IoT Applied to the Monitoring of Photovoltaic Solar Energy Systems

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Abstract

Photovoltaic solar energy has become one of the central technologies of the energy transition, although its real performance depends on highly dynamic physical variables that require continuous supervision. In this context, the Internet of Things has emerged as an infrastructure capable of capturing, transmitting and analysing field data in real time. This article presents a literature review guided by three research questions on the IoT devices used for photovoltaic monitoring, their contribution to performance and efficiency, and the limitations observed in real contexts. The search was conducted in Scopus, following PRISMA guidelines, and was limited to documents published between 2022 and 2026 in the areas of computer science, energy and engineering. The results show that the most frequent architectures combine microcontrollers, electrical and environmental sensors, wireless gateways and cloud platforms. IoT monitoring contributes to detecting faults, losses due to shading, dirt and operational degradation, although challenges of calibration, connectivity, interoperability and longitudinal validation under real conditions persist. The contribution of this work lies in integrating scattered evidence from applied computer science, physics and energy engineering into a synthesis that links devices, measurable parameters and verifiable operational effects.

Keywords

Internet of Things, photovoltaic solar energy, monitoring, energy efficiency, wireless sensors

1. Introduction

The transition towards renewable energy sources has accelerated over the past decade in response to the depletion of fossil fuels and the increase in greenhouse gas emissions. In this context, photovoltaic solar energy has gained prominence due to its capacity to generate electricity in a clean, scalable manner and with increasingly competitive installation costs. Its deployment has grown steadily in both residential installations and large-scale generation plants, establishing itself as a central component in the energy strategies of numerous countries. However, installing photovoltaic capacity does not in itself guarantee optimal performance. The energy produced by a real installation depends on multiple factors that vary continuously, including climatic conditions, the state of the components, the accumulation of dirt and electrical losses throughout the system. Mohsan et al. [1] document that these conditions substantially modify the relationship between the nominal installed power and the useful energy generated, which makes monitoring a necessary tool for understanding the real behaviour of any installation.

Given this scenario, the Internet of Things (IoT) has emerged as a technological solution that allows data to be captured, transmitted and analysed continuously and at low cost. The combination of sensors, microcontrollers, communication modules and cloud platforms makes it possible to supervise photovoltaic installations in real time, identify deviations from expected behaviour and make informed decisions about operation and maintenance. Recent work shows that these systems have evolved from laboratory prototypes to scalable platforms deployed in real installations [2, 3, 4]. Despite this progress, the scientific literature proves to be scattered across studies in electronics, communications, energy

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engineering and data analytics. This situation makes it difficult to obtain an integrated view of which IoT devices are most suitable for photovoltaic monitoring, which physical quantities are of greatest priority and how these measurements translate into verifiable improvements in performance and maintenance. Therefore, this study seeks to fill that gap through a synthesis that connects technological components with the physical behaviour of the photovoltaic system and with operational decisions in real contexts. With this aim, the work is oriented around addressing three research questions:

- **RQ1:** What IoT devices are used for the monitoring of photovoltaic solar energy systems?
- **RQ2:** How does IoT monitoring contribute to improving the performance and efficiency of photovoltaic systems?
- **RQ3:** What limitations and challenges do IoT systems currently present for the monitoring of photovoltaic installations in real contexts?

Under this premise, the contribution of this work is framed within integrating evidence from applied computer science, physics and energy engineering into a synthesis that articulates devices, measurable parameters, operational effects and implementation challenges. In this way, the manuscript is organised into six sections. Section 2 develops the conceptual framework on photovoltaic solar energy, IoT architecture and its applications in energy systems. Section 3 describes the literature review methodology, addressing the search string, the selection criteria and the extraction process. Section 4 synthesises the results around devices, performance, efficiency and current challenges. Section 5 discusses the findings, practical implications and future directions. Section 6 presents the main conclusions of the study.

