

Sustainability in Power Systems: A Review of Grid Reliability, Power Quality, Loss Reduction, and Intelligent Monitoring

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Abstract

Sustainable power systems are often discussed mainly in terms of renewable-energy adoption, yet cleaner generation alone does not guarantee reliable, efficient, and high-quality electricity delivery. The real challenge is that grid reliability, power quality, loss reduction, and intelligent monitoring are still frequently treated as separate technical issues, even though they jointly determine whether a power system can operate sustainably in practice. This review adopted a structured literature-review approach to synthesize current knowledge on sustainability in power systems. A total of 80 papers were initially identified from major academic sources, including Google Scholar, Elsevier/ScienceDirect, SpringerLink, and MDPI, using keywords related to reliability, power quality, technical losses, intelligent monitoring, and renewable integration. After screening for relevance and scope, 56 references published between 2021 and 2026 were retained and thematically analyzed. The review shows that sustainability in power systems has evolved into a multidimensional concept that extends beyond decarbonization to include resilience, voltage and frequency stability, reduced technical losses, efficient network performance, digital monitoring, and coordinated renewable integration. The findings further reveal that intelligent forecasting, smart-grid tools, asset monitoring, and storage coordination are becoming essential for sustainable operation, while key gaps remain in integrated assessment, data quality, implementation realism, and life-cycle awareness. In conclusion, sustainable power systems should be understood not merely as low-carbon systems, but as systems that are reliable, efficient, resilient, and intelligently managed. Future progress will depend on more integrated and context-aware approaches that connect technical performance with long-term sustainability outcomes.

Keyword: Sustainable power systems, grid reliability, power quality, technical losses, renewable energy integration

1. Introduction

Power systems are under growing pressure to become sustainable, but sustainability in this context can no longer be reduced to the simple addition of renewable-energy sources. A modern power system is only sustainable when it can deliver electricity reliably, maintain acceptable power quality, limit avoidable technical losses, and use intelligent monitoring to support stable and efficient operation. Recent review studies have shown that the transition toward renewable-rich grids is simultaneously increasing the importance of resilience, advanced monitoring, and coordinated control, because cleaner generation alone does not guarantee dependable service or efficient network performance (Mohanty et al., 2024; Cavus, 2025). In the same direction, contemporary work on power quality and electricity-loss reduction shows that poor waveform conditions, feeder inefficiencies, and under-monitored assets can quietly undermine both energy efficiency and long-term infrastructure performance, even in systems that are expanding their renewable share (He et al., 2025; Nişte et al., 2025).

The problem, therefore, is not the lack of research on individual power-system issues, but the way these issues are still too often treated in isolation. Reliability studies frequently emphasize continuity of supply without adequately connecting it to power quality, loss reduction, and digital observability. Power-quality studies often focus on mitigation devices and waveform improvement without sufficiently linking them to wider sustainability goals. Loss-reduction studies correctly frame energy dissipation as an efficiency problem, yet they do not always connect technical losses to resilience, asset stress, and long-term system viability. At the same time, the rapid penetration of inverter-based renewable resources is intensifying voltage-control, stability, and monitoring requirements, which means that fragmented analysis is becoming less defensible in both strong and weak grids (Ghanbari & Jiang, 2025; Sadiq et al., 2024; Kumar et al., 2025). Put differently, a grid cannot be meaningfully described as sustainable if it is cleaner but still unreliable, if it is digitalized but still wasteful, or if it has lower emissions but poorer service quality and weaker operational awareness (He et al., 2025; Nişte et al., 2025).

This review is therefore motivated by the need for a more integrated understanding of sustainability in power systems. It argues that grid reliability, power quality, loss reduction, and intelligent monitoring should be treated not as parallel technical topics, but as mutually reinforcing conditions for sustainable power delivery. On that basis, the review synthesizes recent literature to examine how these four dimensions shape sustainable power-system performance, where the strongest points of convergence now lie, and what gaps remain for future research and practical implementation. By doing so, the paper aims to reposition sustainability in power systems as an operational and systems-level question, not merely an environmental one (Mohanty et al., 2024; Cavus, 2025; Ghanbari & Jiang, 2025).

2. Methodology

This review adopted a structured literature-review approach to examine sustainability in power systems, with emphasis on grid reliability, power quality, loss reduction, and intelligent monitoring. The methodology was designed to ensure that only studies directly relevant to the review theme were retained for detailed synthesis.

The literature search was conducted using major academic databases and indexing platforms, including Google Scholar, Elsevier/ScienceDirect, SpringerLink and MDPI relevant to electrical power and energy systems. These sources were selected to provide broad coverage of peer-reviewed journal articles, review papers, and technically relevant studies on sustainable power-system operation.

The search process focused on combinations of keywords related to the review topic, such as sustainability in power systems, grid reliability, power quality, technical losses, loss reduction, intelligent monitoring, smart grid, renewable energy integration, energy efficiency, and power-system resilience. Additional relevant studies were identified through backward referencing from selected papers and through related-article suggestions within database platforms.

A total of 80 papers were initially selected during the search stage. These papers were screened based on title, abstract, scope, and thematic relevance to the review objectives. After screening, 56 references ranging from 2021 to 2026 were retained and used in the final review, while the remaining studies were excluded because they were found to be out of scope, insufficiently aligned with the central review themes, too narrow in application, or not directly relevant to sustainable power-system analysis.

