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Integrating Internet of Things (IoT) with Photovoltaic Systems: Advancing Smart Energy Management for a Sustainable Future in the Era of 4IR

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Abstract: This paper examines the convergence of photovoltaic (PV) systems with the Internet of Things (IoT), marking a new era of technological advancement and connectivity, as characterized by the Fourth Industrial Revolution, often referred to as 4IR. The integration of IoT technologies with PV systems represents a paradigm shift in the development of intelligent, sustainable energy infrastructures. IoT refers to interconnected physical devices, ranging from sensors to smartphones, enabling real-time data acquisition, monitoring, and control. In PV systems, IoT enhances operational efficiency by enabling predictive maintenance, fault detection, energy optimization, and real-time monitoring of critical parameters. This synergy enables decentralized applications across various sectors, including smart buildings, intelligent power plants, and precision agriculture. The adoption of wireless communication technologies and artificial intelligent (AI) algorithms further enhances the intelligence, adaptability, and responsiveness of these systems. Innovations in energy harvesting reduce the dependence of IoT devices on batteries, aligning with environmental goals. Apart from a conceptual framework for IoT-enabled PV systems, this paper also addresses key implementation challenges and highlights applications across various sectors such as smart buildings and agriculture. As these technologies mature, unified and scalable energy networks will emerge, enabling global interconnectivity. Ultimately, the convergence of IoT, AI, and solar energy will drive the transition toward cleaner, smarter, and more resilient energy ecosystems.

Keywords: Artificial Intelligent (AI); Internet of Things (IoT); Photovoltaic (PV)

1. Introduction

The Internet of Things (IoT) refers to a wide range of physical devices that are connected to and exchange data over the internet [1]. Its primary goal is to facilitate information acquisition, connectivity, monitoring, and control. Embedded with sensors, software, and other technologies, physical objects or "things" within the IoT are networked to enable data exchange with other devices and systems via the internet [2]. These protocols and devices can be customized to achieve optimal functionality in highly heterogeneous environments, thereby enabling more intelligent and convenient functions and services [3]. Without the IoT, various challenges may arise, such as the need for manual operation and management, a lack of automation, and the absence of remote management functionalities, all of which may require more manpower and time for device monitoring and control [4]. Additionally, the inability to achieve real-time communication and data sharing among devices can lead to inefficiencies and resource wastage [5]. With the increasing maturity of IoT technology, the urgent need to achieve more efficient management and control of traditional energy management becomes apparent [12]. Addressing the current issues of single-structured, outdated management and high maintenance costs in traditional energy management methods, it is necessary to develop an IoT-based intelligent energy management system using IoT cloud platform technology [13]. In comparison to conventional energy management systems, a smart or an intelligent energy management system can monitor the operation status of specific equipment in real time and propose strategies and processes for dealing with abnormal conditions [14].

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This paper makes several key contributions by exploring the convergence of PV systems with IoT technologies within the context of the Fourth Industrial Revolution (4IR). It presents a conceptual framework for IoT-enabled PV systems that enhances operational efficiency through real-time monitoring, predictive maintenance, fault detection, and energy optimization. The study highlights the applicability of these intelligent systems across various sectors such as smart buildings, precision agriculture, and distributed power generation. It also emphasizes the role of AI and energy harvesting technologies in improving system autonomy and sustainability. Additionally, the paper identifies critical implementation challenges such as data privacy, lack of standardization, and limited sensor coverage while offering a forward-looking vision for scalable, interconnected energy networks. A comparative analysis of review papers covering a similar topic is presented in Table 1.

Table 1. Comparative Analysis of Review Papers Covers a Similar Topic.

Reference	Scope of Review	Advantages	Drawbacks	Published Year
[6]	An intelligent IoT platform for monitoring multiple photovoltaic (PV) power plants, including architecture, AI models, and anomaly detection methods	Monitor multiple PV plants simultaneously, Reduce latency Artificial Intelligence	Requires professionals, Complex	2023
[7]	Development and implementation of a real-time remote monitoring system for PV installations using IoT technology	Real-time monitoring, Remote access, Scalability Data visualization	Complexity, Security, Limited functionality Dependence on Internet connectivity	2023
[8]	IoT-based Hybrid Renewable Energy System, focusing on its architecture and detailed modeling	Comprehensive architecture Detailed modeling	Limited scope, Lack of practical analysis	2021
[9]	Potential applications of next-generation IoT technologies across various fields like healthcare, smart cities, and intelligent agriculture	Improved efficiency and productivity, Enhanced user experience Sustainability	Security and privacy concerns, Cost considerations	2021
[1]	Use of open-source IoT technology to monitor PV power plants	Open source and Scalability Interoperability	Complexity, Lack of standardization	2020
[10]	System architecture for real-time monitoring of PV power generation, including hardware/software design and PV inverter fault diagnosis	Real-time monitoring and fault diagnosis Comprehensive system design	Security Lack of performance evaluation	2020
[11]	Hardware and software components for real-time monitoring and management of large-scale solar PV systems	Low cost, Data analysis Scalability	Lack Security of quantitative data	2018