2. Conceptual Framework

2.1. Photovoltaic solar energy: basic physical principles

The search for alternatives to fossil fuels has placed at the centre of the energy debate a source that has been radiating energy freely for billions of years: the sun. Harnessing that energy directly, without engines, without combustion and without moving parts, is precisely what photovoltaic technology does. When solar rays strike a photovoltaic cell, they hit the atoms of the material and release electrons that begin to move in an orderly fashion. That movement of electrons is, in essence, an electric current. The more light the cell receives, the more electrons are released and the greater the current generated. In practice, the performance of an installation does not depend solely on how much light is available. Temperature, material type, wiring quality and circuit conditions also influence the amount of electricity ultimately obtained. In order to compare modules from different manufacturers under equal conditions, the industry always measures them under the same controlled laboratory conditions. The problem is that in a real installation these conditions change constantly throughout the day and the year, so that the energy produced can differ considerably from what the technical datasheet promises [1]. Therefore, anticipating and measuring this difference is one of the reasons why continuous monitoring proves so valuable [5].

To make the most of these changing conditions, photovoltaic systems incorporate controllers capable of adjusting in real time and always extracting the greatest possible power. These devices, known as MPPT controllers, continuously track the point at which the system operates with the highest efficiency. Over the years they have incorporated increasingly advanced techniques to respond better to sudden changes in light or temperature. Such is the case of Raj et al. [6], who show that optimisation algorithms notably improve this adjustment, while Kavin et al. [7] go a step further by applying machine learning to the control of the system itself. Likewise, Sharma et al. [8] broaden this perspective by demonstrating that these controllers maintain their effectiveness even in wireless communication environments. Therefore, IoT monitoring does not replace these controllers, but rather complements them by providing the data needed to evaluate their performance, detect anomalies and compare expected production with actual production.

2.2. Internet of Things: architecture and components

The Internet of Things can be understood as a set of physical objects capable of capturing information from the environment, processing it, transmitting it and acting accordingly. In photovoltaic systems, this architecture is organised into layers that work in a coordinated manner. The perception layer brings together the sensors responsible for measuring voltage, current, power, energy, irradiance, module temperature, ambient temperature, humidity, wind speed and battery status, among others. The edge layer integrates microcontrollers or embedded computers that condition the signals, filter noise, calculate derived variables and manage connectivity. The network layer transports these data using technologies such as Wi-Fi, LoRa, Zigbee, GSM or Ethernet, selected according to distance, energy consumption, available coverage and project cost. Likewise, the application layer provides storage, alarms, analysis, visualisation and remote access [9]. Specialised IoT nodes feed this layer with precision solar data [4] and, in industrial contexts, the architecture can be extended towards the monitoring and control of production on a larger scale [10].

Each installation context imposes different constraints that condition the choice of components. An urban residential system can rely on Wi-Fi without major complications, while a rural or agrivoltaic plant with limited mobile coverage requires longer-range solutions. In these distributed scenarios, technologies such as LoRa and LoRaWAN are particularly attractive due to their ability to operate with low energy consumption over long distances [11]. Along the same lines, real-time platforms facilitate visualisation and remote maintenance, although their operation depends on stable connectivity [2]. Building on this, experiences in arid regions further reinforce that cost and robustness under extreme environmental conditions remain determining constraints in many real projects [12]. Figure 1 illustrates this architecture through a conceptual map that organises the IoT components into four branches. The perception branch groups the sensors responsible for capturing the physical variables of the system, including those for irradiance, temperature, voltage, current and wind speed. The edge branch brings together the devices that process these signals locally, such as the microcontroller and the embedded computer. The network branch gathers the available communication technologies, from Wi-Fi for urban environments to LoRa, Zigbee or GSM for more remote installations. The application branch closes the cycle with the services that allow data to be stored in the cloud, visualised, alerts generated and the system accessed remotely.

