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IoT-enabled smart grid observability for power quality, energy efficiency, and renewable integration

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ABSTRACT

The increasing penetration of renewable energy resources, distributed generation, and flexible electricity demand creates a growing need for continuous observability and responsive management in modern power systems. This study develops an integrated conceptual framework explaining how Internet of Things (IoT)-enabled monitoring can support power-quality management, energy efficiency, and renewable-energy integration. A structured qualitative literature review and thematic synthesis were conducted on 41 unique scholarly sources published between 2018 and 2026, including prior studies on IoT-based industrial monitoring and power-system operation that establish continuity with the authors' research trajectory. Evidence was organized using a literature-analysis matrix covering sensing and metering, communication, computing, monitoring functions, operational outcomes, and implementation constraints. The synthesis identifies a common pathway from physical sensing and smart metering through IoT communication and edge/cloud processing to analytics and decision support. This observability pathway supports earlier recognition of power-quality conditions, more informed energy-management and demand-response decisions, and improved visibility of variable renewable generation. Cybersecurity, interoperability, scalability, and communication reliability remain cross-cutting constraints. The main contribution is an integrated IoT-enabled smart-grid observability framework that links these previously fragmented domains and clarifies that monitoring is an enabling layer rather than a stand-alone corrective mechanism. The framework provides a basis for subsequent empirical validation in laboratory microgrids, simulation environments, and real power-system deployments.



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Introduction

The rapid transformation of electricity systems through distributed generation, renewable energy resources, smart meters, energy storage, and increasingly active consumers is creating new operational challenges for power-grid management. Conventional electricity networks were primarily designed around centralized generation and relatively predictable demand, whereas contemporary smart grids must accommodate bidirectional power flows, variable renewable generation, flexible loads, and a growing number of digitally connected devices. These changes increase the importance of real-time visibility into voltage, current, frequency,

power consumption, and other operational conditions. Without adequate monitoring, grid operators and energy users may have limited ability to detect power-quality disturbances, identify inefficient consumption patterns, or respond effectively to fluctuations associated with renewable energy generation. Smart-grid development therefore requires not only the deployment of renewable and distributed energy technologies but also digital infrastructures capable of continuously observing and communicating system conditions. In this context, the Internet of Things (IoT) has emerged as a potentially important technological foundation because it enables physical energy assets, sensors, smart meters, communication networks, and computational platforms to operate as interconnected components of an intelligent energy system. In this context, the Internet of Things (IoT) has emerged as a potentially important technological foundation because it enables physical energy assets, sensors, smart meters, communication networks, and computational platforms to operate as interconnected components of an intelligent energy system (Ahmad & Zhang, 2021).

The relevance of IoT to smart-grid monitoring has been established in previous research, particularly through the development of connected metering, sensing, communication, and data-processing infrastructures. Al-Turjman & Abujubbeh (2019) describe IoT-enabled smart grids as an environment in which connected devices and smart meters can support more extensive monitoring and management functions. Saleem et al. (2019) similarly identify sensing, communication, architectures, applications, and intelligent services as important components of IoT-aided smart grids, while Abir et al. (2021) highlight the expanding applications of IoT in smart energy grids alongside challenges related to scalability, interoperability, security, and data management. Alavikia & Shabro (2022) further emphasize the importance of a layered architecture for implementing IoT-enabled smart grids, and Qays et al. (2023) demonstrate that communication technologies and protocols are fundamental to reliable IoT-assisted smart-grid applications. These studies establish that IoT can enhance grid observability, but they also indicate that monitoring performance depends on the integration of sensing, communication, processing, and application layers rather than on sensors alone. This integrated perspective is consistent with broader reviews of smart-grid technologies, which emphasize the interaction among advanced sensing, communication, automation, and energy-management technologies in enabling more intelligent and responsive electricity networks (G, 2019). The practical significance of this integration becomes particularly evident when monitoring is considered in relation to the three interconnected challenges of power quality, energy efficiency, and renewable energy integration. This monitoring-centered perspective also follows the authors' earlier work on IoT integration in SCADA-based industrial automation, where real-time data acquisition, interoperability, and secure information exchange were identified as central requirements for predictive and operational decision support (Yurika, 2025a).

