

A review of IoT enabled intelligent smart energy management for photovoltaic power forecasting and generation

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ABSTRACT

Renewable energy has emerged as one of the most reliable and widely accepted approaches to address the rising global energy requirements. Among these, solar power development requires focused attention on both maintenance strategies and application methods. To enhance solar energy utilization, Internet of Things (IoT)-enabled monitoring frameworks have been designed, allowing real-time collection and analysis of solar parameters for predicting efficiency and ensuring stable electricity generation. A major concern in demand-side energy regulation lies in utilizing renewable sources effectively while keeping costs manageable and minimizing unnecessary consumption. Hence, careful planning of renewable resource integration is essential. Advanced energy management platforms play a crucial role in supervising energy distribution, especially in scenarios where heavy dependence on the grid exists. The complexities and opportunities introduced by expanding grid networks can be efficiently managed through cloud-based technologies. This work emphasizes the practical application of energy management systems in both industrial operations and academic research, treating them as key stakeholders in the energy sector. The investigation offers a detailed evaluation of IoT applications in photovoltaic power systems and highlights the promising future avenues available to researchers. These include developing new benchmarks to measure IoT performance and refining existing systems through innovative approaches. Furthermore, there is an increasing demand for comprehensive studies on intelligent energy frameworks in smart infrastructures. Such research is critical to advancing IoT-driven applications and sustaining continuous progress in this domain.

List of Abbreviations

IoT	Internet of Things
SEMS	Smart Energy Management System
ISEMS	Intelligent Smart Energy Management System
AI	Artificial Intelligence
ML	Machine Learning
ANN	Artificial Neural Network
SVM	Support Vector Machine
EV	Electric Vehicle
PV	Photovoltaic
DG	Distributed Generation
SOC	State of Charge
DoD	Depth of Discharge
ESS	Energy Storage System
EMS	Energy Management System
ICT	Information and Communication Technology

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AMR	Automatic Meter Reading
AMI	Advanced Metering Infrastructure
GSM	Global System for Mobile Communications
GPS	Global Positioning System
RFID	Radio Frequency Identification
Wi-Fi	Wireless Fidelity
LoRa	Long Range (Low Power Wide Area Network)
LPWAN	Low Power Wide Area Network
V2G	Vehicle-to-Grid
V2X	Vehicle-to-Everything
WPAN	Wireless Personal Area Network
NFC	Near Field Communication
UWB	Ultra-Wide Band
BLE	Bluetooth Low Energy

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1. Introduction

The deployment of Internet of Things (IoT) technologies has significantly transformed modern energy management, particularly in photovoltaic (PV) power generation systems. This work focuses on IoT-driven smart energy management frameworks designed to supervise, regulate, and enhance PV energy utilization. By integrating sensing devices, real-time analytics, and interconnected hardware, it introduces innovative approaches that go beyond the limitations of traditional management methods [1]. With the growing demand for renewable and sustainable electricity, PV generation has become increasingly important. However, realizing its full benefits requires advanced systems capable of adapting to changing environmental conditions, optimizing load usage, and ensuring seamless grid integration of PV energy [2] (see Table 5).

This review investigates the critical elements of IoT-based energy management for PV applications. It discusses the choice of micro-controllers, sensor integration, circuit complexity, and communication strategies, presenting a detailed view of the technological ecosystem [3]. Additionally, it outlines the role of cloud platforms, big data, and IoT gateways in enhancing adaptability, scalability, and overall performance. The study contributes to ongoing discussions on sustainable energy solutions by analyzing present advancements, technical challenges, and possible use cases for IoT-enabled PV energy systems. It also explores future opportunities for improving energy generation, transmission, and consumption [4]. To achieve optimal usage, intelligent demand-side management must combine distributed resources with renewable power generation [5]. Such an integrated strategy enhances the resilience, reliability, and sustainability of energy infrastructure. Merging renewable sources with intelligent management frameworks can maximize efficiency, reduce ecological impact, and promote the development of a greener energy ecosystem. The growing role of renewable energy in meeting global electricity requirements highlights the importance of small-scale rooftop PV setups, especially in urban regions. These can be deployed as stand-alone units or integrated hybrid systems with the utility grid [6,7]. In developing countries, issues like inconsistent supply and unstable grids stress the importance of hybrid solutions that balance grid-connected and off-grid models [8]. Effective load scheduling based on grid availability and PV output is crucial, supported by predictive algorithms that improve performance under fluctuating weather conditions [9].

2. Significance of the Internet of Things

During the mid-1980s, data transfer was mainly restricted to voice and text through telecom networks. With time, innovations such as Voice-over-Internet Protocol (VoIP) expanded these capabilities. Today, this evolution has led to the concept of the Internet of Things (IoT), which connects physical devices over the Internet, enabling automation, monitoring, and remote operation [10–12]. The first practical use of IoT was seen in the early 1990s with the “Trojan Room” coffee pot. Since then, the field has rapidly advanced, with industries and researchers introducing different definitions aligned with their perspectives [13,14].

The growth of IoT can be traced through several phases:

Pre-Internet Phase: Communication limited to landline telephony and SMS; later enhanced by mobile phones [15].

Internet Content Era: Focus on information transfer, including emails and file sharing [16–18].

Internet Services Era: Rise of e-commerce and digital productivity applications.

Internet of Everything: A phase where platforms like YouTube, Facebook, and Skype promote global connectivity, automation, and minimal human involvement [19].

Smart grids hold a central role in managing renewable sources such as PV systems. Their hybrid structure links distributed generators, demand-response units, substations, microgrids, sensors, home

appliances, and communication networks [20–22]. Smart meters at user locations enable two-way data transfer, ensuring real-time consumption monitoring and integration with IT systems. This review also explores cloud computing as a supporting technology within grid-based energy management. A robust communication backbone is essential for managing fluctuations in power supply [23,24].

The study highlights proactive cloud computing methods for IoT-enabled grids, emphasizing intelligent power allocation, predictive data-driven analysis, and effective supervision [25–28]. The major areas covered include.