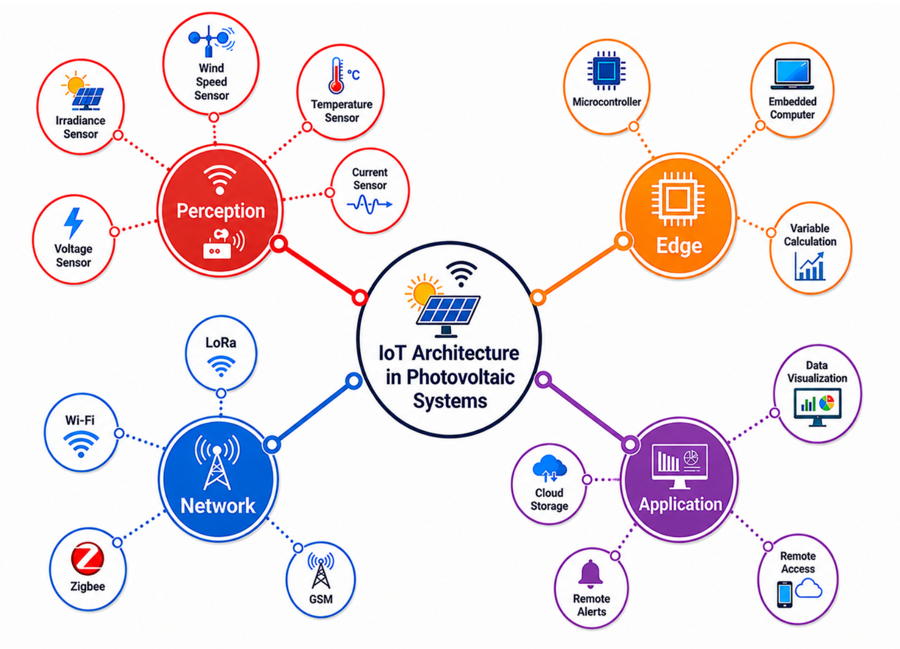

Figure 1: IoT architecture applied to photovoltaic systems.

2.3. IoT applied to energy systems

After understanding how an IoT architecture is structured and which components integrate it, it is worth examining how this technology is applied specifically in energy systems. In this context, IoT makes it possible to move from point measurements to continuous supervision that transforms the way installations are operated. This transition is particularly valuable in variable renewable sources, where operational decisions depend on time series rather than occasional inspections. In hybrid systems, digital twin approaches combined with IoT allow generation, storage and control to be coordinated in real time [13]. In solar homes, the same logic extends to energy management by integrating distributed resources and climatic conditions [14]. In zero-energy buildings, IoT-based monitoring goes further by enabling the quantification of the overall energy performance of the building from its renewable sources [15].

Applied to the photovoltaic domain, this capacity for continuous supervision unfolds through three dimensions that complement each other. The first is operational visibility, which allows knowing in real time whether the plant is producing what is expected of it. From this visibility, the second dimension is diagnosis, which makes it possible to detect faults, shading, dirt, disconnections, overtemperature or degradation before these anomalies translate into significant losses. In this direction, Abdallah et al. [16] illustrate this potential by showing how measured data are transformed into actionable indicators for intelligent shading detection, while Segovia Ramírez et al. [17] extend this diagnostic capacity in large-scale plants through IoT platforms with machine learning. With this diagnosis as a basis, the third dimension is optimisation, which translates the indicators into concrete decisions on maintenance, cleaning, storage and generation prediction. In this way, De Souza et al. [18] show that traversing these three dimensions in an integrated manner is what transforms monitoring into a real management tool and not merely a data log.

3. Methodological Procedure

This review adopted a narrative design guided by three research questions on IoT devices, performance and limitations in photovoltaic systems. Unlike systematic reviews with a complete PRISMA protocol or quantitative meta-analyses, this narrative approach is more appropriate when the available literature is diverse in methods, devices and application contexts, as occurs in the field of photovoltaic monitoring with IoT, where laboratory prototypes, field implementations and commercial platforms that do not share comparable metrics coexist. The bibliographic search was conducted in Scopus as the sole source, a decision that responds to its broad coverage of indexed journals in computer science, energy and engineering, to the comparability of its metadata across records and to its filtering tools that facilitate the systematic processing of the scientific literature. The available studies on photovoltaic monitoring with IoT are concentrated in indexed publications that this database collects consistently, which made it possible to bring together experimental studies, review papers and computational contributions under uniform search and selection criteria that are presented in the following subsections.

