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Smart Monitoring and Control Framework for Landscape-Integrated Renewable Energy Power Systems-A Review

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Abstract: Smart renewable energy systems are no longer installed only as separate technical equipment; they are increasingly built into roofs, facades, farms, public spaces, and community networks. This review discusses how monitoring systems can support such landscape-integrated generations. It draws together work on IoT sensing, embedded controllers, communication links, edge-cloud platforms, energy management, BIPV, agrivoltaics, digital twins, predictive maintenance, and cybersecurity. Most studies show that present systems can record electrical and environmental data reliably and can provide dashboards or alarms. The weaker point is that many designs still ignore the setting in which the system operates. Shading, access, appearance, crop response, user confidence, and maintenance routes all influence long-term performance. The review therefore proposes a context-aware monitoring framework built around dependable sensing, edge processing, flexible communication, secure data handling, user-specific dashboards, and gradual lifecycle intelligence.

Keywords: Renewables; Internet of Things; Building-Integrated Photovoltaics; Agrivoltaics; Cybersecurity

1. INTRODUCTION

Renewable energy has moved from being a specialized alternative to becoming a normal part of power-system planning. Solar PV, wind, and smaller distributed systems are now seen on houses, university buildings, farms, industries, and local energy projects. This growth is linked to decarbonization targets, energy-security concerns, falling technology costs, and the need for local resilience **[1], [3].**

As renewable systems become more common, the value of monitoring becomes clearer. At one time, a basic generation of reading was often enough. Today, that is too limited. A homeowner may want to know why the daily yield has fallen. A farmer may need to understand how a PV structure affects shade and irrigation. A community operator may need fair metering and transparent reporting. In each case, monitoring turns raw equipment data into information that people can use **[2], [5], [17].**

Landscape-integrated power generation adds another layer to the problem. A PV roof, a solar facade, a heritage retrofit, an agrivoltaic system, or a community microgrid is not just a collection of electrical devices. It becomes part of an existing place, with its own visual, social, agricultural, architectural, and maintenance constraints **[29], [30], [40], [51], [56].**

This paper reviews smart renewable energy monitoring from that combined viewpoint. It connects work on IoT sensing, embedded hardware, communication protocols, energy-management systems, BIPV, agrivoltaics, digital twins, predictive maintenance, and cybersecurity. The main argument is that monitoring should be planned from the start, not added at the end as a display feature. For integrated renewable systems, it is one of the links between technical performance, site suitability, maintenance, security, and user trust.

2. BACKGROUND AND CONCEPTUAL FOUNDATIONS

Monitoring in renewable energy involves the acquisition, transmission, storage, analysis, interpretation, and presentation of information regarding the energy system and its environment. Parameters that may be monitored include voltage, current, power, energy, frequency, battery state of charge, solar irradiance, cell temperatures, ambient temperature, humidity, wind speed, inverter state, and load utilisation. In smart monitoring applications, these parameters are used for fault detection, alarm generation, local control, prediction, optimisation, and decision-making **[4], [6], [7].**

Renewable energy monitoring systems may be implemented hierarchically. Sensors and transducers measure electrical quantities and environmental factors. Data from sensors is pre-processed at the edge/fog/embedded computing level, which comprises edge, fog, or embedded computers such as microcontrollers, gateways, and single-board computers.

The next hierarchical layer deals with the communication aspect, where data is transmitted wirelessly via Wi-Fi, cellular, LoRaWAN, Zigbee, Bluetooth Low Energy (BLE), Message Queuing Telemetry Transport (MQTT), and Modbus protocols **[5], [10], [15], [69].**

While this task may normally be limited to performance and reliability of components in a PV system, its significance changes when the system is integrated into the landscape. For example, the performance of a photovoltaic façade could be affected by shading, air flow, façade temperature, accessibility, or human activity inside the building. Agrivoltaic installations require knowledge about soil moisture content, plant growth, microclimate, and irrigation **[31], [32], [35], [51].**