The inclusion process gave priority to studies that addressed one or more of the following areas: power-system reliability, voltage and power-quality performance, technical losses and network efficiency, renewable energy integration, smart-grid technologies, intelligent monitoring, forecasting, digital control, and sustainability-oriented grid management. Review papers were particularly useful for identifying broad trends and conceptual developments, while selected case studies and application-based papers were included to provide practical insight and contextual grounding.

The final set of 56 references was then examined through thematic synthesis. The selected literature was organized into major sections covering: overview of sustainability in power systems; reliability, stability, and power quality in sustainable grid operation; technical losses, energy efficiency, and network performance; intelligent monitoring, forecasting, and smart control approaches; renewable energy integration and sustainability challenges; and regional trends, research gaps, and future directions. This thematic organization made it possible to compare findings across studies and identify areas of convergence, emerging concerns, and unresolved issues within the literature. Figure 1 shows the distribution per year

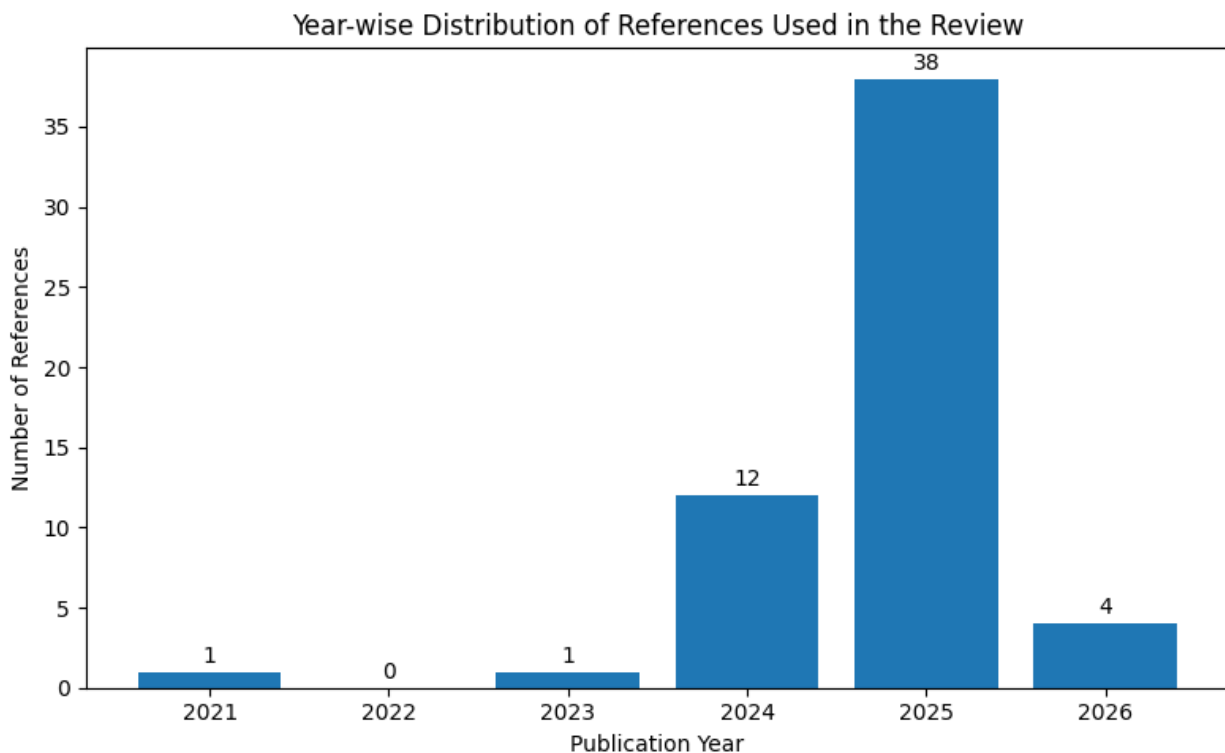


Figure 1. Year-wise distribution of the 56 references selected for the review.

3. Review of Sustainability in Power Systems

3.1 Overview of Sustainability in Power Systems

Sustainability in power systems is now understood as more than the simple inclusion of renewable energy in electricity supply. Recent review studies describe it as a broader objective that combines environmental responsibility with reliable operation, efficient energy delivery, resilience to disturbances, and the ability of the grid to adapt to changing demand and generation conditions (Mohanty et al., 2024; Cavus et al., 2025).

This wider meaning is important because a power system may contain low-carbon generation and still perform poorly if it suffers frequent outages, large technical losses, weak voltage regulation, or poor recovery after disturbances. For that reason, current literature increasingly treats sustainability as a systems issue involving generation, transmission, distribution, storage, monitoring, and control rather than as a generation-only issue (Mohanty et al., 2024; Yeboah et al., 2025).

A major shift in the literature is the idea that sustainable power systems must be both cleaner and stronger. Cleaner systems reduce the environmental burden of electricity production, while stronger systems maintain acceptable service quality under normal operation and under stress. Reviews on renewable integration show that higher shares of renewable energy improve decarbonization potential, but they also increase the need for flexibility, better

coordination, storage support, and advanced grid control because variability and uncertainty can affect stability and operational security (Yeboah et al., 2025; Cavus et al., 2025).

The literature also makes a useful distinction between reliability and resilience. Reliability is often associated with the ability of the system to keep supplying electricity during expected operating conditions and routine component failures, whereas resilience focuses more on how the system prepares for, withstands, and recovers from severe disruptions such as extreme weather, cyber-physical events, or widespread contingencies (Lin et al., 2024; Ghanbari & Jiang, 2025; Rouholamini et al., 2025).