3.1. Search String

The search string was constructed from three conceptual groups. The first delimited the technological dimension through terms associated with IoT and wireless sensor networks. The second delimited the photovoltaic domain with expressions related to PV systems, solar panels and solar energy. The third delimited the purpose of the review through terms linked to monitoring, fault detection, performance and efficiency. The advanced search executed in Scopus was as follows:

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TITLE-ABS-KEY ( “IoT” OR “Internet of Things” OR “wireless sensor network”
) AND TITLE-ABS-KEY ( “photovoltaic” OR “solar energy” OR “PV system” OR
“solar panel” ) AND TITLE-ABS-KEY ( “monitoring” OR “fault detection” OR
“performance” OR “efficiency” )
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The query retrieved 640 initial records, to which the inclusion and exclusion criteria described in the following subsection were applied.

3.2. Inclusion and Exclusion Criteria

Studies were included that addressed photovoltaic systems or energy applications powered by photovoltaics, that employed IoT, sensor networks, wireless communication, cloud platforms or remote data acquisition, that reported measurable parameters such as voltage, current, power, irradiance, temperature, energy, battery status or faults, and that provided evidence of design, implementation, review, diagnosis or optimisation. Works focused solely on photovoltaic materials without monitoring, studies of power electronics without remote acquisition, non-photovoltaic solar applications and documents without sufficient information on monitored devices or parameters were excluded. Documents of the type article, conference paper and review were retained, published in English, within the areas of computer science, energy and engineering, with a time interval from 2022 to 2026.

3.3. Study Selection Process

The selection process followed the PRISMA diagram guidelines and was developed in four stages. The search in Scopus retrieved 640 initial records, of which 12 were eliminated before screening for not meeting the purpose of the study, leaving 628 records for review. In the second stage, a title and abstract reading was applied, after which 513 documents were excluded for not meeting the thematic criteria, leaving 115 records for retrieval. Of these, 3 could not be retrieved, so 112 reports advanced to the eligibility assessment. In the third stage, full-text reading led to the exclusion of 89 works distributed across three reasons: 28 for not incorporating IoT devices applied to photovoltaic monitoring, 39 for not reporting measurable parameters or operational evidence, and 22 for not addressing implementation challenges in real contexts. After this process, the final set consisted of 23 studies included in the review, all of them directly linked to the three research questions and present in the synthesis of results. The complete process is summarised in Figure 2.

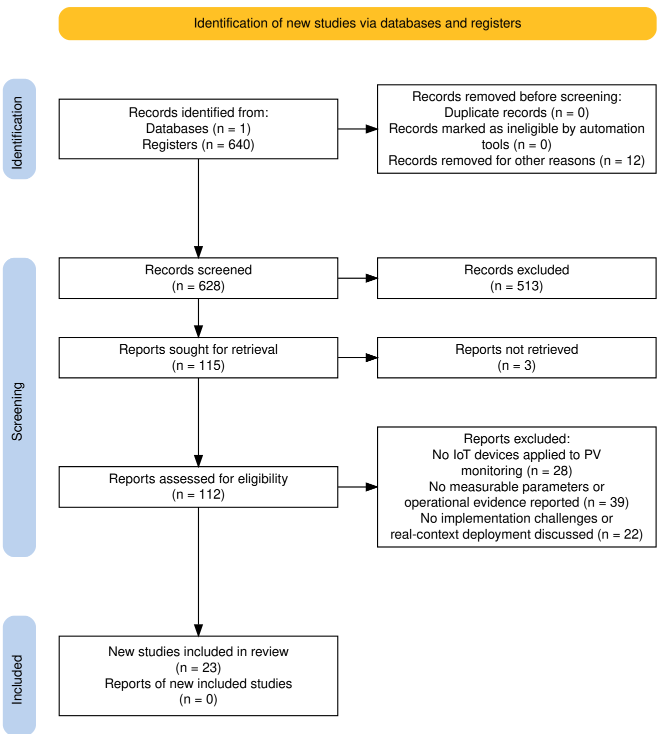

Figure 2: PRISMA diagram of the study selection process.

