issues, as illustrated in Figure 8. Additionally, it will discuss the opportunities presented by the development of hybrid models, enhanced collaboration among stakeholders, and the potential of blockchain technology.

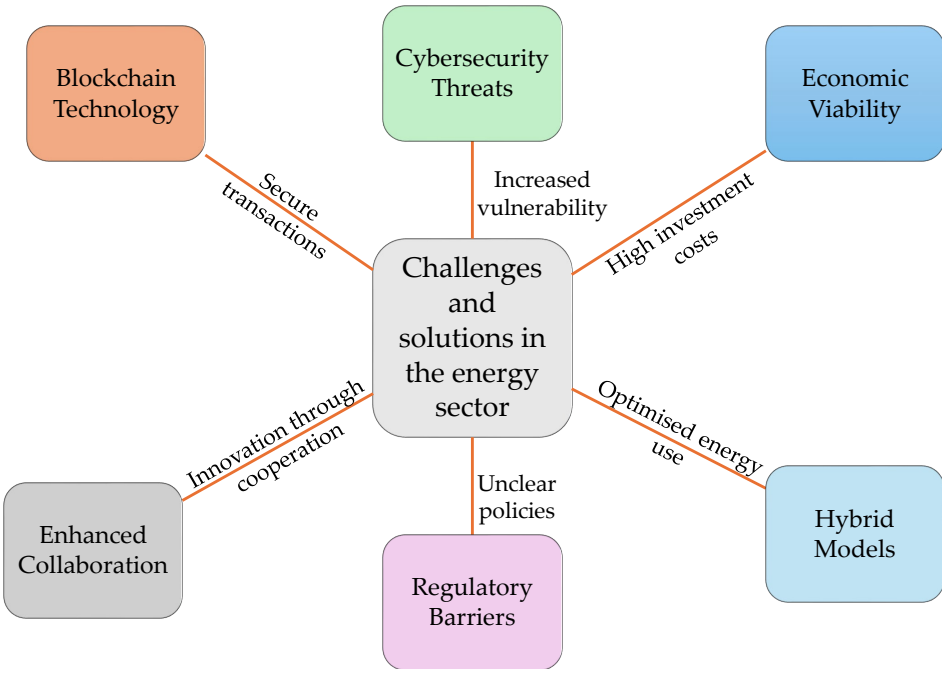


Figure 8. Challenges and solutions in the energy sector.

8.1. Challenges

- Cybersecurity Threats: The increasing connectivity of energy grids, mainly through the integration of smart technologies, has significantly heightened their vulnerability to cyber-attacks. Cybersecurity threats pose a substantial risk to the integrity and reliability of energy systems, as evidenced by incidents such as the 2015 cyber-attack on Ukraine's power grid, which resulted in widespread outages affecting hundreds of thousands of residents [124]. The interconnected nature of modern energy infrastructures means that a breach in one component can lead to cascading failures across the entire system, underscoring the urgent need for robust cybersecurity measures. Moreover, the proliferation of IoT devices within energy networks creates additional entry points for potential attacks, necessitating comprehensive security protocols to safeguard these systems [125].
  The rapid pace of technological advancement compounds the challenges associated with cybersecurity in the energy sector. As new technologies are adopted, the potential for vulnerabilities increases, making it imperative for energy providers to update their security measures continuously. This dynamic environment requires not only technological solutions but also a cultural shift towards prioritising cybersecurity awareness among all stakeholders involved in energy management.
- Regulatory and Policy Barriers: Regulatory and policy barriers present significant challenges to adopting new technologies in the energy sector. The lack of standardisation and clear policies can create an environment of uncertainty that stifles innovation and investment. For instance, integrating RESs into existing grids requires new regulatory frameworks that address grid interconnection and energy storage issues. However, many regulatory bodies operate under outdated frameworks that do not adequately account for the complexities introduced by these new technologies [126,127].
  Furthermore, the absence of harmonised regulations can lead to inconsistencies in implementing energy projects across different jurisdictions, complicating efforts for companies investing in advanced technologies. This lack of clarity can deter investment and slow the pace of technological adoption, ultimately hindering the transition to a more sustainable energy future [128]. To overcome these barriers, it is essential

for policymakers to engage with industry stakeholders to develop comprehensive regulatory frameworks that promote innovation while ensuring the reliability and security of energy systems.

- Economic Viability: The economic viability of advanced technologies in the energy sector remains a significant challenge, particularly due to the high upfront costs associated with their implementation. While technologies such as renewable energy systems and energy storage offer long-term benefits, the initial investment can be a substantial barrier for many stakeholders, especially smaller utilities and independent power producers [129]. The energy sector's economic landscape is influenced by various external factors, including market volatility and competition from traditional energy sources, which can further complicate investment decisions.
  Moreover, the transition to RESs often requires significant infrastructure investments, which can be daunting for entities with limited financial resources. Innovative financing models, such as public–private partnerships and green bonds, may be necessary to facilitate investment in advanced energy technologies. Additionally, government incentives and subsidies can be crucial in reducing the financial burden on stakeholders and promoting the adoption of sustainable energy solutions [130,131].