This distinction matters for sustainability because a grid that performs well only in normal conditions cannot be considered sustainable in the long term if it collapses easily under shock or takes too long to recover. Recent resilience reviews therefore place sustainable power infrastructure within a broader framework of preparedness, disturbance tolerance, restoration capability, and infrastructure hardening (Mohanty et al., 2024; Monie et al., 2025).

Another core part of sustainability in power systems is energy efficiency, especially the reduction of technical losses. Technical losses occur naturally in conductors, transformers, and other network components, but high losses represent wasted electricity, greater operational cost, and avoidable environmental burden across the supply chain. Recent reviews therefore treat loss reduction as a sustainability strategy because it increases the useful electricity delivered from the same infrastructure and reduces pressure on generation resources (Parvizi et al., 2025).

Sustainability is also linked to power quality because poor-quality electricity reduces equipment life, lowers service performance, and creates additional operational challenges for distribution networks with growing distributed generation. Recent review evidence shows that renewable-rich and DG-based networks require stronger attention to voltage regulation, harmonics, compensation methods, intelligent control, and coordinated mitigation techniques if their sustainability benefits are to be preserved in practice (Nabian Dehaghani et al., 2026).

Digitalization has become another defining part of sustainable power-system thinking. Reviews on digitization, smart grids, and intelligent technologies show that real-time data, advanced metering, forecasting, optimization, and AI-based decision support are now being treated as enablers of sustainable operation because they improve visibility, support preventive action, and help operators coordinate variable renewable resources more effectively (Awogbemi et al., 2024; Azizi et al., 2025; Cavus et al., 2025).

For this reason, sustainability in power systems should be viewed as a multidimensional engineering goal built around decarbonization, reliability, resilience, efficiency, power quality, and intelligent operation. This framing is useful for the present review because it provides a clear basis for discussing later sections on stability, losses, monitoring, forecasting, and renewable integration within one coherent power-systems perspective (Mohanty et al., 2024; Parvizi et al., 2025; Yeboah et al., 2025).

3.2 Reliability, Stability, and Power Quality in Sustainable Grid Operation

Reliability, stability, and power quality are central technical conditions for sustainable grid operation because sustainability in power systems depends not only on cleaner energy supply, but also on whether electricity is delivered continuously, securely, and within acceptable operating limits. Recent review work shows that modern power-system performance is increasingly judged by the ability of the grid to maintain service during uncertainty, preserve acceptable voltage and frequency behavior, and support recovery under stressed operating conditions, especially as renewable penetration rises and system dynamics become more complex (Anthony & Arunachalam, 2025; Kumari et al., 2025).

From a reliability perspective, sustainable grid operation requires dependable generation availability, adequate network support, and timely system response to disturbances. This is becoming more difficult in renewable-rich systems because variability in solar and wind output introduces operational uncertainty that must be balanced without compromising service continuity. In low-inertia and weakly interconnected grids, the literature now emphasizes that reliability can no longer be treated separately from dynamic performance, since reserve adequacy, dispatch flexibility, and disturbance response increasingly interact in real time (Olasoji et al., 2024; Saleem et al., 2024).

Voltage stability remains one of the clearest technical indicators of whether a grid is operating sustainably. Renewable-dominated systems are especially vulnerable to voltage instability because non-dispatchable resources can alter reactive-power balance, power-flow patterns, and the ability of the network to maintain acceptable voltage margins under changing conditions. Recent reviews therefore treat voltage-security monitoring, assessment, and corrective control as essential parts of sustainable operation rather than as narrow post-fault concerns (Anthony & Arunachalam, 2025; Dong et al., 2025).

Frequency stability has also become more prominent in sustainability discussions because the transition toward inverter-based generation reduces the number of synchronous machines that traditionally supplied physical inertia to the grid. As synchronous generation declines, the system becomes more sensitive to imbalances between generation and demand, making rate of change of frequency and post-disturbance recovery more difficult to manage. Reviews on low-inertia systems consistently show that inertia estimation, fast frequency response, and coordinated support from storage, loads, and converter-based resources are now critical for secure operation (Zhou et al., 2024; Hadavi et al., 2025).

The challenge becomes even sharper when renewable generation and electric vehicles are integrated at high levels. Recent literature notes that while these technologies support decarbonization, they also introduce new stability burdens, including bidirectional power-flow complexity, higher ramping requirements, converter interactions, and increased control dependence. Sustainable operation under these conditions depends on combining planning tools, control mechanisms, and grid-support technologies that can preserve both voltage and frequency performance under rapidly changing conditions (Saleh et al., 2025).

Power quality is equally important because a technically unstable grid can still appear available while delivering electricity that damages equipment, disrupts industrial processes,

and reduces overall system efficiency. Modern distribution networks increasingly face harmonics, flicker, voltage sags, swells, imbalance, and waveform distortion due to the proliferation of power-electronic interfaces, distributed generation, and nonlinear loads. Recent reviews therefore position power-quality mitigation as a core sustainability issue, since poor-quality supply shortens asset life, lowers consumer confidence, and reduces the useful value of delivered electricity (He et al., 2025).

Smart-grid deployment strengthens this discussion because reliability and power quality are no longer maintained only through passive infrastructure upgrades. Current survey evidence shows that digital monitoring, interoperability, adaptive protection, and coordinated control are increasingly required to manage renewable integration and preserve service quality. This means that sustainable grid operation depends not only on physical assets, but also on the communication and control architecture that supports situational awareness and corrective action (Powell et al., 2024).