4. Review Results

4.1. IoT Devices for Photovoltaic Monitoring

The findings on RQ1 reveal that IoT architectures for photovoltaic systems are organised around four functional blocks that act in a coordinated manner. The first is the electrical block, which brings together voltage, current, power and energy sensors, as well as data acquisition modules and battery sensors. These devices make it possible to estimate the instantaneous power and the operational state of the system [19], to observe the state of charge and the energy stored in microgrids [20] and to record electrical variables together with battery and inverter data in standalone systems [9]. Building on this electrical record, the environmental block complements the picture of the system by incorporating pyranometers or irradiance sensors, thermistors or digital temperature sensors, and humidity, wind, rain and dust sensors. Relating the available solar resource to the electrical output of the system requires simultaneously measuring both dimensions [3]. Irradiance prediction from module parameters also helps to separate environmental variability from real electrical performance [5], a distinction that is particularly relevant in arid regions where environmental conditions can distort the interpretation of losses [12].

With these signals captured, the third block, formed by embedded nodes such as Arduino, ESP32 or Raspberry Pi, is responsible for reading the signals, converting them to physical units, applying basic filters, packaging the data and sending them towards a gateway or the cloud. The literature shows that these nodes have evolved towards specialised solutions for solar measurements [4], with the capacity to integrate with autonomous inspection using UAVs [21] and to be oriented towards production control in industrial environments [10]. The fourth block closes the cycle through communication and visualisation technologies, including Wi-Fi, GSM, LoRa, MQTT, cloud platforms, databases and mobile applications. The choice of protocol depends on the scale of the installation and the real-time monitoring requirements [2]. In distributed installations, LoRaWAN offers long-range coverage with low energy consumption [11], while cloud platforms prioritise the storage and visualisation of generation [22]. Table 1 synthesises the twelve most representative studies for RQ1 and indicates which functional blocks each one covers, which allows direct identification of which device combinations predominate in the recent literature. As Table 1 reveals, the embedded block is the most transversal of the four, present in all of the analysed studies, which reflects that every photovoltaic IoT system requires a local

Table 1
IoT devices identified by functional block in the reviewed studies

Study	Electrical	Environmental	Embedded	Communication
Jacome et al. [19]	✓	✓	✓	✓
Ilori et al. [9]	✓	✓	✓	✓
Mamun et al. [3]	✓	✓	✓	✓
Voicu et al. [4]	✓	✓	✓	
Haddad et al. [2]	✓		✓	✓
Iksan et al. [20]	✓		✓	✓
Nafa et al. [5]		✓	✓	
Hamied et al. [12]	✓	✓	✓	✓
Tradacete et al. [21]	✓	✓	✓	✓
De Souza Filho et al. [10]	✓		✓	✓
Diaz et al. [11]	✓		✓	✓
Rao et al. [22]	✓		✓	✓

✓ = block present in the study

processing node regardless of its scale or purpose. The electrical block appears in eleven of the twelve studies, confirming that the measurement of voltage, current and power constitutes the minimum basis of any monitoring architecture. The environmental block, present in seven studies, proves decisive when the objective is to separate electrical losses from climatic variability. The communication block, present in ten studies, shows that remote data transmission is almost universal, although the chosen technology varies according to the deployment context. Table 2 broadens this view by gathering the 23 studies linked to the research questions, detailing for each one the devices used, the monitored parameters, and the main finding.

Table 2 highlights the diversity of approaches that coexist in the recent literature. Some studies prioritise low-cost instrumentation for residential or rural contexts, while others target scalable platforms for large-scale plants. Therefore, this diversity reflects that there is no universal IoT architecture for photovoltaic monitoring, but rather that the choice of devices, parameters and communication protocols depends on the deployment context, the available resources and the operational objectives of each installation.