Power quality is a critical concern because increasing distributed generation and renewable energy penetration can alter electrical operating conditions and increase the complexity of maintaining stable and acceptable power characteristics. H. Gandoman et al. (2018) emphasize the importance of advanced power-quality technologies in smart grids incorporating renewable energy systems, while Naderi et al. (2018) demonstrate that distributed generation requires appropriate techniques to mitigate power-quality problems in electrical distribution networks. The development of connected metering provides an important pathway for addressing this challenge. Junior et al. (2019) demonstrate the use of smart meters for monitoring power-quality disturbances, and Kumar et al. (2021) show that IoT-based smart energy meters can integrate energy measurement with power-quality analysis. Ahammed & Khan (2022) further connect IoT-based smart meters with power-quality management and demand-side management, while Munoz et al. (2024) demonstrate the development of an IoT smart energy meter incorporating power-quality monitoring within a smart-grid architecture. More recent work by Tabassum et al. (2024a) and Tabassum et al. (2024b) further indicates that IoT-based real-time monitoring can support power-quality enhancement and adaptive management. Sousa & Rabelo (2025) extend this direction to residential environments, while Omeje et al. (2026) identify IoT-based power-quality monitoring as an emerging field requiring advances in sensing, communication, analytics, cybersecurity, and scalability. These findings suggest that the principal value of IoT monitoring is not merely the collection of electrical measurements, but the creation of timely and connected information that can support the detection and management of changing grid conditions.

IoT-enabled monitoring is also closely related to energy efficiency because efficient energy management requires accurate information about electricity generation and consumption. Hu et al. (2019) show that IoT environments can facilitate energy-management strategies for prosumers while considering network constraints, whereas Alam & Arefifar (2019) identify coordinated energy management as an important requirement for modern power-distribution systems. Rathor & Saxena (2020) further position energy management systems as a central element of smart-grid operation. The availability of real-time consumption information can also support demand-response mechanisms, enabling energy use to be adjusted according to system conditions. Hui et al. (2020) highlight the potential of IoT and advanced communication networks for demand response, while Ahmadzadeh et al. (2021) emphasize the importance of communication infrastructures for future IoT-based

demand-response management. Tiwari & Pindoriya (2022) demonstrate that automated demand response depends on the interaction among metering infrastructure, communication technologies, and optimization models, and Khan et al. (2024) identify IoT-enabled demand response as an important opportunity while recognizing continuing implementation bottlenecks. Thus, IoT monitoring can contribute to energy efficiency by improving consumption visibility and providing information required for demand-side coordination, although the effectiveness of these benefits depends on the reliability and integration of the underlying digital infrastructure.

The challenge becomes more complex when renewable energy resources are integrated into the grid at increasing levels. Renewable generation, particularly variable resources, introduces uncertainty and fluctuations that require greater system flexibility, monitoring, and coordination. The increasing penetration of renewable energy also creates challenges for power-system flexibility because variable generation requires greater capacity to balance supply and demand under changing operating conditions (ORAL & VARBAK NEŞE, 2020). Kakran & Chanana (2017) emphasize the operational implications of distributed generation for smart-grid systems, while Alotaibi et al. (2020) identify smart-grid technologies as an important foundation for sustainable electricity systems with renewable energy resources. Impram and Neşe (2020) highlight renewable-energy penetration as a challenge for power-system flexibility, and Judge et al. (2022) identify renewable integration, communication, storage, cybersecurity, and system coordination among the major considerations in smart-grid implementation. Kataray et al. (2023) further demonstrate that smart-grid integration with renewable energy creates both significant opportunities and technical challenges, while Hasan et al. (2023) emphasize the importance of monitoring and control mechanisms in microgrids with large-scale renewable-energy integration. Khalid (2024) likewise argues that smart-grid capabilities are increasingly important for managing the technical challenges associated with renewable energy integration. These findings indicate that renewable integration cannot be considered independently from grid observability: as generation becomes more variable and distributed, the grid requires more timely information to maintain operational balance and power quality. Accordingly, flexibility-oriented monitoring and coordination become increasingly important as renewable resources constitute a larger share of electricity generation. It is also consistent with prior work on transmission-line operation and maintenance, which emphasized monitoring and proactive maintenance as important elements for maintaining power-system stability and reliability under infrastructure constraints (Yurika, 2025b). This perspective is consistent with prior work involving Een Taryana on renewable-energy planning and rooftop photovoltaic systems, which demonstrates the practical importance of generation modelling, energy contribution, and system-level integration in distributed renewable-energy applications (Iskandar, Nurfatah, et al., 2023; Iskandar, Taryana, et al., 2023).