This paper begins with an introduction to the integration of IoT and PV systems within the 4IR context, outlining its objectives and key contributions. It then presents an ecosystem, reviews related work, discusses cross-sector applications, and addresses technical and implementation challenges. The paper concludes with future research directions and a summary of the framework's potential impact on scalable, intelligent energy systems.

2. Ecosystem of Internet of Things (IoT)

As illustrated in Fig. 1, the integration of IoT into business systems revolutionizes various aspects of operations, bringing about efficiency improvements, cost savings, and new revenue streams [15]. IoT transforms business ecosystems by enabling real-time data collection, predictive capabilities, optimization of operations, enhanced customer experiences, and data-driven decision-making, ultimately driving innovation and competitive advantage [16]. Business systems and their primary functions are essential components of the IoT ecosystem.

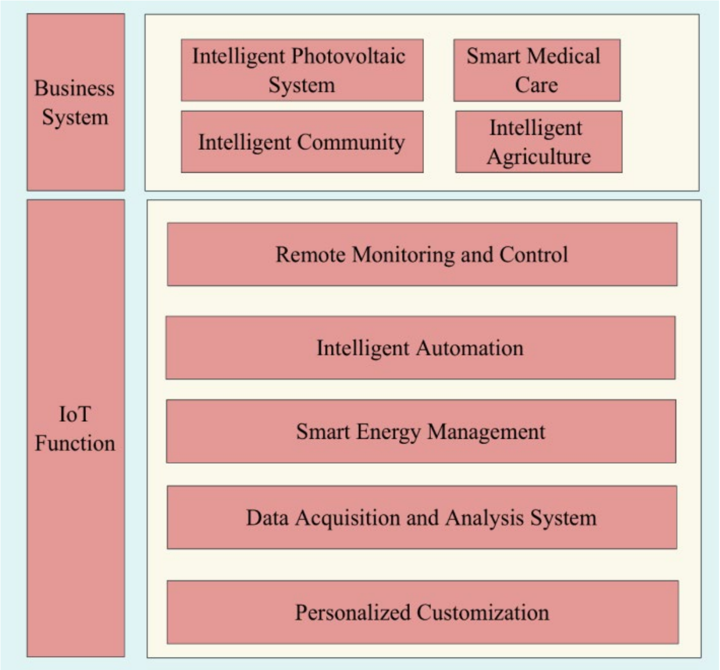

Figure 1. IoT business ecosystems and primary functions [17]

IoT technologies are becoming deeply integrated into daily life, embedding in various objects and surroundings to drive the development of smart homes, cities, healthcare, and transportation systems [18]. These innovations not only amplify convenience but also elevate safety and sustainability, thus enriching the quality of life for individuals and communities alike. By imbuing everyday objects with intelligence, IoT-enabled devices bolster safety and security through real-time monitoring and response capabilities [19]. From fortifying home security systems to optimizing industrial safety protocols, IoT technologies stand as pivotal protectors, actively mitigating risks and averting potential accidents [20]. In Fig. 2, the first connection tool to the IoT ecosystem is the Perception Layer, also known as the foundational tier, which is responsible for the data collection in the IoT ecosystem [21]. Comprising sensors, actuators, and other edge devices strategically deployed at the network's periphery, this layer executes crucial functions like data collection and pre-processing. Its pivotal role lies in capturing and analyzing external data, thus underpinning the scalability and reliability of IoT systems [22]. Enhancing this layer not only fortifies the core infrastructure but also paves the way for more sophisticated applications and insights to flourish.