Recent case-based frequency-stability studies also show that storage-supported inverter control can improve post-disturbance performance in photovoltaic-connected grids. In one recent grid study, battery or supercapacitor support was found to improve frequency response and reduce recovery time under varying renewable penetration, reinforcing the idea that sustainable operation in modern grids requires active support resources rather than reliance on conventional inertia alone (Kahouli et al., 2025).

The broader renewable-integration literature points in the same direction. Reviews focused on renewable-resource integration in modern grids emphasize that system sustainability is constrained not just by generation availability, but by the ability of power-electronic systems, storage technologies, and smart-grid infrastructure to manage intermittency, maintain dynamic balance, and support dependable operation under real network conditions (Ayorinde et al., 2025).

For sustainable grid operation, reliability, stability, and power quality should therefore be treated as interdependent rather than isolated objectives. A grid with low emissions but frequent voltage excursions, weak frequency recovery, or degraded waveform quality cannot be described as sustainable in practical terms. The literature increasingly supports a more integrated view in which dependable supply, stable dynamic behavior, and acceptable power quality together define whether a power system can deliver electricity in a technically sustainable manner over time (Kumari et al., 2025; He et al., 2025; Zhou et al., 2024).

3.3 Technical Losses, Energy Efficiency, and Network Performance

Technical losses, energy efficiency, and network performance are tightly connected in sustainable power systems because every unit of electricity dissipated in lines, transformers, and network components represents energy that was generated but not usefully delivered to the consumer. Recent literature treats this issue as more than a narrow operational concern, since persistent losses weaken grid efficiency, raise operating cost, intensify infrastructure stress, and reduce the sustainability value of existing generation resources (Nişte et al., 2025; Malika et al., 2025).

In distribution networks, technical losses are strongly influenced by feeder length, conductor characteristics, transformer loading, poor reactive-power balance, weak voltage regulation, and suboptimal network configuration. A recent review on distribution-system planning shows that feeder architecture, the siting and sizing of distributed generation, and the placement of energy storage directly affect both present losses and long-term network efficiency, which means network planning decisions have lasting sustainability consequences rather than only short-term operational effects (Malika et al., 2025).

The sustainability importance of technical-loss reduction lies in the fact that it improves the useful output obtained from the same electrical infrastructure. A recent study focused on electricity-loss reduction frames loss minimization as an energy-efficiency priority because lower losses reduce wasted electricity, improve system economics, and support better use of generation and network assets across the grid (Nişte et al., 2025). A complementary review of loss-minimization methods also shows that power-factor correction, network reconfiguration, load balancing, and optimal placement of distributed resources remain among the most effective practical routes for reducing avoidable dissipation in distribution systems (Sadiq et al., 2024).

Network performance cannot be separated from voltage profile, because weak voltage regulation often appears alongside high losses and overloaded feeders. A recent review on voltage-regulation challenges in low-voltage distribution networks explains that the growing penetration of renewable energy sources and electric vehicles is making voltage management more difficult, especially in active networks where traditional passive design assumptions no longer hold (Licari et al., 2025). Related work on photovoltaic-energy-storage distribution systems similarly shows that voltage-regulation strategies now need to support both acceptable bus voltages and reduced network losses if modern grids are to remain efficient under high distributed-resource penetration (Dong et al., 2025).

Transformer performance is another major part of this discussion because overloaded or poorly monitored transformers do not only increase losses; they also accelerate insulation aging, reduce service life, and create localized reliability problems. Recent work on smart transformer monitoring emphasizes that efficient transformer supervision is necessary for early fault detection, condition tracking, and better operational management, all of which contribute to improved network efficiency and safer asset utilization (Nkinyam et al., 2025).

Load-flow analysis also remains fundamental to energy-efficiency improvement because it reveals undervoltage conditions, branch overloads, and inefficient power-flow patterns before they become more severe operational problems. A recent review of load-flow methods in electric distribution networks notes that these methods are central to checking voltage limits, avoiding overload, and improving overall network effectiveness, especially in modern systems with more distributed and dynamic operating conditions (El-Fergany et al., 2025).

Electric-vehicle growth adds another layer to network-performance concerns. Recent research shows that unmanaged charging can introduce feeder congestion, voltage instability, and higher technical losses, which means energy-transition technologies can create new inefficiencies if network reinforcement and smart control do not develop at the same pace (Ebrahim et al., 2025). This reinforces the point that sustainability is not achieved simply by

adding cleaner technologies, but by ensuring that the surrounding grid can absorb them efficiently (Licari et al., 2025).

Distributed generation can improve this picture when it is properly integrated. Recent evidence from distribution-feeder studies shows that embedded generation can help relieve overloaded feeders and improve voltage conditions, but the benefit depends on technical coordination rather than indiscriminate connection. In other words, distributed generation improves sustainability when it reduces upstream loading and losses, not when it is added without regard to feeder behavior or network limits (Olabode et al., 2024; Malika et al., 2025).

There is also growing recognition that efficient networks require stronger digital coordination. Recent work on integrated network-order systems argues that modern distribution-network management increasingly depends on real-time data analysis, intelligent resource allocation, rapid fault correction, and remote monitoring, all of which help stabilize power delivery and improve operational efficiency in complex grids (Jia et al., 2024). This aligns with recent voltage-control research showing that distributed optimization can reduce losses and manage voltage violations even when measurement availability is limited, which is especially relevant in practical medium-voltage networks with uneven monitoring coverage (Lu et al., 2025).