Despite substantial progress, the literature remains fragmented across IoT architecture, power-quality monitoring, energy management, demand response, and renewable-energy integration. Existing reviews commonly explain these domains separately, while fewer studies explicitly identify the information pathway that connects them. This creates a conceptual gap: the operational contribution of IoT is often described as connectivity or measurement, but the mechanism through which monitoring information becomes useful for multiple smart-grid objectives is less clearly integrated. The present study addresses this gap by positioning IoT-enabled observability as a common enabling layer that connects sensing and metering, communication, computing, analytics, and decision support with power-quality management, energy efficiency, and renewable-energy integration.

Accordingly, this study asks: How can IoT-enabled monitoring support power-quality management, energy efficiency, and renewable-energy integration through a common smart-grid observability pathway? The study has three objectives: (1) to synthesize recurring technological relationships across the selected literature; (2) to identify cross-cutting implementation constraints affecting monitoring effectiveness; and (3) to develop an integrated conceptual framework that can guide subsequent empirical validation. The contribution is therefore not a claim that monitoring alone improves grid performance, but a structured explanation of how monitoring establishes the information foundation required by analytical, management, and control functions.

The significance of this study lies in its attempt to reposition IoT-enabled monitoring from a narrowly defined measurement function toward an integrated smart-grid capability. Such a perspective is increasingly relevant because the effectiveness of digitalized energy systems depends on the quality, timeliness, interoperability, and security of information generated by distributed devices. Pitchai et al. (2024) emphasize the potential of green IoT to contribute to sustainable smart-grid development, while Feng et al. (2020) demonstrate the opportunities created by edge computing for processing smart-grid data closer to its source. Wang et al. (2021) further illustrate the potential of IoT-based decision-making in addressing uncertainty in smart-grid operations, while Akkad et al. (2023) demonstrate that information security must be considered an integral component of IoT-enabled smart-grid architectures. These perspectives reinforce the argument that monitoring effectiveness cannot be

separated from communication, computation, decision-making, and security. By bringing these dimensions together with power quality, energy efficiency, and renewable-energy integration, this study seeks to provide a more integrated conceptual explanation of the role of IoT in contemporary smart-grid development. The study therefore asks one central research question: How can IoT-enabled monitoring support power-quality improvement, energy efficiency, and renewable-energy integration in smart-grid environments? The answer is expected to clarify the technological pathways through which IoT-based observability can generate operational value, identify the principal challenges that may constrain its implementation, and highlight unresolved issues requiring further empirical investigation.

The conceptual synthesis is further anchored to previously published empirical evidence from Yurika's research trajectory. Earlier work by Asmida and Yurika (2024) demonstrated IoT-based monitoring of a hybrid solar–wind generation system using ThingSpeak, where electrical variables including source voltage, battery voltage, charging current, load voltage, current, and power were monitored as operational information. These previous results are not treated as new experimental observations in the present study; instead, they serve as case-based empirical evidence for assessing whether the monitoring pathway identified in the literature is consistent with practical renewable-energy monitoring and energy-observability applications.

Method

This study employed a structured qualitative literature review to examine how IoT-enabled monitoring supports power-quality management, energy efficiency, and renewable-energy integration. The approach was selected to integrate evidence from electrical engineering, communication, computing, energy management, and cybersecurity without claiming a statistical meta-analysis. The review emphasized conceptual transparency, thematic comparability, and conservative interpretation of causal claims.

The analytical corpus comprised 43 unique scholarly sources published between 2018 and 2026. Sources were retained when they contributed substantive evidence to IoT architecture and connectivity, sensing or smart metering, power-quality monitoring, energy management, demand response, renewable-energy integration, communication and computing infrastructure, sustainability, decision support, or cybersecurity. Duplicate records were removed before synthesis. The corpus also included relevant prior work by Yurika on IoT-SCADA monitoring and power-system stability, and by Een Taryana and co-authors on renewable-energy forecasting and rooftop photovoltaic integration, to establish continuity with the authors' research domains.