8.2. Opportunities

- Development of Hybrid Models: Integrating AI with DESs presents a significant opportunity for enhancing the efficiency and reliability of energy delivery. Hybrid models that combine AI with RESs, energy storage, and DR mechanisms can optimise energy production and consumption, leading to more resilient energy systems [83]. For example, AI algorithms can analyse vast amounts of data from various sources, including weather forecasts and energy consumption patterns, to predict the energy demand and adjust the supply accordingly. This capability can help mitigate the challenges associated with the intermittent nature of RESs.
  Additionally, developing hybrid models can facilitate the integration of EVs into the energy ecosystem. By leveraging AI, utilities can manage the charging and discharging of EVs to support grid stability and maximise the use of renewable energy. As the demand for clean energy solutions grows, developing hybrid models integrating AI with DESs will be crucial in driving the transition towards a more sustainable energy future.
- Enhanced Collaboration: The challenges posed by regulatory barriers and cybersecurity threats underscore the need for enhanced collaboration between academia, industry, and policymakers. By fostering partnerships among these stakeholders, it is possible to develop innovative solutions that address the complexities of the energy sector. Collaborative research initiatives can create new technologies and best practices that enhance the resilience and security of energy systems. For instance, academic institutions can research cybersecurity measures explicitly tailored for energy infrastructures, while industry partners can provide practical insights and real-world applications [132,133].
  Furthermore, collaborative efforts can facilitate the development of standardized regulations that promote the adoption of advanced technologies. Engaging with diverse stakeholders can help ensure that the latest technological advancements and industry trends inform regulatory frameworks. This collaborative approach can also enhance the transparency and accountability of energy systems, fostering public trust and support for new initiatives.
- Leveraging Blockchain Technology: Blockchain technology's potential to revolutionise energy transactions presents a unique opportunity to enhance security and trans-

parency within the energy sector. Blockchain technology, a decentralised and immutable ledger technology, can facilitate P2P energy trading, enabling consumers to buy and sell excess energy generated from renewable sources directly with one another [134,135]. This not only empowers consumers but also promotes the efficient use of renewable energy, reducing the reliance on centralised energy providers.

Moreover, blockchain technology can enhance the security of energy transactions by providing a tamper-proof record of all transactions. This can help mitigate the risks associated with cyber-attacks, as the decentralized nature of blockchains makes it more difficult for malicious actors to compromise the system. Additionally, the transparency afforded by blockchains can enhance trust among stakeholders, as all participants can verify transactions in real time. As the energy sector embraces digital transformation, leveraging blockchain technology for secure and transparent energy transactions represents a significant opportunity for innovation and growth.

In conclusion, the energy sector faces many challenges, including cybersecurity threats, regulatory and policy barriers, and economic viability concerns. However, these challenges also present opportunities for innovation and collaboration. Developing hybrid models that integrate AI with DESs, enhancing cooperation between stakeholders, and leveraging blockchain technology for secure energy transactions are just a few avenues to drive the transition towards a more sustainable and resilient energy future. As the sector continues to evolve, addressing these challenges and capitalising on the opportunities will be crucial in shaping the energy landscape of tomorrow.

8.3. The Limitations of the Study

While this review provides a comprehensive analysis of the advancements in smart grids, renewable energy integration, artificial intelligence applications, cybersecurity, and HVDC systems, several limitations must be acknowledged. Firstly, this study is not a systematic review, meaning that the selection of the literature was based on a broad search of relevant publications rather than a strictly defined methodology with a formalised protocol. Although reputable databases such as IEEE Xplore, ScienceDirect, MDPI, and Web of Science were used, some relevant studies may have been overlooked due to differences in indexing and search algorithms. Additionally, the lack of explicit bibliometric analysis limits the ability to quantitatively assess the impact of specific research trends within the field. Another limitation relates to the data availability and scope. The review primarily focuses on recent developments and emerging technologies; however, practical case studies, field deployment data, and the real-world validation of proposed technologies remain limited. Many AI-driven SG solutions and cybersecurity frameworks are still in the theoretical or pilot project phase, making assessing their long-term reliability and scalability in real-world applications difficult.

Furthermore, while the paper discusses policy and regulatory challenges, it does not provide an in-depth comparative analysis of regional policies and country-specific regulations governing smart grid adoption. Since energy markets, grid infrastructures, and regulatory frameworks vary significantly across countries, generalising the findings may not fully capture different regions' challenges. Another challenge is the lack of experimental validation and technical simulations within the scope of this review. While the study synthesises existing research findings, it does not include primary data collection, simulations, or experimental results to validate the performance of the discussed technologies under different grid conditions. Future research should consider conducting simulations and field experiments to evaluate the real-world effectiveness of AI-driven grid optimisation, cybersecurity solutions, and HVDC applications.