Interoperability is an engineering problem that should not be disregarded. Renewable energy facilities consist of inverters, smart meters, battery storage systems, electric vehicle chargers, weather stations, grid tie-ins, and energy management systems from many different vendors. Without interoperability, the monitoring system would not be coherent. That is why the following criteria should be considered: standardization of measurements, open data protocols, secure message transfer, and flexible communication interfaces **[4], [16], [17], [70].**

3. REVIEW APPROACH AND SCOPE

The first research gap relates to the lack of development of the methodology of creating monitoring in the context of integrated renewable energy. Most of the research concentrates on each element separately – monitoring in the solar energy telemetry system, requirements for the creation of the BIPV, agrivoltaics, microgrid system creation, and AI-based monitoring **[7], [29], [51], [63].**

The second research gap is associated with the context of measurement parameters. While the measurement of the basic parameters is necessary, at times, not all factors are considered. For example, in the case of a façade solar system, information on shading and the state of the building's façade is needed. In the case of agrivoltaics, it is essential to measure the parameters of soil, vegetation, irrigation, and microclimate. Finally, in the case of the community system, the participation factor needs to be considered.

4. LITERATURE REVIEW AND THEMATIC SYNTHESIS

4.1 IoT-enabled monitoring architectures

The architecture of IoT is the most frequently used base in modern monitoring systems for renewable energy. It integrates sensors, controllers, gateways, databases, and user interfaces into a single network. Using this network, operators can monitor the generation process, get notifications, identify errors, monitor the demand, and perform energy optimization without excessive manual inspections **[5], [6].**

Many prototypes also confirm this trend. For instance, PV monitoring systems were built to calculate irradiance, temperature, humidity, voltage, current, and power output before transmitting these parameters to web interfaces **[7], [11].** IoT systems can be applied in smart homes, where generation and consumption information could be interconnected and provide users with insights about generation and demand processes **[10].** IoT systems in renewable-energy communities can use distributed meters to quantify the contribution made by each component of the system **[8].**

One difference in this literature is that researchers are no longer focusing solely on cloud architecture. Processing at the edge is employed to pre-process information, decrease latency and bandwidth consumption, as well as maintain basic functions when network conditions are unfavorable **[15], [69].**

In addition, this very architecture is associated with security problems. Sensors may be located outside, battery-operated, or hard to reach for repair. Information can flow through gateways, APIs, and cloud servers. Therefore, it would be wise to include power management, privacy of information, and communication reliability in a sound monitoring architecture along with sensors **[13], [14].**

4.2 Monitoring in photovoltaic, hybrid, and community systems

PV systems receive much attention in monitoring research because they are used at many scales, from small rooftops to large power plants. Good PV monitoring does not stop at the output-power reading. It also considers irradiance, module, ring behavior where possible, inverter status, temperature, degradation, and fault patterns. Standards such as IEC 61724-1 support this need for consistent performance measurement **[4], [6], [7], [11].**

Hybrid renewable systems and community energy projects are more demanding. Generation, storage, load, grid exchange, user behavior, and billing may all interact. A solar wind microgrid, for example, needs coordinated monitoring so that storage and dispatch decisions are not based on delayed or incomplete information. Community metering has a similar requirement because transparent contribution tracking affects user confidence **[8], [10], [18], [19].**

Predictive maintenance is another important development. Many PV systems contain parts that are spread across roofs, facades, fields, or small community sites. Routine manual inspection can be costly and sometimes misses early faults. AI-supported diagnosis and health-management methods can improve fault detection, but they depend heavily on reliable data collection and careful interpretation **[60], [61], [62].**

The lesson from this group of studies is that monitoring data should be dependable enough to guide action. If a dashboard only displays numbers without validation, synchronization, or explanation, it may give a false sense of control. For distributed renewable systems, the quality of the data path is almost as important as the number of measured parameters.