Table 2
Summary of the analysed studies on IoT and photovoltaic monitoring

Author	**IoT devices used**	**Monitored parameters**	**Main finding**
Jacome et al. [19]	Autonomous IoT acquisition system	Voltage, current, power and environmental variables	Real-time acquisition improves operational traceability and diagnosis of isolated systems.
Ilori et al. [9]	Wireless sensor network and IoT	Electrical and environmental variables of the PV generator	A WSN-IoT architecture enables low-cost remote monitoring.
Haddad et al. [2]	Scalable real-time monitoring system	Production and operation of PV systems	Scalability is critical for comparing strings and orientations.
Voicu et al. [4]	IoT sensor node for solar measurements	Solar energy quantities and measurement conditions	Specialised nodes facilitate distributed instrumentation.
Balakrishnan et al. [23]	IoT platform for panel diagnosis	Electrical signals associated with faults	IoT enables early detection and diagnosis of panel faults.
Raj et al. [24]	IoT platform with data analytics	PV plant operation data	Analytics improves fault classification and maintenance support.
Segovia Ramírez et al. [17]	IoT platform with machine learning	Multi-source data from large PV plants	ML on IoT data strengthens fault detection and diagnosis.
Iksan et al. [20]	IoT battery monitoring in PV microgrid	Current, voltage, power, energy and battery	Storage monitoring improves energy continuity management.
Hamied et al. [12]	Low-cost PV system with IoT	PV variables and arid region conditions	Low-cost solutions are viable but depend on environmental robustness.
Abdallah et al. [16]	Intelligent monitoring with neural networks	Signals for shading detection	AI can identify shading and support corrective actions.
Mamun et al. [3]	ESP32 with mobile application	Temperature, humidity, voltage and current	Low-cost hardware enables remote monitoring from mobile devices.
Nafa et al. [5]	Irradiance and temperature sensor	W/m^2 and °C	Separates losses from low solar resource from losses due to overheating.

Table 2. Summary of analysed studies (continued)

Author	**IoT devices used**	**Monitored parameters**	**Main finding**
Tradacete et al. [21]	IoT electronics integrated with UAV	Electrical and environmental variables	UAV integration extends autonomous inspection of large installations.
De Souza Filho et al. [10]	Industrial IoT architecture	Solar production variables	Industrial architectures orient IoT towards production control at scale.
Diaz et al. [11]	LoRaWAN nodes	Electrical variables in distributed installations	LoRaWAN offers long-range coverage with low energy consumption.
Rao et al. [22]	Cloud platform	Photovoltaic generation data	The cloud facilitates long-term storage and visualisation of generation.
Saeed et al. [25]	IoT cleaning system	Production and soiling state of modules	Data-driven cleaning reduces water consumption and manual labour.
Xie et al. [26]	IoT cleaning robot	Production and surface state of panels	Robotic solutions connected to IoT automate preventive maintenance.
Chalal et al. [13]	Digital twin with IoT	Generation, storage and control	The digital twin extends management towards coordinated control in hybrid systems.
Fadillah et al. [27]	Hybrid diesel-solar IoT system	Real-time operational variables	Real-time data integration supports operational continuity in hybrid pumping.
Heo et al. [28]	IoT sensors with predictive model	Expected vs. measured generation	Prediction models improve the anticipation of operational deviations.
Petcut et al. [29]	Edge-AI nodes	Energy optimisation variables	Edge-AI decentralises energy optimisation at the field nodes.
De Souza et al. [18]	IoT management platform	Operation and maintenance indicators	Integrated management links monitoring with operation and maintenance decisions.

4.2. Impact on Performance and Efficiency

To address RQ2, the reviewed studies converge on a central idea. IoT monitoring improves the performance of a photovoltaic system when it manages to convert physical data into concrete operation and maintenance actions, as Table 3 synthesises. The most immediate contribution is the detection of deviations between expected power and measured power. When irradiance is high and production falls below the historical pattern, the system can signal shading, dirt, disconnections, inverter faults or module degradation before these anomalies translate into prolonged losses. Balakrishnan et al. [23] demonstrate this capacity in the early diagnosis of panel faults, while Raj et al. [24] broaden this scope by incorporating data analytics to classify faults and guide maintenance decisions. In large-scale installations, Segovia Ramírez et al. [17] go a step further by applying machine learning on IoT platforms, which reduces dependence on extensive manual inspections.