This broader argument is reinforced by recent Nigerian case-based studies that connect network inefficiency with real operational evidence. At the distribution-substation level, Eyenubo et al. (2025) showed in the Oria Abraka 33/11 kV substation that persistent power-supply inadequacy, transformer overloading, delayed switching, high transmission losses, and pronounced voltage drops were all linked to poor technical performance. Their study further reported excessive power dissipation at peak current and prolonged restoration periods, showing that weak network performance is not only a reliability issue but also an efficiency and sustainability concern. This is important because it grounds the general review literature in an actual feeder environment where overloaded conductors, unstable voltage conditions, and power losses directly limit the useful energy delivered to consumers (Eyenubo et al., 2025).

A related insight emerges from industrial monitoring studies, where energy efficiency is increasingly tied to operational visibility. In a conveyor telemetry study, Otuagoma et al. (2025) showed that integrating current, temperature, vibration, and speed sensors with PLCs, VFDs, and a real-time visualization dashboard improved predictive maintenance performance and reduced monthly maintenance cost by 60%. The study detected rising current, increasing vibration, and falling conveyor speed before major downtime occurred, demonstrating that real-time condition monitoring can reduce hidden inefficiencies and extend equipment life. Although this work was carried out in a manufacturing environment, the implication for power systems is clear: sustainability improves when technical stress is detected early and corrected before it develops into greater energy loss, service interruption, or component damage (Otuagoma et al., 2025).

The same logic applies to low-cost sensing and quality assurance in broader energy systems. Obuseh et al. (2025) developed an Arduino- and MQ2-based fuel adulteration detection and

alert system capable of identifying contaminated fuel samples in real time within 2–7 seconds. While this study focused on fuel-quality monitoring rather than electrical feeders, it still contributes conceptually to this section because it shows how embedded sensing, rapid detection, and low-cost instrumentation can improve system efficiency by preventing poor-quality inputs from degrading operational performance. In sustainable network thinking, this supports the wider position that efficient systems depend not only on infrastructure design but also on measurement, verification, and early warning mechanisms that reduce waste and improve decision-making (Obuseh et al., 2025).

Data-driven modeling studies also strengthen this perspective. Sada et al. (2022) demonstrated that neural-network parameter selection significantly affected prediction accuracy in machining-performance estimation, showing that model structure plays an important role in engineering efficiency and performance prediction. Although the paper was not written directly for power networks, its methodological relevance is strong because modern grid-loss estimation, load behavior analysis, anomaly detection, and predictive maintenance increasingly rely on similar intelligent modeling principles. This means that network performance is being shaped not only by conductors, transformers, and loads, but also by the quality of the predictive tools used to interpret operating data and guide intervention (Sada et al., 2022).

Technical losses, energy efficiency, and network performance should therefore be treated as core sustainability variables in power-system analysis. A network with persistent feeder losses, overloaded transformers, poor voltage control, and weak operational visibility cannot be regarded as sustainable even if cleaner generation is available on the supply side. Current literature points instead toward a more integrated view in which planning, voltage regulation, loss minimization, asset monitoring, and active network control work together to improve how much useful electricity the grid delivers, how securely it delivers it, and how efficiently it uses its infrastructure over time (Nişte et al., 2025; Sadiq et al., 2024; El-Fergany et al., 2025).

3.5 Renewable Energy Integration and Sustainability Challenges in Power Systems

Renewable energy integration has become one of the defining pathways for sustainable power-system development because it reduces dependence on fossil-based electricity and supports long-term decarbonization goals. Current review literature, however, shows that the sustainability value of renewable integration depends not only on adding solar, wind, or other distributed resources, but on whether the grid can accommodate them without undermining reliability, control, and service quality (Saxena et al., 2024; Ayorinde et al., 2025).

A major challenge is the variability and uncertainty of renewable output. Because solar and wind generation fluctuate with weather and time of day, their large-scale integration complicates dispatch, reserve management, and real-time balancing. Recent reviews note that this variability affects planning across generation, transmission, storage, and flexibility resources, making renewable integration a system-wide coordination problem rather than a generation-side upgrade alone (Barrera-Singaña et al., 2025; Cheng et al., 2025). This planning difficulty becomes more evident in localized power systems where irregular demand patterns already exist before renewable penetration is increased. In such systems, accurate

short-term forecasting becomes essential for coordinating renewable generation, storage dispatch, and transformer loading. In the Oleh power-system study, a hybrid ANN-PSO forecasting model achieved stronger predictive performance than standalone approaches and was shown to support real-time scheduling, transformer tap optimization, and energy management, indicating that intelligent forecasting is becoming an important operational requirement for sustainable renewable integration rather than an optional add-on (Eyenubo et al., 2025).

The transition toward inverter-based renewable resources also changes grid behavior at a fundamental level. Unlike conventional synchronous generators, inverter-based resources do not inherently contribute physical inertia, which means high renewable penetration can weaken frequency response, complicate voltage support, and reduce system strength if compensating measures are not in place. Recent review work therefore treats the integration of inverter-based resources as both a sustainability opportunity and a control challenge that requires new grid-support technologies and operating frameworks (Mirza et al., 2026; Khan et al., 2026).

Another recurring issue is protection and power-quality coordination in active networks. Distributed renewable generation can alter fault-current levels, reverse conventional power-flow assumptions, and introduce harmonics or local voltage excursions, especially in distribution systems not originally designed for bidirectional flows. Review studies on distributed generation and smart-grid transition therefore emphasize that renewable integration must be accompanied by adaptive protection, stronger monitoring, and revised technical standards if its sustainability benefits are to be realized in practice (Saxena et al., 2024; Ohanu et al., 2024).