4.3 Smart grids, microgrids, and energy-management systems

The integration of renewables into smart grid or microgrid networks results in the incorporation of monitoring into control procedures. Monitoring is required to inform operators on generation of variability, voltage behavior, storage status, demand response, power quality, bi-directional energy exchange, and equipment status. These factors cannot be tackled by individual devices alone, but require integrated information systems **[16], [17].**

Research on microgrids provides insights into using monitoring data for prediction, dispatching, resiliency, and optimization of energy consumption. IoT and AI-enabled technologies are among those that have been suggested as means of generation, load, and storage management amid variable conditions **[18], [19], [20].** General overviews of microgrid control and data-driven energy management confirm the same result: monitoring should contribute to decision-making, and not just record **[21], [22], [23], [24], [25].**

Energy management research has also focused on prediction and optimization. Techniques such as machine learning can aid in predicting production capacity, estimating demand, and optimizing the utilization of renewable energy sources when sufficient data is available **[26], [27], [28].** However, all these techniques require a stable, secure, and properly calibrated monitoring system in place.

Another issue that is often overlooked in this area of study is the maturity of the infrastructure itself. Connectivity, competent operators, ample computing power, and stringent cybersecurity measures are often assumed. In landscape-integrated energy management, where applications may be found in small-scale structures like homes, farms, and communities with limited budgetary constraints, these assumptions may not apply. Therefore, it would be practical to start with reliable fundamental processes and incorporate advanced analysis later.

4.4 Landscape-integrated generation: BIPV, retrofits, and agrivoltaics

The link between monitoring and landscape integration is especially visible in BIPV. In these systems, PV modules may act as roofing, facade material, shading elements, or part of the building envelope. They must therefore meet energy, structural, thermal, architectural, and visual expectations at the same time **[29], [31], [32], [33], [34].**

Monitoring requirements in BIPV and retrofit projects are not identical to those in open-field PV plants. A facade system may be influenced by orientation, partial shading, ventilation, indoor comfort, wiring access, and maintenance restrictions. Heritage and retrofit projects can also limit the position of sensors, cables, and visible equipment. Studies on BIPV markets, retrofit systems, heritage renovation, and net-zero buildings show that technical yield alone is not enough; the system also has to be understandable and maintainable for the people responsible for it **[30], [35], [36], [40], [45], [48], [50].**

Agrivoltaics broadens the monitoring problem further. These systems combine electricity generation with agricultural production, so energy output must be considered alongside crop growth, microclimate, soil moisture, irrigation, shading patterns, and land-use planning. Reviews in this area describe agrivoltaics as a multifunctional land-use system rather than a simple placement of PV panels above crops **[51], [52], [53], [54], [57], [58].**

For that reason, agrivoltaic monitoring should not be limited to electrical variables. It should also gather information that helps farmers and planners judge whether the dual-use arrangement is working in practice. Policy and planning studies further show that stakeholder communication and governance matter for scaling these systems responsibly **[55], [56], [59].**

4.5 Digital twins, predictive maintenance, and cybersecurity

In addition to the above technologies, the modernization process includes digital twins, predictive maintenance, and cybersecurity. The digital twin technology implies the development of a digital representation of real devices and the usage of data to predict the device behaviour, run diagnostics, perform various simulations, optimize the whole lifecycle.

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Moreover, it has been suggested recently that the use of the technology can help to manage solar energy, produce sustainable energy, etc. **[63], [64], [65], [66], [67], [68].**

On the other hand, the model will be only as effective as the data used to develop it. Inaccurate information from sensors, lack of timestamps, poor technical documentation of devices or the wrong format of data may impact the results substantially. Speaking of the landscape-integrated system, future digital twins will include much more information than only the data related to the electrical behaviour of components.

The same goes for cybersecurity. Smart grid monitoring systems include several elements, like sensors, gateways, communications channels, cloud storage, application programming interfaces, graphical user interface, user account, and possible control modules. All these elements can become vulnerable to attacks if they remain unprotected. The cybersecurity literature on smart grids suggests that cybersecurity needs to be addressed during the design process **[70].** Likewise, the IoT literature recommends paying attention to the confidentiality of data and its secure transfer **[13].**

Overall, future monitoring will no longer depend on collecting additional information; rather, it will rely on using reliable data in a secure way. When it comes to landscape power generation, the end-users may include technologists, farmers, property owners, architects, facility managers, planners, and community administrators.