A literature-analysis matrix was used to record bibliographic identity, year, technological context, monitoring function, communication or computing approach, relationship to the three outcome domains, reported benefits, constraints, and operational implications. The matrix served as a qualitative extraction instrument rather than a quantitative scale. The review followed five stages: definition of the research question and outcome domains; relevance and duplication checking; extraction of comparable information; thematic grouping; and cross-theme synthesis. A publication could contribute to more than one theme when its findings connected monitoring with multiple smart-grid functions.

Thematic synthesis involved familiarization, coding, theme development, cross-theme comparison, and conceptual integration. Evidence was organized around a sensing–communication–computing–decision pathway and then related to power quality, energy efficiency, and renewable integration. Recurring constraints such as cybersecurity, interoperability, communication reliability, and scalability were treated as cross-cutting conditions. Credibility was strengthened by applying the same analytical dimensions across sources, comparing claims across multiple publications, retaining complementary or conflicting perspectives, and avoiding causal claims unsupported by the reviewed evidence. The synthesis therefore distinguishes monitoring as an enabling information capability from the control or optimization actions that ultimately produce operational improvement.

The method has limitations. It does not provide primary field measurements, laboratory experiments, simulations, surveys, or statistical hypothesis tests, and the purposive corpus is not an exhaustive representation of all smart-grid publications. The findings should therefore be interpreted as a structured conceptual synthesis and framework requiring subsequent empirical validation. In addition to thematic synthesis, a case-based evidence mapping was performed using quantitative results reported in the previous study by Asmida and Yurika (2024). Only values explicitly reported in the original publication were considered. No re-analysis of raw measurements, recalculation, or claim of new experimentation was made. The evidence was mapped to the proposed monitoring pathway: renewable source, sensing/metering, IoT communication, monitoring and processing, and decision support. This step was used to examine practical consistency between the literature-derived framework and a previously demonstrated IoT-based renewable-energy monitoring application.

Results and Discussions

The thematic synthesis indicates that IoT-enabled monitoring contributes to smart-grid operation through four interconnected functions: acquisition of electrical and energy data, communication of monitoring information, processing and analysis, and transformation of information into operational decision support. Across the 41-source corpus, these functions converge on three outcome domains power-quality management, energy efficiency and demand response, and renewable-energy integration while cybersecurity, interoperability, scalability, and communication reliability operate as cross-cutting constraints. Table 1 summarizes the principal themes, and Figure 1 integrates them into a common observability framework.

Table 1. Thematic findings on the role of IoT-enabled monitoring in smart-grid operation.

Analytical dimension	Main finding from the literature	Representative references	Operational implication
IoT architecture and connectivity	IoT connects sensors, meters, grid assets, communication networks, computing platforms, and applications	Al-Turjman & Abujubbeh (2019); Saleem et al. (2019); Abir et al. (2021); Alavikia & Shabro (2022); Yurika (2025a)	Greater system observability and information exchange
Communication infrastructure	Reliable communication is fundamental to real-time monitoring and smart-grid applications	Hui et al. (2020); Ahmadzadeh et al. (2021); Qays et al. (2023)	Faster and more reliable transmission of grid information
Power-quality monitoring	Smart meters and IoT devices can monitor electrical disturbances and power-quality parameters	Junior et al. (2019); Kumar et al. (2021); Ahammed & Khan (2022); Munoz et al. (2024); Sousa & Rabelo (2025)	Earlier identification of power-quality problems
Power-quality enhancement	Real-time monitoring can support adaptive identification and management of power-quality conditions	H. Gandoman et al. (2018); Naderi et al. (2018); Tabassum et al. (2024a); Tabassum et al. (2024b)	Improved basis for corrective and adaptive actions
Energy management	IoT-generated information supports monitoring and coordination of generation and consumption	Hu et al. (2019); Alam & Arefifar (2019); Rathor & Saxena (2020)	Improved visibility for energy-management decisions
Demand response	Connected metering and communication enable more responsive demand-side management	Hui et al. (2020); Ahmadzadeh et al. (2021); Tiwari & Pindoriya (2022); Khan et al. (2024)	Greater capacity to coordinate flexible demand
Renewable-energy integration	Monitoring supports management of variable generation and changing grid conditions	Kakran & Chanana (2017); Alotaibi et al. (2020); Kataray et al. (2023); Hasan et al. (2023); Khalid (2024); Yurika (2025b)	Improved visibility for renewable integration
Computing and decision support	Edge computing and IoT-based decision systems can process information closer to operational sources	Feng et al. (2020); Wang et al. (2021)	Potentially faster data processing and decision support
Sustainability	Green IoT and digitalization can support more sustainable energy-system operation	Khatua et al. (2019); Pitchai et al. (2024); Mahmood et al. (2024)	Greater potential for efficient and sustainable operation
Security and scalability	Cybersecurity, interoperability, scalability, and data management remain significant constraints	Abir et al. (2021); Akkad et al. (2023); Tabassum et al. (2024a); Omeje et al. (2026)	Benefits depend on secure and scalable infrastructure