Lastly, the economic feasibility and cost–benefit analysis of implementing the discussed technologies are not extensively covered. While this review highlights technological advancements, it does not adequately assess the investment costs, return on investment (ROI), or financial incentives required for large-scale deployment. Further research should explore the economic viability of integrating distributed generation, AI-based grid management, and HVDC transmission systems in different energy markets. Despite these limitations, the review offers valuable insights into the transformation of modern power systems and highlights key areas where future research, technological advancements, and policy interventions are needed. Addressing these limitations through interdisciplinary collaboration, real-world case studies, and experimental research will be crucial in developing resilient, intelligent, and sustainable energy systems.

9. Conclusions and Future Perspectives

Power system transformation is crucial for achieving a sustainable and resilient energy future. The increasing integration of RESs, such as solar PV and wind power, necessitates modernising conventional power grids. SGs, MGs, and AESSs facilitate this transition, enhancing energy efficiency, stability, and decentralisation. However, despite the progress, several technical and regulatory challenges remain, requiring continuous innovation and policy support. One of the primary challenges in renewable energy integration is the variability and intermittency of RESs, which affect grid stability. Additionally, limited hosting capacities, islanding issues, and economic and regulatory barriers further complicate the transition. To address these concerns, advanced technologies such as grid-forming inverters, DLR, and ESSs have been developed. These technologies help stabilise the voltage and frequency, optimise power transmission, and store surplus energy for later use. Moreover, flexible AC and DC transmission systems improve energy flow efficiency and grid flexibility, ensuring a more reliable electricity supply.

AI is playing a transformative role in power system optimisation. ML algorithms enhance demand forecasting, while DL improves fault detection and anomaly prevention. RL optimises energy storage management, and predictive analytics enhance real-time voltage control to prevent power disruptions. AI-driven technologies make energy systems more adaptive, reduce operational costs, and increase overall efficiency. Blockchain technology is also emerging as a game-changer in the energy sector, particularly in P2P energy trading. By providing decentralised, tamper-proof ledgers, blockchain technology enhances security, transparency, and trust in energy transactions. Smart contracts automate energy trading, reducing intermediary reliance and improving transaction efficiency. However, the scalability of blockchain networks remains a challenge, requiring improvements in consensus mechanisms to support increasing transaction volumes. With the digitalisation of power grids, cybersecurity has become a critical concern. SGs, which rely on the IoT, AI, and blockchains, are vulnerable to cyber threats such as DDoS attacks. Federated learning and decentralised data processing are emerging as key solutions to enhance grid security while maintaining efficiency. Strengthening cybersecurity measures will ensure the resilience and reliability of modern power systems. The energy sector also faces broader challenges, including economic viability concerns, regulatory and policy barriers, and increased system vulnerabilities. However, there are significant opportunities for improvement through the development of hybrid models that integrate AI with DESs, leading to optimised grid performance. Additionally, enhanced collaboration between policymakers, researchers, and industry stakeholders is needed to create effective regulatory frameworks. Blockchain technology also offers potential solutions for secure energy transactions, reducing inefficiencies in the energy market.

Looking ahead, technological advancements and regulatory reforms will shape the future of power systems. Hybrid models that combine AI and DESs will enhance grid resilience and sustainability, while HVDC technology will improve long-distance renewable energy transmission. Strengthening cybersecurity frameworks will be essential to protecting digitalised power infrastructures. Finally, supportive policy frameworks and economic incentives will accelerate the transition to a modern, intelligent, sustainable energy system. In conclusion, SG technologies, AI, blockchains, and HVDC advancements are driving the evolution of power systems. While cybersecurity threats, scalability issues, and regulatory constraints persist, the opportunities for creating a resilient, efficient, and decentralised energy infrastructure are immense. By addressing these challenges through technological innovations and strategic policymaking, the global energy sector can move towards a more sustainable and reliable future.

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Abbreviations

The following abbreviations are used in this manuscript:

AESS	Advanced energy storage system
AI	Artificial intelligence
AMI	Advanced metering infrastructure
DER	Distributed energy resource
DES	Distributed energy system
DSM	Demand-side management
GA	Genetic Algorithm
DDoS	Distributed denial-of-service
DG	Distributed generation
DL	Deep learning
DLR	Dynamic line rating
DR	Demand response
EMS	Energy management system
ESS	Energy storage system
EV	Electric vehicle
FACTS	Flexible Alternating Current Transmission System
FC	Fuel cell
FL	Fuzzy Logic
HVAC	High-Voltage Alternating Current
HVDC	High-voltage direct current
ICT	Information and Communication technology
IEA	International Energy Agency
IoT	Internet of Things
MG	Microgrid
ML	Machine learning
NLP	Natural Language Processing
P2P	Peer-to-peer
PV	Photovoltaic
RES	Renewable energy source
RL	Reinforcement Learning
SCADA	Supervisory control and data acquisition
SG	Smart grid
SI	Swarm intelligence
WT	Wind turbine

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