Building on this continuous diagnosis, monitoring also enables predictive maintenance and condition-based cleaning, dimensions that Table 3 illustrates through the critical parameters of each technological layer. A system that triggers cleaning only when data evidence a production drop attributable to dirt consumes less water and manual labour than one that operates with fixed calendar routines. In this direction, Saeed et al. [25] and Xie et al. [26] document this trend in photovoltaic cleaning systems

Table 3
Interpretive reading of the relationship between IoT devices and operational improvement

Author	IoT device or layer	Critical parameter	Interpretation for PV operation
Nafa et al. [5]	Irradiance and temperature sensor	W/m^2, °C	Differentiates losses from low solar resource from losses due to overheating or generator anomalies.
Jacome et al. [19]	Voltage and current sensors	V, A, W	Enable detection of power deviations, string imbalance and possible disconnections.
Ilori et al. [9]	Energy meter and connected inverter	kWh, efficiency, alarms	Relates daily production to availability and facilitates performance ratio monitoring.
Haddad et al. [2]	Wireless node or gateway	Latency, coverage, packet loss	Determines whether the alert arrives in time to avoid prolonged losses.
Segovia Ramírez et al. [17]	Cloud or edge analytics	Percentage deviation, temporal trend	Converts data series into diagnosis, maintenance prioritisation and evidence of improvement.

connected to IoT, including robotic solutions. As a complement, battery monitoring allows storage to be managed in photovoltaic microgrids with greater precision [20], while hybrid systems with a digital twin extend this management towards the coordinated control of generation and storage [13]. Along the same lines, neural networks allow shading patterns to be identified that would be difficult to detect with fixed thresholds [16], prediction models combine IoT sensor data with expected generation estimates to anticipate deviations [28] and Edge-AI solutions decentralise energy optimisation directly at the field nodes [29].

As Table 3 shows, the impact of IoT monitoring on performance does not depend on a single device or a single variable, but rather on the capacity of the system to articulate sensors, communication and analytics around concrete operational decisions. Nevertheless, this quantitative impact ultimately depends on data quality, sensor calibration, sampling frequency and the real capacity to transform alerts into timely interventions.

4.3. Current Limitations and Challenges

Regarding RQ3, the reviewed studies show that the limitations of IoT systems for photovoltaic monitoring are distributed across three levels that condition each other, as Table 4 records. At the physical level, sensors are exposed to radiation, humidity, dust, corrosion, elevated temperature and electrical noise. A poorly calibrated current or irradiance measurement can produce erroneous diagnoses and inefficient maintenance decisions. Furthermore, module temperature can differ substantially from ambient temperature, so that using a single thermal variable oversimplifies the real behaviour of the generator [19]. In arid regions, these conditions make this distinction more critical [12], and systems that combine electrical and environmental variables reduce this interpretive risk [9]. In this way, at the technological level, the challenges include loss of connectivity, node energy consumption, device compatibility, platform scalability, alarm latency, data security and dependence on cloud services. Low-cost solutions are attractive for laboratories or residential users, but may present limitations in precision, encapsulation and field service life. Scalable real-time platforms improve operational robustness, although they require communication infrastructure and data management [2]. Cloud systems facilitate remote supervision, but may increase technological dependence [22]. Plant optimisation proposals using IoT also show that adoption depends on the management and maintenance capabilities available

Table 4
Limitations and challenges identified in IoT systems for photovoltaic monitoring

Level	Identified challenge	Studies
Physical	Sensor degradation due to environmental exposure	[12]
	Calibration errors in current and irradiance measurement	[19]
	Difference between module temperature and ambient temperature	[9]
Technological	Loss of connectivity and latency in alarm transmission	[2]
	Precision and service life limitations in low-cost solutions	[12]
	Dependence on cloud services and data security	[22]
	Adoption conditioned by organisational management capabilities	[18]
Organisational	Studies based on short-duration prototypes	[19, 9]
	Diversity of climates, plant sizes and evaluation metrics	[17]
	Absence of longitudinal studies in diverse real conditions	[2, 22]

in each organisation [18]. Whereas at the organisational level, short-duration prototypes or pilots are evident, which makes it difficult to estimate annual degradation, failure rate, total cost of ownership and real benefits in recovered kWh. The diversity of climates, plant sizes, inverter configurations and evaluation metrics also prevents direct comparison of all results.

Table 4 makes clear that the challenges are not independent of each other. A poorly calibrated sensor at the physical level generates unreliable data that compromise the diagnosis at the technological level, and this uncertainty about data quality in turn makes decision-making more difficult at the organisational level. Therefore, the available evidence supports the value of IoT for photovoltaic monitoring, although it still requires greater attention and comparative studies on the real conditions in which they are implemented in order to consolidate this support with verifiable long-term data.