Energy storage has emerged as one of the most important enablers for addressing these challenges. Recent reviews show that battery energy storage systems help smooth renewable variability, improve reliability, support frequency and voltage control, and increase the usable share of variable generation in the grid. At the same time, storage integration introduces its own sustainability considerations, including cost, control complexity, battery management requirements, and environmental trade-offs across storage technologies (Ahmad et al., 2025; Malik et al., 2025). This concern is reinforced by battery-comparison evidence from a recent experimental study, which showed that deep-cycle batteries sustained longer discharge duration than regular starting-lighting-ignition batteries, with an average discharge period of about 20 hours compared with 15.1 hours for the regular battery, even though the regular battery produced slightly higher output power under low-resistance loading conditions (Ilori et al., 2025). That result is important for renewable integration because storage sustainability is not only about having a battery present in the system, but also about matching battery type to operating profile, discharge depth, and expected service duration in off-grid and hybrid renewable applications (Ilori et al., 2025).

Hybrid and distributed energy-system architectures are also gaining attention because they combine multiple resources in ways that improve flexibility and reduce dependence on a single intermittent source. Recent reviews argue that distributed and hybrid systems can strengthen resilience and local supply adequacy, but they still require careful coordination of control, resource sizing, conversion technology, and operational strategy to avoid shifting

instability from the central grid to the local network level (Cheng et al., 2025; Samala et al., 2025). In practice, this coordination challenge is closely linked to forecasting and storage behavior. The Oleh ANN-PSO study showed that weekday and weekend load patterns can differ significantly and that sensitivity to weather-linked variables such as cooling degree days materially affects forecast quality, suggesting that hybrid renewable systems in localized grids need demand-aware operational control if they are to remain sustainable and efficient (Eyenubo et al., 2025).

Grid codes and compliance frameworks are becoming increasingly important under high renewable penetration. As renewable and inverter-based resources grow, recent literature stresses that technical standards must evolve to define fault ride-through behavior, voltage and frequency support obligations, testing methods, and grid-forming capability requirements. Without these frameworks, renewable deployment can expand faster than the technical rules needed to keep the grid secure and interoperable (Khan et al., 2026; Rajendran et al., 2025).

There is also a growing link between renewable integration and transport electrification. Reviews of renewable-powered charging systems indicate that coupling renewable generation with electric-vehicle infrastructure can support low-carbon mobility, but it also adds new operational burdens involving charging coordination, storage needs, and local network stress. This means sustainable integration increasingly depends on sector coupling, not just on power-system planning in isolation (Ramkumar et al., 2025).

This broader sustainability question becomes even more important in developing-country contexts, where renewable integration is shaped by governance quality, affordability, and implementation capacity as much as by resource availability. A recent review on decarbonization argues that sustainability cannot be reduced to emissions reduction alone, because transitions that neglect social equity, institutional coordination, and economic resilience often weaken their own long-term effectiveness (Obuseh et al., 2025). The same review further notes that one-size-fits-all transition strategies are often ineffective, especially where fragmented policy frameworks, weak monitoring systems, and limited financial safeguards constrain inclusive energy transitions (Obuseh et al., 2025).

Nigeria provides a useful example of this tension. Although the country has strong solar potential, with nearly 290 days of sunlight annually and average solar insolation ranging from about 4.0 kWh/m²/day in the southern regions to 7.0 kWh/m²/day in the northern regions, large-scale renewable integration is still constrained by affordability barriers, limited public awareness, technological gaps, and inconsistent policy support (Alele et al., 2024). Stakeholder-based evidence also suggests that market readiness, infrastructure limitations, and the need for stronger policy incentives continue to shape the practical feasibility of deeper solar deployment in Nigeria (Alele et al., 2024). At the same time, the battery study by Ilori et al. (2025) also shows that practical renewable deployment decisions in Nigeria are shaped by storage economics and battery behavior, since regular batteries may still be used in deep-cycle applications despite their shorter discharge duration, largely because low-cost and availability considerations often influence technology choice in real installations.

There is also the question of whether renewable integration should automatically be assumed to be sustainable once installed. Recent PV sustainability review evidence shows that solar systems are not inherently sustainable simply because they generate low-carbon electricity at the point of use. Their wider sustainability depends on how upstream manufacturing burdens, storage choices, transport assumptions, and end-of-life management are handled, as well as whether regional conditions are properly represented in assessment and planning (Obuseh et al., 2026). This is especially important for power-system integration because high renewable penetration without attention to storage burdens, waste governance, and context-specific planning may solve one sustainability problem while shifting pressure to another stage of the system (Obuseh et al., 2026).

From a sustainability perspective, the challenge is therefore not whether renewable energy should be integrated, but how it should be integrated. Current literature consistently points toward a coordinated pathway built on storage, smart-grid infrastructure, adaptive protection, flexible resources, grid-supportive inverter control, and updated regulatory frameworks. In that sense, renewable integration is best understood as a transition in overall power-system architecture rather than a simple substitution of generation sources (Ayorinde et al., 2025; Ahmad et al., 2025; Mirza et al., 2026).