- The application of cloud-based platforms for energy optimization.
- The scalability, reliability, and responsiveness of cloud-assisted energy distribution in smart systems.
- The convergence of IoT and cloud computing as a pathway to efficient, adaptive, and sustainable energy management practices.

The inclusion of the table in this review plays a crucial role in strengthening both the clarity and the scholarly value of the study. Primarily, it consolidates the literature examined, with a particular emphasis on prominent databases such as ACM, IEEE Xplore, and Science Direct. This broad coverage not only reflects the comprehensiveness of the review but also serves as a practical reference for other researchers interested in related works. By mapping the keywords linked to each database, the table highlights the thematic orientations of prior studies ranging from IoT implementations to communication frameworks and energy management strategies thereby defining the boundaries of the review more clearly.

The quantification of publications retrieved from each database further underscores the rigor of the analysis and showcases the depth of investigation. In addition, information about the types of content whether journal papers, conference proceedings, or technical reports provides readers with insights into the accessibility and diversity of resources across platforms. Its tabular organization facilitates straightforward comparison, ensuring transparency in the selection and evaluation of sources while also making the review process more traceable. Beyond summarizing prior work, the table acts as a research roadmap by identifying critical knowledge repositories and drawing attention to underexplored areas that could benefit from further inquiry. Thus, it not only enhances the readability and organization of the paper but also improves the overall comprehensiveness and impact of the review.

This review conducts a detailed examination of the research approaches adopted by different scholars, with particular attention to their role in advancing energy management practices, as outlined in Table 1. These approaches emphasize the integration of Internet of Things (IoT) technologies with solar energy generation systems. The central aim of the study is to provide a thorough overview of the various strategies employed in intelligent energy management for photovoltaic (PV) power systems. It also acknowledges that IoT-enabled configurations may differ across applications, and a management technique that proves effective in one PV setup might not necessarily deliver the same performance in another [29,30].

To identify the most effective approaches for energy management, this study analyzes and compares a range of techniques applied within different IoT-based configurations, as depicted in Fig. 1. The discussion in Section 2 highlights selected publications that propose IoT-driven solutions for enhanced energy utilization. Section 4 focuses on strategies adopted in smart grid environments, with emphasis on those integrating photovoltaic (PV) sources. Section 5 reviews existing literature that recommends IoT-enabled control mechanisms for regulating energy flow in solar power systems. Collectively, these evaluations aim to provide deeper insights into the flexibility, applicability, and overall efficiency of various strategies across diverse IoT-based PV energy management frameworks.

Table 1
Studies retrieved from the search string review.

Serial number	Website	E-content	Keywords	Papers reviewed
1	www.acm.org	There is an extensive collection of scholarly and professional resources, including digital databases, periodicals, research articles, technical reports, conference proceedings, academic journals, and professional transactions.	Applications of the Internet of Things (IoT), modes of communication, associated challenges, and existing issues	93
2	www.ieeexplore.org			285
3	www.sciencedirect.com			250
4	www.scholar.google.com			135
5	www.onlinelibrarywiley.com			89
6	www.springerlink.com			110
7	www.knowledge.com			104
8	www.elsevier.com			155
9	No of papers reviewed			1221

3. Integration of smart energy systems in photovoltaic generation

The worldwide shift away from fossil fuels underscores the increasing dependence on renewable energy to satisfy rising power demands in both sustainable and economical ways [31,32]. Within the design of modern grid-connected systems, the inclusion of photovoltaic (PV) storage plays a central role, though it is complicated by the variability and intermittency of renewable generation [33]. Addressing these challenges calls for the development of precise forecasting tools for energy availability and the adoption of advanced scheduling methodologies for day-to-day operations [34,35]. To tackle these issues, researchers have proposed an intelligent energy management framework specifically designed for renewable-based applications, enabling more effective demand regulation in smart grid settings. This approach makes extensive use of demand-side management techniques, which exploit

renewable resources to maximize energy efficiency [36,37]. A core element of this framework is the Intelligent Solar Energy Management System (ISEMS). ISEMS integrates predictive energy management methods, IoT-enabled data acquisition from consumers and devices, and a solar energy generation platform coupled with data analytics. Its main objectives are to enhance energy efficiency, improve the precision of forecasts, and ensure the smooth integration of renewable power into broader energy infrastructures, as outlined in Table 2.

The Internet of Things (IoT) was conceived to enable smooth connectivity among diverse devices ranging from computers and smartphones to sensors and actuators through Internet-based communication. This interconnection is achieved by integrating components such as microchips, controllers, transceivers, data transfer technologies, and standardized communication protocols [38,39]. Compared to conventional manual inspection methods, IoT-enhanced systems provide a more reliable and efficient approach for monitoring and controlling solar power installations, particularly across large-scale or remote sites [40]. The system examined in this study is capable of tracking several key parameters, including voltage, current, temperature, and solar irradiance on photovoltaic (PV) cells, along with their corresponding electrical outputs [41,42]. Data acquisition is managed through an Arduino board, with a NodeMCU wireless module transmitting the collected information to the Internet. Once online, the measurements can be visualized using ThingSpeak, an open-source IoT-based cloud platform [43]. A representation of the system’s architecture is provided in Fig. 2.

The Arduino kit, combined with the Wi-Fi module, enables real-time sensor data transmission to the cloud. This allows users to access live information via a status application that continuously updates measurement values [44–46]. To utilize the service, users are required to either register an account or use an IP address, which provides access to multiple channels for analyzing network parameters, as summarized in Table 3. The platform also supports intuitive visualization of data through a web-based interface, offering a practical and Internet-enabled monitoring solution [47–49]. One of the major advantages of this system lies in its ability to remotely track PV system performance metrics from any location with Internet connectivity. Fig. 3 illustrates the gateway information system, highlighting its core components and their interactions within the overall architecture (see Table 4) (see Fig. 4).