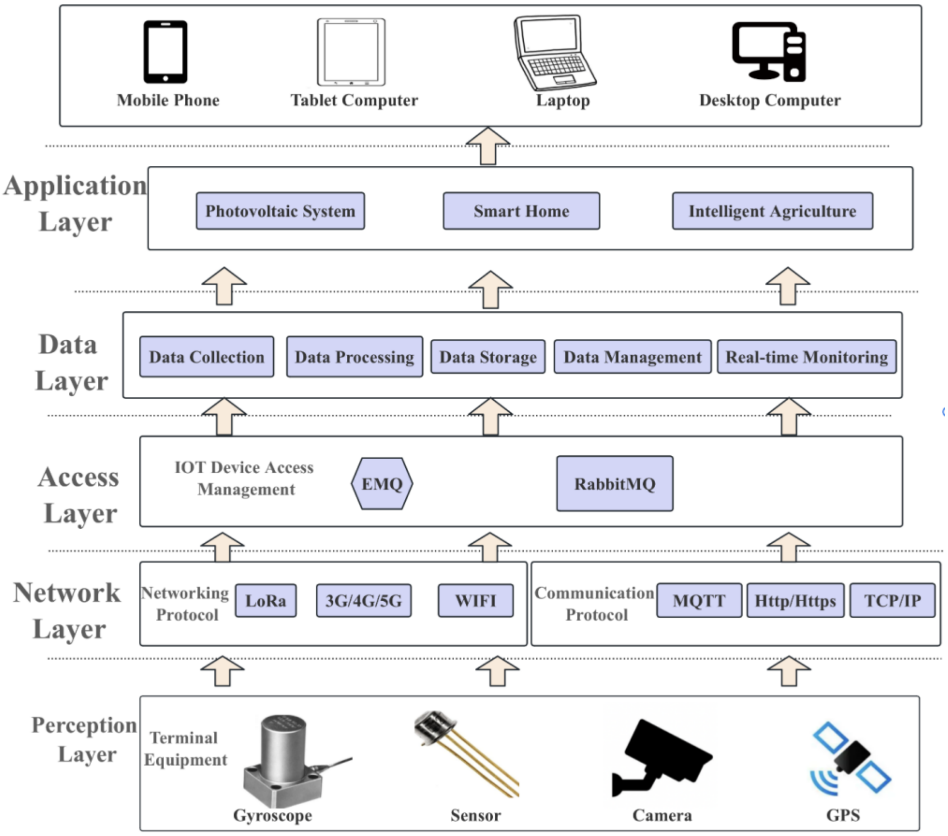

Figure 2. A major layer of connection tools of an IoT ecosystem

Furthermore, the Network Layer, which handles data transmission from the Perception Layer to designated destinations using various communication technologies; the Access Layer, which manages device connectivity and message brokering through scalable platforms like MQTT and RabbitMQ; the Data Layer, which is central to the system, responsible for storing, processing, and analyzing data from IoT devices to ensure efficient data management; and the Application Layer, which serves as the user-facing component, enabling interaction through user interfaces, applications, and dashboards that present data insights in a clear and accessible way [23][24][25][26]. Overall, the various components of an IoT ecosystem work seamlessly together, collecting, processing, and leveraging data from IoT devices. This enables the development of intelligent solutions across diverse domains, including homes, cities, healthcare systems, energy and transportation networks [27].

3. Major Application of IoT

The application of IoT spans across a wide range of industries, offering numerous benefits such as efficiency improvement, cost reduction, and service enhancement. However, the impact of data transmission rates varies across IoT systems, and selecting appropriate speed rates is crucial to meet specific application requirements and scenarios, as depicted in Fig. 3 [28]. Low speed means reducing energy consumption, improving system stability, and reducing maintenance and costs. Data is collected periodically or triggered by specific events, such as changes in environmental conditions or sensor readings [29]. Medium-speed data transmission operates at a moderate rate, supporting near real-time or minimal latency data transfer. This allows for more timely responses compared to low-speed applications, facilitating quicker decision-making and automation. Although it may require more energy compared to low-speed transmission, it strikes a balance between responsiveness and efficiency. High-speed data transmission enables faster real-time monitoring and response, crucial for supporting critical operations such as what autonomous vehicles rely on real-time transmission and reception of large volumes of sensor data to make immediate decisions. High-speed transmission meets the low-latency requirements, ensuring rapid exchange and processing of data [30]. However, this approach comes with trade-offs, including increased device energy consumption, shortened battery life, and higher network burden [31]. High-frequency data transfers occur rapidly [32], often in real time, necessitating fast processing and response times to ensure effective operation and decision-making. By carefully considering the specific application requirements and scenarios, IoT stakeholders can determine the optimal data transmission rate to achieve the desired balance between efficiency, responsiveness, and cost-effectiveness [33][34].