Source: Author synthesis based on Al-Turjman and Abujubbeh (2019), Saleem et al. (2019), Hui et al. (2020), Feng et al. (2020), Abir et al. (2021), Tiwari and Pindoriya (2022), Qays et al. (2023), Kataray et al. (2023), Tabassum et al. (2024a, 2024b), and Khalid (2024).

The first finding is that IoT-enabled monitoring strengthens smart-grid observability by linking sensors, smart meters, communication networks, processing resources, and applications. IoT therefore functions as an ecosystem rather than a single device. Studies on IoT architectures and communication protocols consistently show that measurements become operationally valuable only when they can be transmitted, processed, and interpreted (Al-Turjman & Abujubbeh, 2019; Saleem et al., 2019; Abir et al., 2021; Alavikia & Shabro, 2022; Qays et al., 2023). Yurika (2025a) similarly shows, in an industrial automation context, that IoT-SCADA integration can strengthen real-time monitoring while introducing interoperability and cybersecurity requirements. This continuity supports extending IoT observability concepts from industrial automation to energy systems.

The second finding concerns power quality. IoT-enabled smart meters can extend conventional metering toward continuous observation of voltage, current, consumption, and disturbance-related conditions. Evidence from Junior et al. (2019), Kumar et al. (2021), Ahammed and Khan (2022), Munoz et al. (2024), and Sousa and Rabelo (2025) indicates that connected meters can improve the visibility of power-quality conditions. This is particularly relevant in networks with distributed generation, where power-quality management becomes more complex (H. Gandoman et al., 2018; Naderi et al., 2018). Yurika (2025b) also emphasizes monitoring and maintenance as important foundations for power-system reliability and stability.

Monitoring, however, should not be equated with correction. The reviewed evidence supports a pathway from measurement to awareness and decision support, while actual power-quality improvement requires subsequent analysis, compensation, adaptive control, or other corrective mechanisms (Tabassum et al., 2024a; Tabassum et al., 2024b; Omeje et al., 2026). This distinction prevents overstatement of IoT effects and clarifies the role of monitoring as an enabling layer.

The third finding is that IoT monitoring provides an information foundation for energy management. Granular visibility of generation and consumption can support identification of inefficient patterns, resource coordination, and demand-side decisions (Hu et al., 2019; Alam & Arefifar, 2019; Rathor & Saxena, 2020). Energy savings are therefore not an automatic result of monitoring; they depend on optimization, automated control, or behavioral and operational responses based on the information collected.

Demand response illustrates this relationship clearly. IoT and advanced communication networks enable information exchange among meters, controllable devices, consumers, and operators, while optimization determines the response itself (Hui et al., 2020; Ahmadzadeh et al., 2021; Tiwari & Pindoriya, 2022; Khan et al., 2024). Nature-inspired artificial intelligence techniques have also been applied to coordinated day-ahead scheduling to improve energy management in smart grids, demonstrating the growing role of intelligent optimization in coordinating energy resources and demand (Z. Khan et al., 2019). Communication reliability and latency consequently become part of the energy-efficiency problem rather than merely supporting infrastructure.