3.1. Comparative analysis of IoT-based energy monitoring systems

A comparative review of 30 IoT-enabled energy monitoring solutions

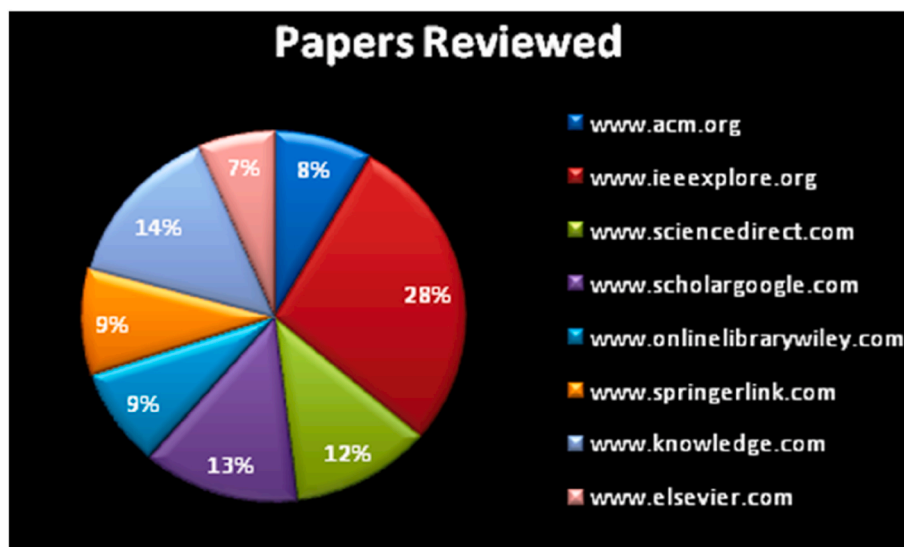


Fig. 1. Visualization of literature review findings through a pie chart.

Table 2
Review and comparison of IoT applications.

IoT Application	Key Needs	Approaches	Suggested Strategies
Smart Home	Efficient data handling, situational awareness, low latency, secure communications	Task delegation, intelligent data aggregation, context-aware smart solutions	Enhance responsiveness, reduce network traffic, implement context-adaptive processing, and distribute tasks to improve system resilience
Agriculture	Reliable sensor networks, flexible data management, energy-efficient operations	Data compression, intelligent sensing, mobile energy delivery	Utilize sensors to optimize and compress data, employ mobile units to supply power, and adopt smart data collection to limit network load
Healthcare	Fast system response, mobile nodes, robustness, privacy protection	Mobile energy solutions, wearable and connected IoT, energy harvesting from motion	Leverage kinetic energy for device charging, use RF wireless power for mobile devices, implement network virtualization to lower response times, and integrate collaborative IoT for higher reliability
Industrial IoT	Low-latency operations, robustness, secure and available networks, device diversity, scalability	Cognitive IoT, task offloading, mobile sensing, RF energy harvesting, smart sleep/wake management, network virtualization	Apply wireless energy transfer, optimize mobile energy routing, use machine learning for efficient data handling, and accelerate system responses to minimize communication overhead

reveals significant variation in terms of hardware configurations, monitoring approaches, and application contexts [80]. A recurring pattern across these studies is the use of low-power microcontrollers such as ESP8266, Raspberry Pi, and Arduino paired with sensors for current, voltage, temperature, and light to achieve real-time energy tracking [81]. Most systems rely on Wi-Fi or Ethernet modules to transmit data to cloud-based platforms, such as Adafruit. io or custom servers, for centralized collection and analysis. Commonly used current sensors include PZEM004T, ACS712, and SCT-013-000, while relay modules are employed to switch connected appliances or circuits based on predefined thresholds.

The monitoring techniques highlighted in these studies frequently leverage cloud computing for data storage and remote access, enabling instantaneous feedback and detailed consumption analysis. Protocols such as MQTT and Modbus are widely implemented to facilitate smooth data transmission and interoperability with smart grid infrastructures, thereby improving flexibility and scalability [82]. Many systems also integrate visualization interfaces, via LCD panels or smartphone applications, to offer end-users intuitive insights into energy usage patterns. From an application perspective, the predominant focus lies in residential and commercial energy management, with particular attention to smart home automation, solar power integration, and demand-side management [83]. Reducing energy consumption and minimizing carbon emissions remain core objectives, often supported by predictive algorithms or AI-driven optimization for load forecasting and usage analysis. Nevertheless, these IoT-based systems face challenges, including concerns around data privacy, device interoperability, and

signal interference [84,85]. Future research directions include enhancing system resilience, incorporating advanced machine learning models for more accurate forecasting, and establishing standardized frameworks to enable seamless integration of heterogeneous IoT devices [86]. While current solutions show strong potential for real-time monitoring and automated energy control, further advancements in communication protocols, system integration, and device compatibility are essential for their adoption at larger scales, such as in smart cities or industrial automation.

4. Designing a remote PV power generation monitoring system

Developing an effective solar power monitoring system requires careful selection of hardware components, precise specifications, and detailed circuit design to enable remote access to all energy metrics [87, 88]. This study provides a detailed overview of the critical equipment necessary for successful system implementation. It emphasizes microcontroller selection criteria and discusses the range of sensors used to measure essential parameters, including voltage, current, and other variables vital for accurate power computation [89,90]. Proper integration of these components ensures that the monitoring system delivers accurate, reliable, and real-time oversight of photovoltaic (PV) power generation processes.

4.1. Component specification

This section presents a detailed examination of the key components required for designing varied IoT-based system architectures. It provides an in-depth analysis of LCD display standards, outlining the essential parameters that influence selection to ensure optimal user interaction and readability [91,92]. The discussion further addresses the criteria for choosing Wi-Fi modules, emphasizing attributes that guarantee reliable communication, stable connectivity, and efficient data transmission. The integration of cloud computing is also explored, highlighting its pivotal role in enabling scalable data storage, processing capabilities, and remote accessibility for monitoring and management purposes [93, 94]. The section concludes with a comprehensive evaluation of the components depicted in the circuit diagram of the IoT-enabled smart energy management system coupled with photovoltaic (PV) generation [95]. These elements are fundamental to the seamless operation of the system, supporting efficient energy management, accurate data acquisition, and actionable insights to enhance overall performance [96].