5. COMPARISON AND ANALYSIS OF PREVIOUS WORKS

In summary, relevant literature can be divided into several thematic areas: IoT monitoring solutions, net-metering and community approaches, smart-grid and microgrid solutions, BIPV and retrofitting solutions, agrivoltaics studies, and advanced digital twin solutions, analytics, and cybersecurity. All the mentioned research directions contribute to overcoming the issues of renewable energy, yet each of them fails to provide the complete solution.

The IoT monitoring solutions are usually good in terms of low-cost sensors and fast deployment, but they lack the higher-level perspective. The smart grid and microgrids tend to have better coordination and control mechanisms, but they usually depend on an elaborate infrastructure. BIPV and agrivoltaics show their understanding of context, but the question of monitoring architecture remains secondary. Digital twin, predictive maintenance, and other advanced technologies usually require well-prepared data and secure communication.

Thus, all the mentioned trends are fragmented, and no single approach provides a comprehensive overview of the issues related to renewable energy. As a result, there is no unified approach that would allow for creating technologically advanced and environmentally friendly solutions.

Category	**Representative works**	**Main strengths**	**Main limitations**
IoT PV monitoring	Rao et al. **[6]**; Rouibah et al. **[7]**; Alombah et al. **[11]**	Low-cost sensing, real-time telemetry, quick deployment, and remote viewing.	Often remains device-centered; site context and interoperability receive less attention.
Community and net-metering monitoring	Bonavolonta et al. **[8]**; Pathare and Sethi **[10]**	Contribution tracking, prosumer visibility, distributed metering, and practical dashboards.	Governance, privacy, cybersecurity, and data sharing are difficult.
Smart-grid and micro-EMS	Khalid **[17]**; Votava et al. **[18]**; Tasmat et al. **[19]**	Good support for control, forecasting, resilience, and system coordination.	Often assumes strong infrastructure, reliable communication, and trained operators.
Agrivoltaics and land-use integration	Widmer et al. **[51]**; Pandey et al. **[52]**; Alves et al. **[55]**	Explains crop-energy interaction, land-use value, and environmental co-benefits.	Monitoring needs go beyond electrical data but are not always formalized.
Digital twins, maintenance, and security	Mbasso et al. **[63]**; Hamza et al. **[60]**; Abbasi **[70]**	Supports diagnosis, prediction, lifecycle management, and security planning.	Requires reliable data, secure architecture, and interoperable datasets.
BIPV and retrofit integration	Bonomo and Fronitini **[29]**; Del Pero et al. **[30]**; Del Hierro Lopez and Olivieri [40]	Strong attention to building fit, aesthetics, retrofit limits, and acceptance.	Monitoring architecture is often treated as secondary to design or market issues.

Table 1. Comparative analysis of reviewed monitoring and integration literature.

6. RESEARCH GAP AND PROBLEM IDENTIFICATION

The first one is in the lack of a holistic approach in the design of the monitoring process for the overall renewable system. Indeed, research works discuss the design of monitoring either for solar energy telecommunication systems, for BIPV systems, for agrivoltaic lands allocation, for microgrids design, and for AI-driven monitoring solutions **[7], [29], [51], [63].**

The second gap exists in the application of context-aware measurements. Even though it is necessary to measure the main electrical and environmental characteristics of a system, this does not necessarily include all the necessary system information. Thus, a façade solar installation may require information on shading and the current status of a building facade; an agrivoltaics system would greatly benefit from the soil measurements, information about plants used and watering regime, and even microclimate data; community-based systems would benefit from knowing contribution of the users, which might be sensitive personal information.