3.6 Regional Trends in Sustainable Power-System Research

Regional trends in sustainable power-system research show that the field is no longer centered only on decarbonization. Recent review studies increasingly define sustainability through a broader combination of renewable integration, resilience, digital control, system flexibility, and equitable access to electricity (Mohanty et al., 2024; Cavus, 2025; Goforth et al., 2025). This means that the question has shifted from whether power systems should become cleaner to how different regions can build power systems that are cleaner, more reliable, more adaptive, and socially inclusive at the same time (Monie et al., 2025; Ghanbari & Jiang, 2025).

A clear regional pattern is that high-income power systems are concentrating more on resilience, intelligent grid operation, and the technical management of high renewable penetration. Reviews from Europe and other advanced-grid contexts place strong emphasis on resilience metrics, cyber-physical preparedness, storage coordination, AI-enabled grid management, and inverter-dominated system operation, reflecting the fact that many of these systems are already moving deeper into renewable-heavy operation (Mohanty et al., 2024; Cavus, 2025; Monie et al., 2025). In these regions, sustainability is increasingly discussed as a problem of maintaining system strength, flexibility, and recovery capacity while the generation mix changes rapidly (Ghanbari & Jiang, 2025).

By contrast, research from Africa and other developing regions continues to place stronger emphasis on electricity access, infrastructure deficits, affordability, and the practical feasibility of renewable deployment. A recent review focused on Africa argues that renewable-energy progress on the continent must be assessed not only by installed technologies but also by how effectively it improves electricity access, economic resilience, and sustainable development outcomes under local policy and financing constraints (Panja et al., 2025). This regional emphasis makes sustainable power-system research in Africa more

development-oriented than in many mature grids, since the challenge is often to improve basic service reliability while also expanding clean-energy adoption (Panja et al., 2025; Ayorinde et al., 2025).

Another regional trend is the growing importance of smart-grid and renewable-integration research in African and Global South contexts. In a 2025 review, Ayorinde et al. argue that the integration of renewable energy resources into power grids increasingly depends on improved power electronics, smart-grid infrastructure, and energy storage, especially where intermittency and weak grid support still constrain reliable operation (Ayorinde et al., 2025).

Similarly, Yeboah et al. show that current smart-grid research is moving toward hybrid optimization, predictive models, advanced control, and storage-enabled coordination to improve reliability and sustainability during renewable integration (Yeboah et al., 2025). Together, these studies suggest that regional sustainability research is no longer satisfied with simply adding renewable capacity; it is increasingly concerned with the operational tools required to keep the grid stable after that capacity is added (Ayorinde et al., 2025; Yeboah et al., 2025).

There is also a noticeable regional shift toward decentralized and distributed energy architectures. Recent reviews of distributed energy systems show growing interest in microgrids, hybrid systems, localized storage, and flexible distributed configurations that can reduce dependence on fragile centralized supply structures (Cheng et al., 2025). This trend is especially relevant in regions with weak transmission and distribution performance, because distributed systems are increasingly being studied not just as clean-energy options, but as practical responses to supply insecurity and grid unreliability (Cheng et al., 2025; Panja et al., 2025).

A further trend is the move from purely technical sustainability to socio-technical sustainability. Recent literature now treats energy justice, equity, and inclusion as central rather than peripheral to sustainable power-system planning. Goforth et al. show that most power-system models still underrepresent justice and equity objectives, even though these shape who benefits from transition pathways and who remains exposed to poor-quality or unaffordable electricity (Goforth et al., 2025). This is important for regional analysis because sustainability pressures are not the same everywhere: in some regions the central issue is emissions reduction, while in others it is affordability, under-electrification, institutional weakness, or uneven access to modern energy services (Goforth et al., 2025; Panja et al., 2025).

The Nigerian literature fits clearly within this broader regional pattern. Recent Nigerian review work presents renewable integration as both a sustainability opportunity and a grid-management challenge, with strong emphasis on intermittency, storage, smart infrastructure, and the need for better control strategies (Ayorinde et al., 2025). This suggests that in Nigeria, sustainable power-system research is moving in two directions at once: it still addresses long-standing structural problems of inadequate supply and weak infrastructure, but it is also increasingly adopting the language of resilience, smart operation, and renewable-enabled transition seen in wider international literature (Ayorinde et al., 2025; Cavus, 2025).

One more regional trend is the stronger linkage between sustainability and resilience. Earlier literature often separated these two ideas, but recent review studies increasingly connect them, especially under conditions of climate stress, energy insecurity, and variable renewable generation. Mohanty et al. frame resilience as part of sustainable infrastructure, while Monie et al. extend that discussion to integrated energy systems with renewable penetration and cross-sector coupling (Mohanty et al., 2024; Monie et al., 2025). In practical terms, this means regional power-system sustainability is now being assessed not only by emissions or efficiency, but by how well systems prepare for shocks, absorb disruptions, and recover afterward (Ghanbari & Jiang, 2025).

Overall, the regional literature points to an uneven but recognizable convergence. Mature grids are leading in research on intelligent control, resilience, and high-renewable system operation, while developing regions are contributing more work on access, affordability, decentralized deployment, and the institutional conditions needed for clean-energy expansion (Panja et al., 2025; Cheng et al., 2025; Goforth et al., 2025). The common direction across regions is that sustainable power systems are increasingly being understood as systems that must be low-carbon, operationally reliable, digitally coordinated, and socially workable at the same time (Cavus, 2025; Yeboah et al., 2025; Ayorinde et al., 2025).