The fourth finding concerns renewable-energy integration. Variable and distributed generation increases the need for timely information about generation, load, voltage, and network conditions. Smart-grid studies consistently identify monitoring, flexibility, and coordination as important for integrating renewable resources (Kakran & Chanana, 2017; Alotaibi et al., 2020; Kataray et al., 2023; Hasan et al., 2023; Khalid, 2024). Research involving Een Taryana provides a practical connection: hybrid renewable-energy forecasting and rooftop PV modelling demonstrate how renewable contribution, system configuration, and operational planning depend on reliable system information (Iskandar, Nurfatah, et al., 2023; Iskandar, Taryana, et al., 2023).

These findings reveal an interdependence among the three outcome domains. Renewable penetration can influence voltage and power-flow conditions; demand response can improve renewable utilization; and power-quality information can indicate undesirable conditions associated with distributed generation. IoT monitoring therefore provides common information infrastructure rather than three isolated monitoring solutions.

Communication and computing capabilities determine whether this information can be used in time. Studies on 5G/IoT communication and smart-grid protocols highlight reliability and latency requirements, while edge computing can move processing closer to data sources (Hui et al., 2020; Ahmadzadeh et al., 2021; Feng et al., 2020; Qays et al., 2023). IoT-based decision systems further illustrate how processed information may support operation under uncertainty (Wang et al., 2021). Recent developments in AI-enabled IoT-based smart grids further demonstrate the potential of combining intelligent fault detection with load optimization to support renewable-energy integration (Ammar Jalal Abdulrazzaq Al-Tabatabaee, n.d.). Effective architectures should therefore be evaluated as integrated sensing–communication–computing systems.

Cybersecurity, interoperability, and scalability are cross-cutting constraints. Greater connectivity expands both information exchange and potential attack surfaces, while heterogeneous devices can create isolated data

if standards and interfaces are incompatible (Abir et al., 2021; Akkad et al., 2023; Tabassum et al., 2024a; Omeje et al., 2026). Consequently, measurement capability alone is insufficient; secure and scalable integration is required for grid-wide observability.

Sustainability adds a further qualification. Digitalization and green IoT can support better coordination of energy resources, but digital infrastructure also consumes energy and resources (Khatua et al., 2019; Pitchai et al., 2024; Mahmood et al., 2024). The sustainability value of IoT therefore depends on whether operational and renewable-integration benefits outweigh deployment and computing burdens.

The synthesis can be represented as an integrated pathway: sensing and smart metering form the physical observation layer; communication transfers measurements; edge/cloud resources process data; and analytics convert data into decision-relevant information. That information supports power-quality management, energy-efficiency management, and renewable integration, while cybersecurity, interoperability, reliability, and scalability influence every layer.

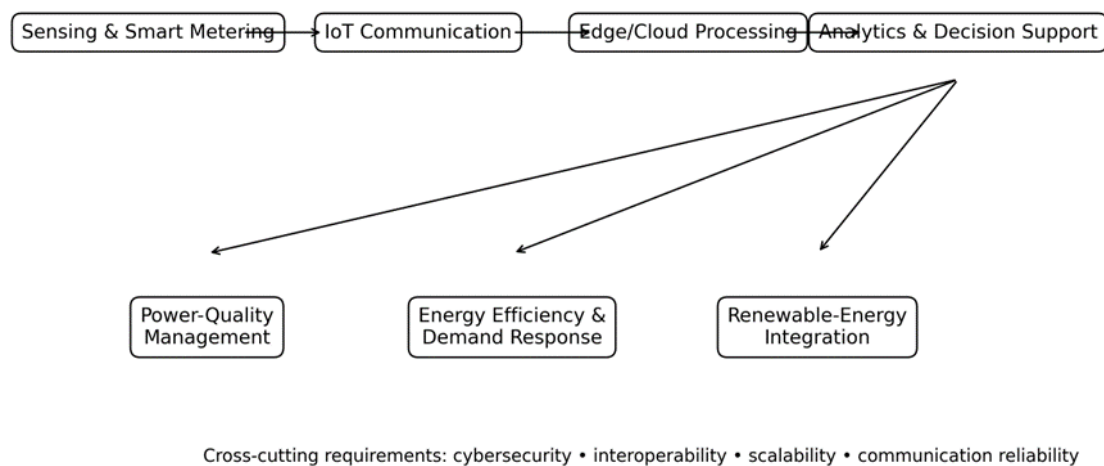


Figure 1. Integrated IoT-enabled smart-grid observability framework derived from the thematic synthesis.