Implementation Realism is the third gap. Advanced research tends to assume flawless communication channels, persistent availability of the cloud, huge volumes of historic data, and high-level security. However, in real-world situations, small and decentralized systems can function under conditions of tight budgeting, sporadic connectivity, challenging accessibility, and strict aesthetic or physical requirements. Thus, local processing, modular scaling, robustness off-cloud, and design-for-security become particularly vital **[13][15][70].**

Decision Support for Monitoring is the fourth gap. There are examples of providing numerical indicators on a dashboard without much effort towards diagnosing malfunctions, allocating maintenance, guiding users, or modifying control algorithms. In the context of landscape-based power generation, monitoring needs to address practical queries, such as: Is the system functioning as intended? Does the site impact its performance? Is maintenance necessary? Is the obtained data interpretable by the appropriate user?

7. PROPOSED FRAMEWORK AND FUTURE SCOPE

One possible direction to explore is the context-aware monitoring system architecture which involves six layers. The first layer is Sensing. Basic measurements should include voltage, current, power, energy, irradiation, solar cell temperature, ambient temperature, humidity, and battery characteristics if energy storage is involved. Then special purpose sensors specific to certain contexts could be used for measuring wind speed, soiling, integrity of façade structures, structural behavior, moisture content, crops' health conditions, or even microclimate.

The second layer is Edge Computing. Microcontrollers, gateways, or single-board computers can verify data from sensors, provide timestamping, filter out noise, detect basic faults, and issue first warnings. It proves useful anytime full-fledged connectivity cannot be guaranteed as some functions related to monitoring must continue at close proximity to the monitored object **[15][69]**.

The third layer is Mixed Communication. There is no universally applicable communication protocol. High-density sites, open areas, and urban districts have different requirements with respect to transmission distance, data throughput, energy needs, and maintenance efforts. Hence, the system shall allow for combinations of such technologies as Wi-Fi, MQTT, LoRaWAN, Cellular Networks, Zigbee, Bluetooth Low Energy, and Fieldbuses.

Fourthly, there should be secure data management and analytics. The use of a hybrid architecture of edge and cloud computing could be ideal in this context as the former will handle real-time analytics and the latter, storage, visualization, benchmarking, learning models, and fleet analytics. Data encryption, authentication, role-based access control, firmware update security, event logging, and vulnerability assessment must be incorporated into the design of the system as standard **[13][70]**.

Fifthly, there is a layer where there will be specific applications based on the intended purpose by the user. A technician, a farmer, a building manager, a homeowner, and a community administrator do not have similar screen requirements. Information should be presented to the appropriate user based on their roles.

The last level is the intelligence of the life cycle. Predictive maintenance, predictive capabilities, and digital twin are required to be introduced in stages once all other levels have been successfully integrated into the solution. Advanced analytics do not make up for data foundation weaknesses **[60][63][68]**.

Future research must focus on empirical validation. It is imperative to develop low-cost sensors that can be retrofitted to existing structures or used in historically protected buildings where no wires can be installed, nor can there be visual intrusion. Sensors for agrivoltaic systems must incorporate measurements related to energy, agronomy, hydrology, soil moisture, and microclimatic factors in one consolidated dashboard. There should be similar openness and protection of privacy for community energy dashboards.

8. CONCLUSION

This review explored smart monitoring technologies for renewable energy systems integrated into landscapes. The reviewed studies covered IoT, PV and hybrid solar energy monitoring, smart grids, microgrids, BIPV, retrofitting, agrivoltaics, predictive maintenance, digital twins, and renewable cyber-security. All the above-mentioned applications indicate that energy system monitoring is much more than just an auxiliary tool. It plays an integral role in energy efficiency, maintenance, reliability, performance, and users' trust.

The current state of monitoring technologies also indicates another major problem associated with renewable energy installations, namely their poor consideration of contexts in design. The platforms that work well for technical demonstrations might not be appropriate in the conditions of a facade, a farm, historic buildings, and community assets. In these cases, successful performance implies both the technical accuracy of sensors and other devices, and such aspects as accessibility, aesthetics, usability, privacy protection, and long-term maintenance.

The proposed framework attempts to solve this problem by employing context-oriented sensing techniques, edge computing, hybrid communication, secure analytics, tailored user interfaces, and lifelong monitoring and prediction. Such an approach will enable improved energy management in addition to making site selection, installation, maintenance, and sustainability decisions easier.

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