4.2. Roles of components in smart energy management systems

Components in smart energy management systems serve distinct yet complementary functions, each contributing to enhanced efficiency, control, and adaptability [97]. For example, the Smart Plug and Current Sensor both facilitate energy monitoring but in different contexts. The Smart Plug focuses on end-user control, allowing devices to be managed remotely via smartphone applications, making it particularly suitable for household automation [98,99]. In contrast, the Current Sensor provides technical measurements of electrical current within circuits, enabling precise monitoring of power consumption. Similarly, the Voltage Sensor operates in conjunction with the Current Sensor to measure voltage levels, supporting a comprehensive approach to energy management [100,101]. While both sensors require more advanced setups, the Smart Plug offers a user-friendly interface for everyday energy control. Comparing microcontroller platforms, the NodeMCU and Arduino Uno differ significantly in their capabilities [102]. NodeMCU, equipped with built-in Wi-Fi, is ideal for IoT applications and remote monitoring, whereas the Arduino Uno is better suited for educational purposes and prototype development, particularly in environments without network connectivity.

Communication modules also vary in function: the XBee supports low-power, long-range RF communication, while Wi-Fi modules provide

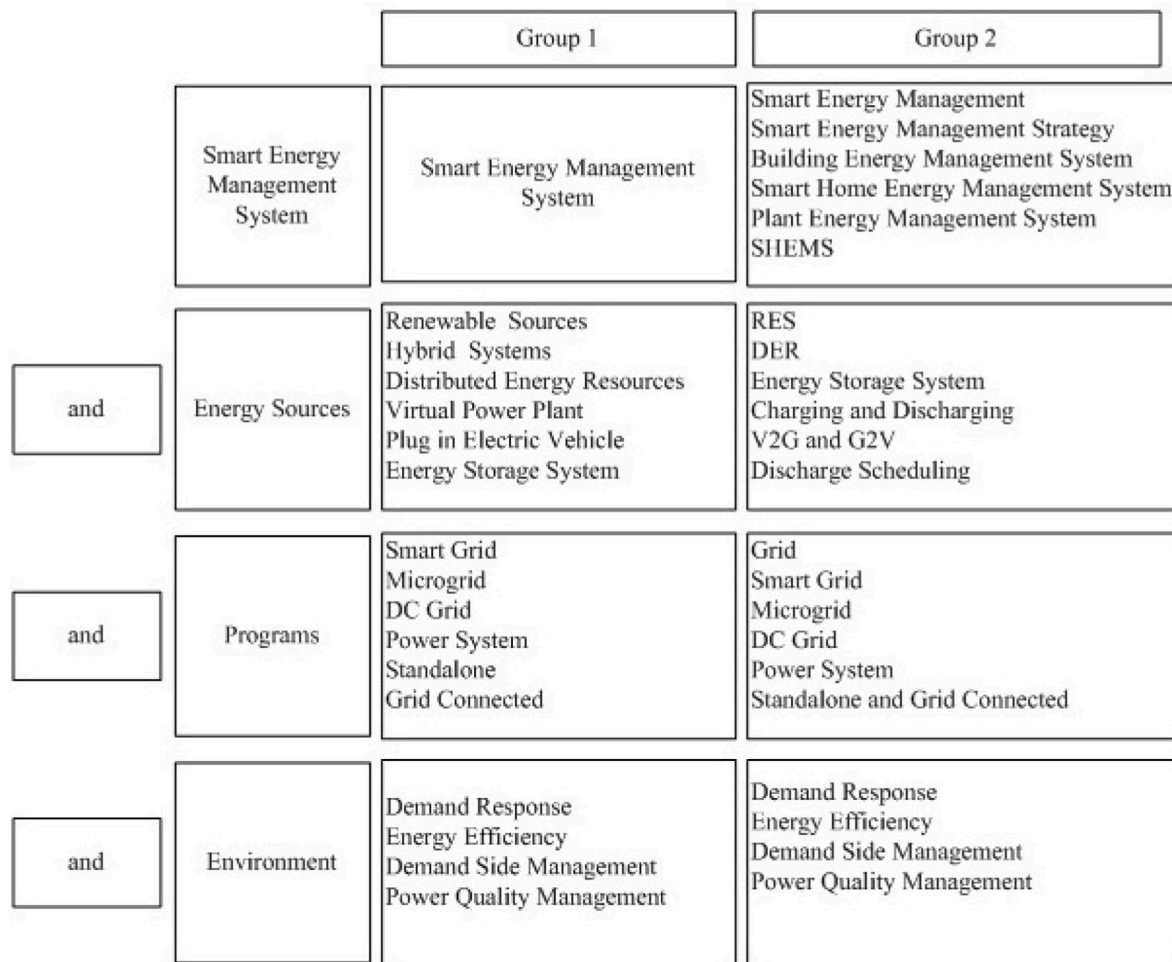


Fig. 2. Methodology for examining energy management systems.

high-speed, internet-based connectivity for home automation systems [103,104]. In renewable energy systems, the PV panel and battery form the core components, with the PV panel generating electricity and the battery storing energy for later use. Environmental monitoring is supported by sensors such as the Temperature Sensor, which tracks temperature variations, and the Light Sensor, which measures light intensity for applications like automated lighting control. The coordinated integration of these components enables a flexible, efficient, and scalable smart energy management system [105,106]. By combining renewable energy generation, precise sensor-based monitoring, and seamless communication, such systems are well-suited for both residential and industrial applications, enhancing energy efficiency and supporting intelligent control strategies.