Source: Author-developed framework synthesized from Al-Turjman and Abujubbeh (2019), Saleem et al. (2019), Feng et al. (2020), Abir et al. (2021), Wang et al. (2021), Qays et al. (2023), Kataray et al. (2023), and Tabassum et al. (2024a, 2024b).

Figure 1 is the principal conceptual output of this review. Its contribution is to integrate three operational objectives frequently discussed separately into one observability pathway. The framework distinguishes observation from intervention: IoT generates and transports operational information, whereas measurable improvement occurs when analytics, energy management, control, storage, demand response, or protection mechanisms act on that information.

The research question can therefore be answered as follows: IoT-enabled monitoring supports power quality, energy efficiency, and renewable integration by increasing observability and linking physical grid conditions with communication, computation, analysis, and decision support. Its value is enabling rather than automatically corrective, and its effectiveness depends on the quality, timeliness, security, and interoperability of the resulting information.

For implementation, five implications follow. Monitoring variables should be selected from operational objectives; communication should match application latency and reliability needs; processing should be located centrally, at the edge, or in hybrid form according to requirements; cybersecurity should be embedded at architecture level; and interoperability and scalability should be considered from initial design. These principles are more transferable than prescribing one universal technology.

The study remains limited by its qualitative, purposive review design and by heterogeneity among the selected publications. It does not quantify effect sizes or experimentally validate causal relationships. Future work should test the proposed framework in laboratory microgrids, simulation environments, or operational systems using measurable indicators such as voltage deviation, harmonic distortion, energy consumption, demand-response performance, renewable-energy utilization, latency, packet reliability, and cybersecurity resilience.

Overall, the evidence supports IoT-enabled monitoring as a common information layer connecting energy measurement with smart-grid decision processes. This interpretation is consistent with the authors' prior

domains: Yurika's work on IoT-SCADA monitoring and power-system stability, and Een Taryana's work on renewable-energy forecasting and photovoltaic integration. The present study extends those strands into a unified smart-grid observability framework.

The framework provides a testable basis for subsequent empirical research. Rather than claiming that IoT alone improves grid performance, it specifies where information is acquired, transmitted, processed, and converted into operational decisions, and identifies the technical conditions that can enable or constrain measurable outcomes.

Case-based empirical evidence from previous research

To strengthen the connection between the conceptual synthesis and the authors' established research trajectory, previously reported empirical results from Asmida and Yurika (2024) were mapped qualitatively to the proposed IoT-enabled energy-monitoring pathway. The evidence is presented as secondary evidence rather than as new experimental data. The hybrid solar-wind monitoring study demonstrates the practical acquisition and transmission of electrical variables through an IoT platform, showing that the pathway from physical renewable-energy assets to sensing, digital communication, monitoring, and operational information is technically consistent with a system previously implemented in Yurika's research.

The case-based evidence from the previous study by Asmida and Yurika (2024) provides a practical illustration of the monitoring pathway identified in the literature synthesis. In the hybrid solar-wind system, the reported measurements included a photovoltaic-source voltage of 18 V, a battery voltage of 13.01 V, a charging current of 1.05 A, and load-side measurements of approximately 226.6 V and 59 W. These previously published values are used here only as secondary evidence, not as new experimental results. They demonstrate how electrical variables originating from renewable-energy assets can be acquired, transmitted through an IoT-based monitoring platform, and transformed into operational information for observing generation, storage, and load conditions. In the context of the proposed framework, the source and battery measurements represent the sensing and metering layer, while the ThingSpeak-based data transmission represents the IoT communication and monitoring layer. The evidence therefore supports the practical feasibility of linking renewable-energy sources, electrical sensing, digital communication, and real-time monitoring within an integrated energy-observability pathway (Asmida & Yurika, 2024).