4. Research Gaps and Future Directions

4.1 Evidence Gaps in Sustainable Power-System Research

Despite the growing body of work on sustainable power systems, several important gaps remain in the literature. One major gap is the fragmentation of research themes. Many studies still examine reliability, technical losses, renewable integration, storage, monitoring, forecasting, and policy as separate subjects, even though these issues are closely linked in real power systems. This creates a situation where sustainability is often discussed in parts rather than as a complete system property shaped by technical performance, operational efficiency, resilience, governance, and long-term adaptability.

Another major gap is the uneven treatment of sustainability itself. In many studies, sustainability is still discussed mainly in terms of renewable energy penetration, carbon reduction, or energy efficiency, while other critical dimensions such as affordability, resilience, implementation feasibility, and equity receive much less attention. This narrow view makes it difficult to evaluate whether a system is truly sustainable in practice. A power system may appear environmentally cleaner, but still remain unreliable, financially inaccessible, operationally weak, or institutionally difficult to manage.

There is also a methodological gap in the literature. A large number of studies remain case-specific, short-term, or focused on a single variable, which limits broader comparison across regions, grid conditions, and operational environments. While case studies are useful for understanding local conditions, the field still lacks enough comparative and multi-location studies that can reveal wider trends and distinguish isolated technical problems from larger structural issues.

A further gap lies in data availability and operational visibility. Many sustainable power-system ideas now depend on real-time monitoring, digital control, predictive analytics, and data-supported decision-making. However, in many practical settings, especially in weak or transitional grids, such data systems are still incomplete or unreliable. This creates a mismatch between the advanced solutions proposed in the literature and the actual conditions under which many power systems operate.

Another important weakness is the limited connection between operational performance and life-cycle sustainability. Many studies discuss the technical benefits of renewable integration, storage, and smart-grid technologies without fully considering upstream production burdens, replacement cycles, material constraints, or end-of-life management. This means some sustainability assessments remain incomplete because they focus mainly on operation and do not fully account for impacts across the full technology chain.

There is also a clear implementation gap. Many studies identify the technical actions that should improve sustainable power-system performance, such as better voltage control, reduced losses, stronger monitoring, energy storage deployment, or smart-grid integration. However, fewer studies explain how these measures can be funded, regulated, phased, and maintained under real institutional and economic conditions. This leaves a gap between technical recommendation and practical execution.

Overall, the literature shows that sustainable power-system research is growing in depth, but it still needs stronger integration, broader assessment frameworks, better comparative evidence, more realistic implementation thinking, and greater alignment between technical performance and long-term sustainability goals.

4.2 Future Research Directions

Future research should move toward more integrated sustainability frameworks for power systems. Instead of studying reliability, voltage stability, technical losses, renewable integration, storage, digital monitoring, and policy as isolated areas, future work should combine them within broader system-level models. This would allow researchers to judge whether a proposed intervention improves the system as a whole rather than solving one problem while creating another elsewhere.

There is also a strong need for more comparative and region-specific studies. Future work should move beyond single-case assessments and compare multiple substations, feeders, local grids, or utility environments across different geographic and operational settings. This would help improve generalizability and make it easier to identify which sustainability challenges are local and which are systemic.

Digitalization should become a more central direction for future work. Real-time monitoring, smart metering, predictive maintenance, intelligent forecasting, anomaly detection, and automated control are becoming increasingly important in sustainable grid operation. Future studies should therefore focus not only on isolated digital tools, but on coordinated digital frameworks that support decision-making, improve operational visibility, reduce inefficiency, and strengthen resilience across the network.

Renewable-integration research should also become more holistic. Future studies should connect operational performance with broader sustainability issues such as storage replacement, battery degradation, upstream manufacturing effects, material use, and end-of-life management. This would make renewable-integration analysis more realistic and prevent sustainability from being judged only at the point of electricity generation.

Another important research direction is the development of hybrid planning models for weak and transitional grids. Future work should explore how conventional grid reinforcement, distributed generation, storage, smart metering, demand-side management, and intelligent control can work together rather than being treated as separate alternatives. In many regions, sustainable improvement will likely come from coordinated hybrid pathways rather than from one single intervention.

Implementation realism should also receive greater attention in future studies. Technical recommendations need to be matched with discussion of financing, regulation, market structure, utility capability, maintenance culture, and institutional readiness. Research will be more useful when it not only identifies technically sound solutions, but also explains how those solutions can be introduced and sustained under real operating conditions.

Future work should also expand the meaning of sustainability in power systems. A sustainable system should not be understood only as one with more renewable energy or lower losses, but as one that is reliable, efficient, resilient, affordable, adaptable, and socially workable over time. This broader view is necessary because future power systems will be judged not just by their generation mix, but by how well they serve users under changing technical, economic, and social conditions.

In general, the next stage of research should aim to make sustainable power-system analysis more integrated, context-aware, data-driven, and implementation-oriented. That direction would better reflect the real challenges facing modern power systems, especially in regions where sustainability depends not only on cleaner energy, but also on stronger infrastructure, better management, and practical long-term system viability.

5. Conclusion

Sustainability in power systems extends beyond renewable-energy adoption to include reliability, stability, energy efficiency, network performance, intelligent monitoring, and effective renewable integration. The review has shown that sustainable power-system operation depends on a balanced combination of technical strength, operational flexibility, and long-term adaptability. It also showed that current research is growing, but still faces gaps in integration, data depth, implementation realism, and broader sustainability assessment. Future progress will depend on more coordinated studies that combine technical, economic, operational, and strategic perspectives. Overall, sustainable power systems should be pursued not only as cleaner energy systems, but as reliable, efficient, resilient, and practically manageable systems that can meet present and future electricity needs.

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