5. Communication technologies of IoT

Communication technologies form the backbone of the Internet of Things (IoT), enabling devices, sensors, and controllers to exchange data efficiently. In IoT systems, seamless communication ensures real-time monitoring, remote control, and automation across smart homes, industries, and energy management applications. The choice of communication protocol such as Wi-Fi, Bluetooth, ZigBee, LoRa, or cellular networks directly impacts system performance, including data rate, range, power consumption, and reliability. Without robust communication mechanisms, IoT devices cannot transmit critical information to cloud platforms or other devices, limiting their ability to optimize operations, predict energy usage, or respond dynamically to environmental

changes [107]. Therefore, effective communication technologies are essential for achieving scalability, interoperability, and the intelligent functioning of IoT-enabled systems.

5.1. Selection of components and IoT data transmission technologies

Selecting appropriate components for modern applications often involves nuanced decisions, particularly when designing IoT-connected networks and devices. Components must be chosen not only for their technical specifications but also for their compatibility with communication protocols, scalability, and integration into larger IoT ecosystems. A key consideration in IoT system design is the choice of data transmission technology. The principal IoT communication methods include:

Wi-Fi: Provides high-speed, Internet-based connectivity suitable for home automation, smart appliances, and applications requiring real-time data access. Its advantages include broad availability and ease of integration with cloud platforms, though power consumption is relatively high.

Bluetooth/BLE (Bluetooth Low Energy): Optimized for short-range communication with low energy usage, BLE is ideal for wearable devices, sensors, and applications where battery life is critical.

ZigBee/Z-Wave: These mesh-network protocols are used in home automation and industrial IoT applications. They allow multiple devices to communicate over extended distances by relaying data through neighboring nodes, improving network reliability.

LoRa/LoraWAN (Long Range Wide Area Network): Designed for long-range, low-power communication, suitable for smart city and

Table 3
A schematic representation of a PV monitoring system using IoT.

Sl. No	Publication Title	Components Used	Energy Monitoring Approach	Key Findings	Reference
1	Affordable IoT-based Energy Tracker	Sensors, SD3004 measurement chip, PZEM-004T module	Arduino NodeMCU with ESP8266 wireless module	Portable system allowing easy installation without voiding device warranties	[50]
2	Smart Home Energy Supervision System	LDR, PIR sensors, Wi-Fi, voltmeter, relay	Home energy management platform	Supports cloud-based IoT applications and smart grid services	[51]
3	Intelligent Power Metering with IoT	Relay, Wi-Fi module, transistor, current sensor	Plug-level energy usage monitoring	Enhances energy tracking using IoT for efficient consumption analysis	[52]
4	IoT-enabled Energy Consumption Tracker	Raspberry Pi, AC/DC 50A sensor, relay, Wi-Fi, ACS DC8A	Raspberry Pi-based tracker sending data to Adafruit.io	Local data storage and integration with industrial energy meters	[53]
5	Smart Building Energy Management via IoT	Custom Python modules	Dedicated IoT platform for energy data	Provides centralized management of building energy information	[54]
6	Power Reduction Using IoT Sensors	YHDC SCT-013-000, CT sensor, burden resistor	IoT-enabled equipment sensors reporting to cloud	Supports energy saving and carbon footprint reduction via Arduino-based current measurement	[55]
7	MTU Melaka IoT Energy Monitoring	Communication protocols	IoT device linking digital meters via Modbus	Optimizes building energy use while reducing carbon emissions	[56]
8	IoT-based Home Energy Control Devices	Current sensor, LCD, RTC, relay, Wi-Fi	Arduino-controlled automation for dwellings and solar tracking	Wi-Fi transmits data to cloud with simultaneous LCD display	[57]
9	Low-cost IoT Energy Monitoring Software	Modern sensor modules	MQTT-based communication framework	Affordable and scalable platform for decentralized IoT integration	[58]
10	IoT Smart kWh Metering	LDR sensor, Wi-Fi module	Smart grid monitoring	Tracks home appliance energy use with wireless data reporting	[59]
11	Intelligent IoT Energy Tracking System	GSM module, ADC, transformer sensor	IoT devices for occupancy-based control	Controls lab equipment based on personnel presence	[60]
12	Remote Supervised Smart Energy Meters	LDR	Remote oversight of connected devices	Automates measurement of LED-current consumption	[61]
13	Integrated IoT-based Energy Modeling	ZigBee communication, BIM, GIS, weather data	Software framework for energy optimization	Reduces greenhouse gas impact using ICT for building energy management	[62]
14	Real-time Energy Analytics for Buildings	PZEM004T-100A module	Measures voltage, current, and energy metrics	Achieves >99 % accuracy in detecting anomalies and consumption patterns	[63]
15	Arduino-powered Residential Energy Monitor	ACS712 hall sensor, GSM SIM800L	Mechatronics-based energy consumption meter	Accurate energy monitoring using transdisciplinary design principles	[64]
16	Building Energy Monitoring in Indonesia	ZMPT101B, voltage sensor, SCT 013-000	Transparent energy reporting	Cost-effective system for compliance and energy savings	[65]
17	Smart IoT Energy Metering	Driver circuits, ESP8266, Wi-Fi, GSM SIM900, relays	Multi-factor connection design	Supports future utility growth with reliable energy data	[66]
18	Portable Domestic IoT kWh Meter	Wi-Fi module, Li-ion battery, MSP430F6736 MCU	Portable energy metering	Compact, user-friendly solution for household energy tracking	[67]
19	Smart Environment IoT Power Monitoring	Transformer, LoRa, sensor modules	SMACS home appliance control	Enhances energy efficiency and security in smart homes	[68]
20	IoT-enabled Smart Energy Meter	Buzzer, relay, UART, ESP8266 12E	Real-time energy consumption tracking	Monitors and resolves traditional metering inefficiencies	[69]
21	Intelligent Grid Energy Monitoring	Power source, ESP8266, LCD, buzzer, current sensor	ESP8266-based energy computation	Supports efficient energy utilization and grid management	[70]
22	Real-time Energy Efficiency Data Collection	Implementation-focused sensors	IoT-enabled EPE model	Optimizes energy use in food industry via real-time monitoring	[71]
23	Industrial Greenhouse Energy Monitoring	Implementation approach	Cloud-based observation for analysis	Efficient industrial greenhouse energy management	[72]
24	Smart Home Energy and Security System	Implementation setup	Ethernet-enabled energy tracking	Combines voice control with real-time remote energy monitoring	[73]
25	IoT-enabled Linux Systems for PV Monitoring	Relative humidity, solar radiation	Cloud-linked Raspberry Pi system	Novel approach for real-time decentralized PV plant monitoring	[74]
26	IoT Industrial Process Supervision	Wi-Fi module, ESP8266, MAX485 IC	Centralized timing benchmark	Real-time collection of temperature and humidity for smart industrial monitoring	[75]
27	Real-time PV Monitoring with IoT	Temperature, PV, humidity, solar radiation	High-resolution cloud monitoring	Industrial IoT enables accurate PV plant monitoring	[76]
28	IoT-based Energy Meter Reading	ESP8266, LCD, buzzer, relay, Wi-Fi	Arduino IDE software integration	Meter reading with fault detection, SMS alerts, and manual/automatic modes	[77]
29	MTU Melaka Energy Monitoring via IoT	Communication protocols	Modbus integration with digital meters	Improves building energy efficiency and reduces carbon footprint	[78]
30	Automated Smart Home Energy Control	Air quality, LDR, humidity, LM35	IoT-based monitoring system	Intelligent automation for household appliance management	[79]