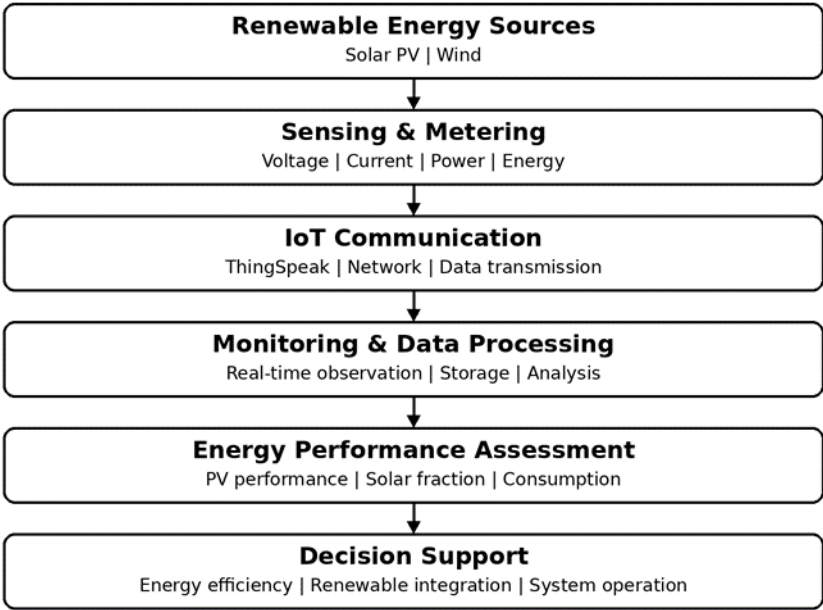


Figure 2. Integrated IoT-enabled renewable-energy monitoring and decision-support pathway.
Author-developed synthesis based on the literature reviewed in this study and supporting case-based evidence from Asmida and Yurika (2024).

Conclusions

IoT-enabled monitoring can be positioned as a critical information and observability layer for contemporary smart-grid operation, particularly in addressing the interconnected requirements of power quality, energy efficiency, and renewable energy integration. The qualitative library research demonstrates that the principal

value of IoT does not arise from connectivity alone, but from its capacity to connect sensing and metering devices with communication, data processing, monitoring, and decision-support functions. In relation to power quality, IoT-enabled monitoring strengthens the visibility of electrical conditions and disturbances, providing information that can support timely assessment and subsequent corrective actions. In relation to energy efficiency, continuous and granular monitoring provides an information foundation for energy management and demand-response mechanisms by improving visibility of generation and consumption patterns. In relation to renewable energy integration, enhanced observability supports the management of distributed and variable generation by providing information concerning changing system conditions. The findings therefore answer the research question by demonstrating that IoT-enabled monitoring can support these three smart-grid objectives through an interconnected pathway from physical measurement to information, analysis, and operational decision support. However, monitoring should not be interpreted as a sufficient condition for achieving these outcomes because its effectiveness depends on the integration of appropriate communication, computing, management, control, interoperability, scalability, and cybersecurity mechanisms.

The contribution of this study lies in integrating these dimensions into a single conceptual perspective rather than treating IoT connectivity, power-quality monitoring, energy management, and renewable-energy integration as isolated technological issues. This perspective extends the existing body of knowledge by emphasizing IoT-enabled observability as a common enabling layer through which diverse smart-grid functions can be connected. The practical significance is that future smart-grid development should evaluate monitoring infrastructures according to their ability to generate reliable, timely, secure, and operationally meaningful information, rather than merely according to the number of connected devices deployed. At the same time, the conclusions should be interpreted within the methodological boundaries of qualitative library research, which provides conceptual synthesis rather than direct empirical verification of performance improvements. Future research should therefore validate the identified relationships through real-world smart-grid deployments, laboratory microgrids, and simulation-based experiments, particularly by examining measurable relationships among IoT monitoring, power-quality performance, energy efficiency, renewable-energy utilization, communication reliability, and cybersecurity. Such empirical validation would strengthen the transition from a conceptual understanding of IoT-enabled observability toward evidence-based design principles for resilient, efficient, and renewable-integrated smart-grid systems.

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