5. Conclusions

This review shows that IoT has established itself as a technological tool capable of transforming the monitoring of photovoltaic systems, not as an instrumental add-on, but as a layer that connects measurable physical quantities with real operation and maintenance decisions. The results obtained make it possible to answer the three questions that guided the work. Regarding the devices used, the recent literature shows that IoT architectures are organised into four functional blocks: electrical sensors to measure voltage, current, power and energy; environmental sensors to capture irradiance, temperature, humidity and wind; embedded nodes such as Arduino, ESP32 or Raspberry Pi to process and transmit data; and communication and visualisation technologies such as Wi-Fi, LoRa, MQTT and cloud platforms. The embedded block appears in all of the analysed studies, which confirms that no monitoring architecture dispenses with a local processing node.

Regarding performance, IoT monitoring generates value when it closes the cycle between measurement, diagnosis and action. The most documented contributions are early fault detection, condition-based cleaning, evaluation of maximum power point tracking, battery management and microgrid operation. However, this impact depends on the metrological quality of the sensors, the robustness of the communications and the real capacity to transform alerts into timely interventions. A system that only accumulates data without generating maintenance decisions has limited operational value. Regarding the challenges, IoT systems for photovoltaic monitoring face limitations at three mutually conditioning levels. Sensor degradation and calibration errors compromise data reliability at the physical level. Loss of connectivity and dependence on external services condition sustainability at the technological level.

The scarcity of long-duration studies under diverse real conditions limits the capacity to generalise findings at the organisational level.

5.1. Practical Implications

For those who design or manage photovoltaic installations, the priority should not be to install the greatest possible number of sensors, but to ensure that at least the variables that allow the real behaviour of the system to be interpreted are covered: irradiance, module temperature, string voltage and accumulated energy. In rural or distributed installations, technologies such as LoRaWAN offer long-range coverage with low consumption, although they require local storage mechanisms in the event of disconnections. In systems with energy storage, battery monitoring must be integrated into the generation diagnosis and not treated as an optional module. For installation managers, the value does not lie in accumulating data but in configuring thresholds, alarms and reports that indicate losses in W, kWh or percentage deviation from a verifiable baseline.

5.2. Study Limitations

Like any literature review, this work has a scope defined by methodological decisions that should be acknowledged honestly.

- The use of Scopus as the sole source may have excluded relevant studies published in IEEE Xplore, ACM Digital Library, Web of Science or regional open-access repositories, especially works from countries with less indexed scientific output but with significant photovoltaic deployment.
- The analysed studies do not share the same metrics, hardware configurations or installation conditions, which prevents direct quantitative comparisons between results.
- The geographical and climatic diversity of the documented contexts limits the transferability of the identified patterns to any environment without prior local validation.
- The literature tends to report successful implementations, while systems that did not achieve their objectives or were abandoned in the pilot phase rarely generate publications, which may produce a more favourable image of the maturity of the field than actual practice reflects.

5.3. Future Research Directions

The available evidence leaves open several directions that merit attention in the coming years. The most urgent is the conduct of studies that evaluate the performance of IoT systems for at least one complete annual cycle and in contrasting climates, from arid and tropical zones to coastal and high-mountain environments. A second direction is the comparison between low-cost sensors and calibrated reference instrumentation, with the aim of quantifying measurement uncertainty and establishing evidence-based selection criteria. A third direction is the integration of artificial intelligence in the field nodes, so that the system not only classifies anomalies but also identifies whether these are associated with irradiance, temperature, dirt, shading or power electronics. Furthermore, autonomous UAV inspection integrated with IoT electronics at the panel level also opens up opportunities for the maintenance of large installations [21], and Edge-AI solutions complement this direction through decentralised optimisation and fault detection at runtime [29]. Therefore, advancing along these directions will allow IoT monitoring to be consolidated as a verifiable and replicable energy management tool in diverse real contexts [18].

Declaration on Generative AI

During the preparation of this work, the authors used generative artificial intelligence tools as support for organising ideas, reviewing the writing and improving the clarity of the text. The authors reviewed, edited and verified the resulting content, and assume full responsibility for the final content of the publication.

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