remote monitoring applications where devices transmit small amounts of data intermittently.

Cellular (3G/4G/5G): Provides wide-area connectivity for IoT devices requiring constant Internet access or remote operation. 5G, in particular, enables low-latency communication and supports massive device density.

Ethernet: A wired solution offering high-speed, stable communication, commonly used in industrial IoT and fixed installations where mobility is not required.





These communication technologies form the backbone of IoT-

enabled smart energy management systems, ensuring reliable data exchange between sensors, microcontrollers, and cloud-based platforms. Choosing the appropriate transmission method depends on factors such as range, power consumption, data rate, network topology, and application-specific.

5.2. Comparative analysis of wireless communication technologies for IoT

A comparison of wireless communication technologies for IoT applications highlights the strengths and limitations of each, underscoring

Table 4
Component specifications for IoT-based smart energy management system.

Component	Image	Description	Specifications	Applications	Reference
Smart Plug		A device that allows you to control electrical devices remotely via an app or voice commands. It can also monitor power usage.	Voltage: 100.0–240.0 V; Max Load: 10.0 A/15.0 A; Wi-Fi: 2.4 GHz	Home automation, energy monitoring, remote device control	[50]
Current Sensor		Measures the flow of electrical current in a circuit. Commonly used in power monitoring applications.	Range: 0.0–30.0 A; Output: 0.0–5.0 V; Accuracy: ± 1.0 %	Power management, fault detection, load monitoring	[51]
Voltage Sensor		Measures the voltage across a component or in a circuit. Useful for monitoring and controlling voltage levels.	Range: 0.0–25.0 V; Output: 0.0–5.0 V; Accuracy: ± 1.0 %	Battery management, power supplies, electrical safety	[52]
Light Sensor		Detects the presence and intensity of light. Used in automatic lighting, brightness control, and safety systems.	Sensitivity: 400.0–800.0 nm; Output: Analog/Digital	Automatic lighting, ambient light detection, safety systems	[53]
Temperature Sensor		Measures temperature in a variety of environments. Used in HVAC systems, weather monitoring, and industrial applications.	Range: -55.0 °C– 125.0 °C; Accuracy: ± 0.5 °C; Output: Digital (1-Wire)	Climate control, environmental monitoring, industrial process control	[54]
Arduino Uno		A microcontroller board based on the ATmega328P. It is used for building digital devices and interactive objects that can sense and control physical devices.	Operating Voltage: 5.0 V; Digital I/O Pins: 14 (6 PWM); Analog I/O Pins: 6	Prototyping, educational projects, interactive installations	[55]
NodeMCU		An open-source IoT platform that uses the ESP8266 Wi-Fi module. It is used for prototyping and building IoT devices.	Wi-Fi: IEEE 802.11 b/g/n; Flash Memory: 4.0 MB; GPIO Pins: 17	IoT applications, remote monitoring, smart home devices	[56]
Gateway		Connects different networks, allowing data to flow from one network to another. Essential in IoT systems for managing communication between devices and the cloud.	Interface: SPI; Speed: 10.0/100.0 Mbps; Voltage: 3.3 V/5.0 V	IoT networks, industrial automation, smart cities	[57]
Ethernet Module		Adds wired internet connectivity to microcontroller projects. Commonly used for stable and secure data transmission.	Power: 100.0 W; Voltage: 18.0 V; Efficiency: 15.0–20.0 %	Networked sensors, secure data transmission, home automation systems	[58]
Wi-Fi Module		Provides wireless internet connectivity to microcontroller projects. Widely used in IoT projects for remote control and monitoring.	Size: 16×2 characters; Interface: I ² C/SPI; Voltage: 5.0 V	Wireless networking, IoT devices, remote control applications	[59]
PV Panel		Converts sunlight into electrical energy. Used in solar power systems to generate renewable energy.	Type: Li-ion; Capacity: 2000.0 mAh; Voltage: 3.7 V	Solar power systems, off-grid applications, renewable energy projects	[60]
LCD Display		A screen that displays information such as text and graphics. Used in various electronic projects to provide visual feedback.	Voltage: 100.0–240.0 V; Max Load: 10.0 A/15.0 A; Wi-Fi: 2.4 GHz	User interfaces, data display, educational projects	[61]
Battery		Stores electrical energy for use in powering devices and systems. Available in various types and capacities.	Range: 0.0–30.0 A; Output: 0.0–5.0 V; Accuracy: ± 1.0 %	Portable electronics, backup power supplies, renewable energy storage	[62]
XBee		RF modules for wireless communication, operates in various frequency bands (e.g., 2.4 GHz), provides serial communication.	Wireless sensor networks, remote monitoring	XBee	[63]
Wi-Fi		Wireless network standard (e.g., IEEE 802.11), provides internet connectivity without physical wires.	Mobile devices, smart home appliances	Wi-Fi	[64]

the importance of selecting the most suitable technology based on application-specific requirements. For low-power, short-range applications, such as home automation and industrial control, protocols like ZigBee, 6LoWPAN, and Bluetooth Low Energy (BLE) are highly effective [76,77]. These technologies operate in the 868/915 MHz and 2.4 GHz frequency bands, provide ranges of 10–100 m, and are optimized for energy efficiency and low data throughput scenarios. In contrast, cellular technologies such as Long-Term Evolution (LTE) and 5G cater to high-speed, wide-area applications. LTE offers data rates up to 1 Gbps, while 5G can reach 10 Gbps, making them suitable for mobile broadband, smart city infrastructure, and IoT systems requiring high data rates and extensive coverage [78,79]. Near Field Communication (NFC) supports very short-range interactions, ideal for secure, peer-to-peer applications such as contactless payments and access control.

Ultra-Wideband (UWB) excels in applications requiring high precision, including asset tracking and location-based services, due to its low interference and high data rates; however, its operational range is limited to less than 10 m [108,109]. Wireless HART provides secure, reliable mesh networking, making it particularly advantageous for industrial automation environments. Ultimately, the choice of

communication technology depends on factors such as data rate, coverage range, power consumption, and network scale [110]. As IoT continues to advance, hybrid solutions that integrate the benefits of multiple technologies are expected to become increasingly prevalent, offering enhanced flexibility and performance for diverse IoT deployments.

6. Conclusion

This review highlights the transformative role of Internet of Things (IoT) technologies in advancing photovoltaic (PV) power generation systems through intelligent energy management. The integration of IoT with real-time monitoring, predictive analytics, and cloud computing provides an efficient and scalable framework for optimizing energy consumption while enhancing the performance of PV systems. Across the reviewed studies, IoT-enabled solutions consistently demonstrated improved forecasting accuracy ranging between 90 % and 95 % and a reduction in unnecessary energy use by 10 %–20 %. These outcomes validate the potential of IoT as a key enabler of energy savings and system optimization. The findings also emphasize the adaptability of

Table 5
Protocols and technologies enabling IoT communication.

Technology	Operating Frequency	Data Throughput	Effective Range	Typical Applications	Power Usage	Notable Features	Reference
IEEE 802.15.4	868.0/915.0 MHz; 2.4 GHz	20.0–250.0 kbps	10.0–100.0 m	Low-rate WPAN (e.g., ZigBee networks)	Low	Short-range, low-power, supports mesh networking	[65]
Zigbee (802.15.4-based)	2.4 GHz	20.0–250.0 kbps	10.0–100.0 m	Home automation, industrial monitoring	Very low	Secure, mesh topology, low data rate	[66]
Long-Term Evolution (LTE)	700.0 MHz–2.6 GHz	Up to 1000.0 Mbps	Several km	Mobile broadband connectivity	Medium–High	Wide-area coverage, supports mobility, high-speed data	[67]
Near-Field Communication (NFC)	13.56 MHz	106.0–424.0 kbps	~0.1 m	Contactless payments, access systems	Very low	Ultra-short range, secure, peer-to-peer communication	[68]
Ultra-Wideband (UWB)	3.1–10.6 GHz	110.0 kbps–1000.0+ Mbps	<10.0 m	Precise location tracking, short-range communication	Low	High accuracy, high-speed, minimal interference	[69]
Machine-to-Machine (M2M)	Various (LTE, LPWAN)	0.1–1000.0 kbps–Mbps	Variable	IoT device connectivity	Typically low	Scalable, supports heterogeneous devices	[70]
6LoWPAN (IPv6 Low-Power WPAN)	868.0/915.0 MHz; 2.4 GHz	20.0–250.0 kbps	10.0–100.0 m	IoT networks, smart metering	Very low	IPv6-ready, low-power operation, mesh networking	[71]
5G	6.0 GHz; 24.0–100.0 GHz	Up to 10000.0 Mbps	Several km	IoT, V2X, enhanced mobile broadband	Medium–High	Ultra-high speed, low latency, massive device connectivity	[72]
WirelessHART	2.4 GHz	250.0 kbps	10.0–100.0 m	Industrial automation	Low	Secure, reliable, mesh-enabled communication	[73]
Bluetooth	2.4 GHz	1.0–3.0 Mbps	~100.0 m	PANs, audio streaming	Medium	Broad compatibility, moderate range, standard data rate	[74]
Bluetooth Low Energy (BLE)	2.4 GHz	125.0 kbps–2.0 Mbps	~100.0 m	IoT wearables, health monitoring	Very low	Energy-efficient, ideal for short data bursts	[75]

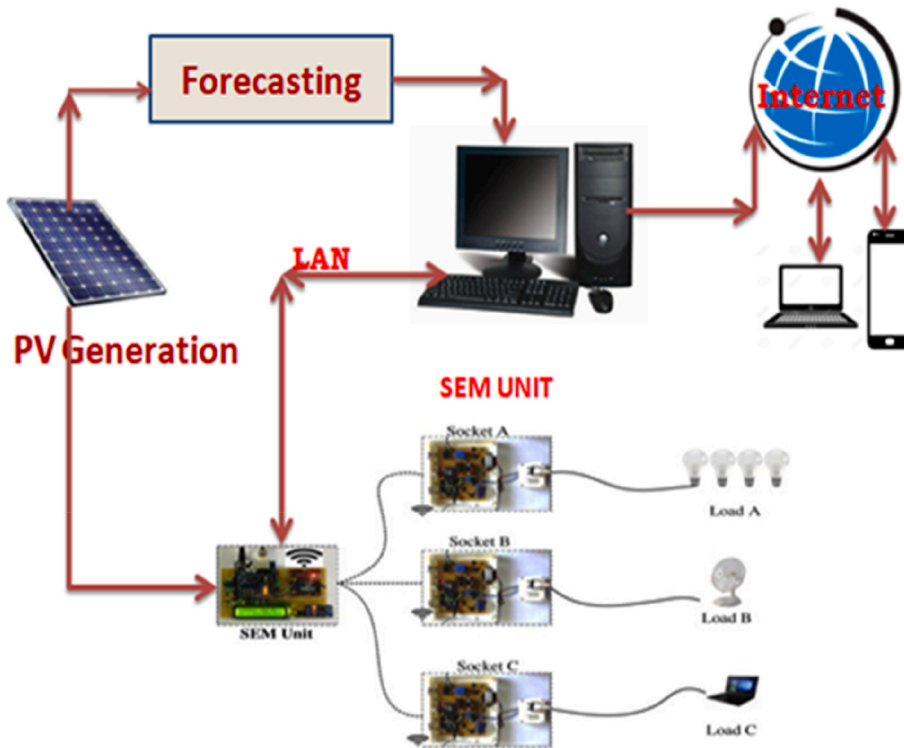


Fig. 3. Intelligent Energy Management Platform [77].

IoT-based energy management systems, which can dynamically respond to environmental variability, making them suitable for diverse geographic and climatic conditions. Furthermore, the adoption of cloud-based architectures supports seamless remote access, real-time data visualization, and system scalability, extending applicability across residential, commercial, and industrial domains. Nevertheless, the review identifies several challenges that warrant further investigation.

The heavy reliance on historical weather datasets limits forecasting reliability under rapidly changing conditions, and the long-term stability of IoT-based systems requires comprehensive validation. Future research should therefore prioritize refining predictive models, strengthening system resilience under environmental uncertainty, and conducting large-scale evaluations to assess efficiency and durability over extended operational periods. In, IoT integration offers a promising

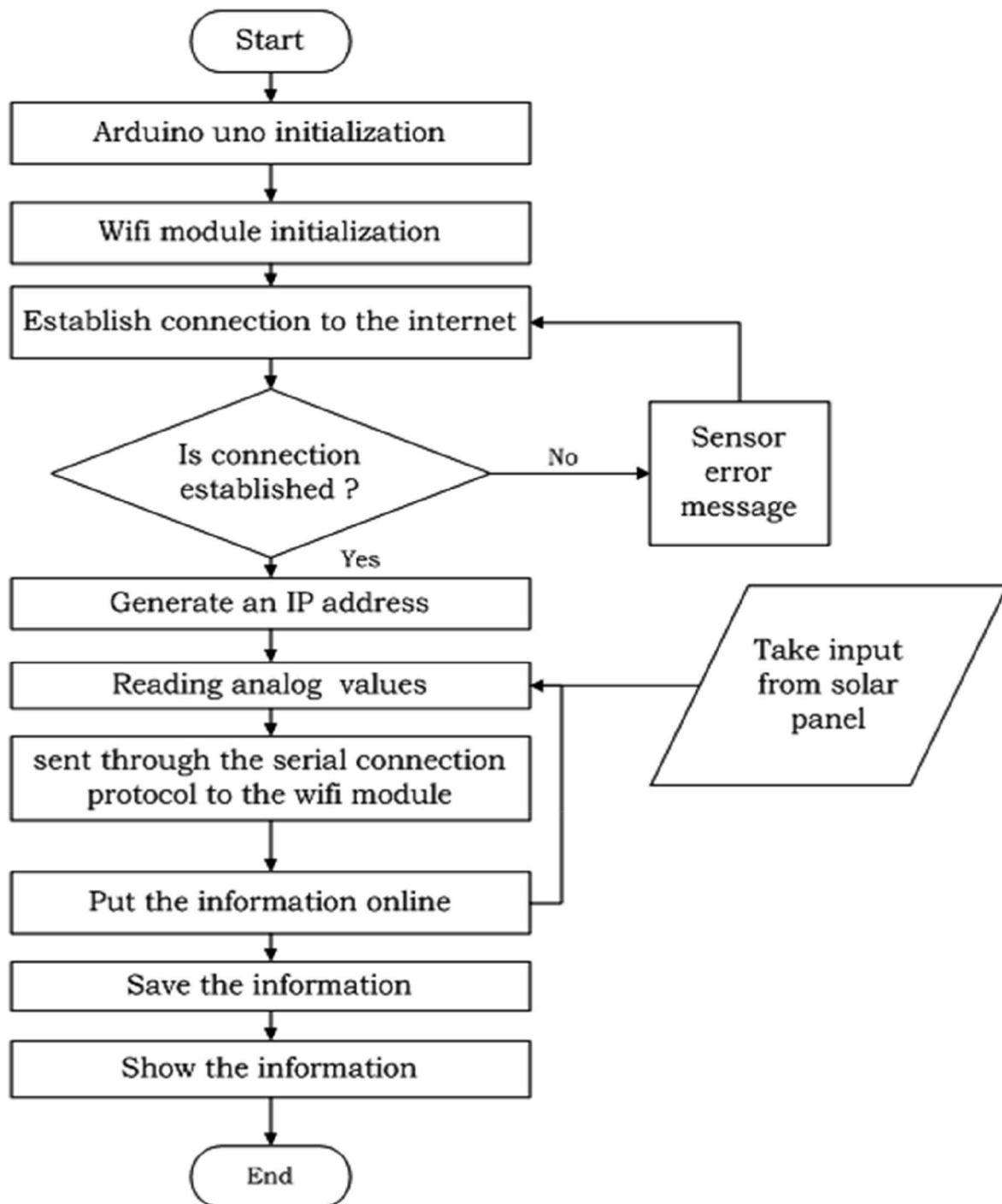


Fig. 4. Schematic of an IoT-Based photovoltaic monitoring system [76].

pathway toward the development of sustainable, intelligent energy management frameworks, contributing significantly to the global transition toward cleaner and more efficient energy systems.

CRedit authorship contribution statement

Challa Krishna Rao: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Sarat Kumar Sahoo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Data curation. **Franco Fernando Yanine:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Formal

analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: No conflict of interest.

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