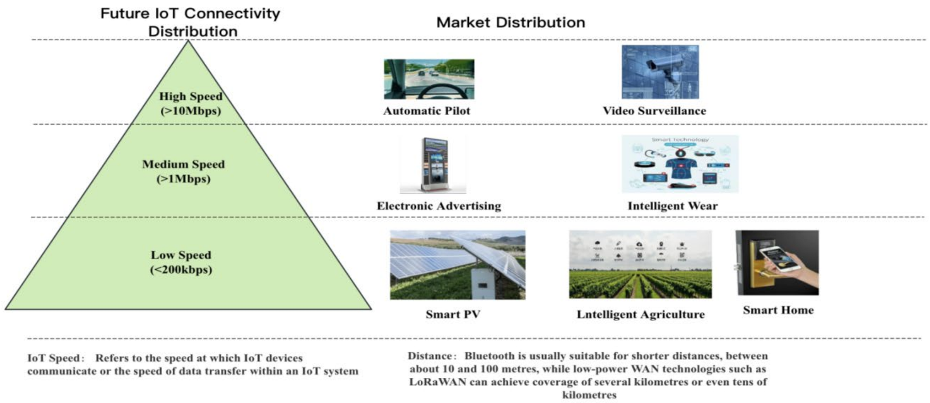

Figure 3. Wide range of IoT applications at different speed levels

Highly accurate sensors and communication devices often come at a significantly higher cost, which can limit their deployment [35][36]. Precision sensors that provide detailed real-time monitoring and fault detection tend to require advanced hardware and frequent calibration, increasing both upfront investment and maintenance expenses. On the other hand, lower-cost alternatives may reduce financial barriers and enable wider adoption but often sacrifice measurement precision and data reliability, which can impact system performance and decision-making quality. Many studies highlight that finding an optimal balance is essential [37][38]. Hybrid approaches that combine affordable sensors with smart algorithms, such as machine learning for data correction or predictive analytics, can partially overcome accuracy limitations without drastically increasing costs [39][40]. Furthermore, advancements in energy harvesting and low-power IoT devices are enabling more cost-effective, self-sustaining monitoring systems that maintain acceptable accuracy levels. Ultimately, the choice between cost and accuracy depends on the specific application requirements, such as the scale of deployment, criticality of data precision, and budget constraints, which must be carefully evaluated to ensure the effectiveness and sustainability of IoT-enabled PV systems.

4. Role of IoT in Improving Solar Energy Management Systems

IoT is an advanced technology that provides intelligence and user-friendliness to devices through communication protocols and cloud platform connectivity. In the field of solar energy, IoT plays a crucial role in connecting physical devices to networks to optimize PV power generation, as illustrated in Fig. 4 [41][42]. The existing photovoltaic (PV) system configuration of the IoT-based PV system includes solar panels, current, voltage, and power sensors, as well as environmental and solar panel temperature sensors, all managed by a NodeMCU microcontroller module [43]. Through the utilization of IoT technology, power plants can achieve intelligence, automation, and sustainable development, providing more stable, efficient, and environmentally friendly energy supply solutions [44].

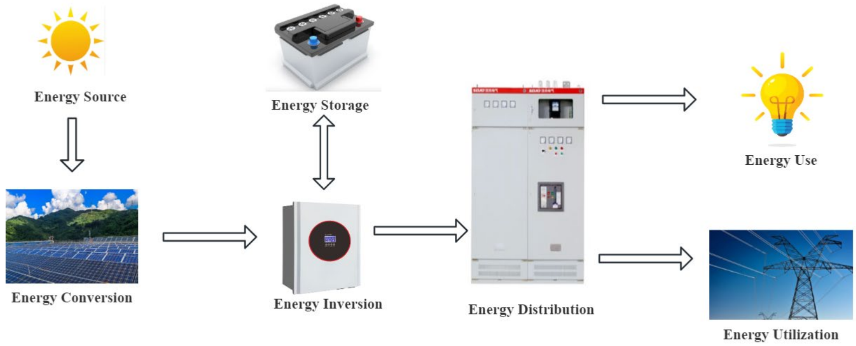

Figure 4. Major components of conventional PV generation systems

A. Real-time Monitoring for Photovoltaic Systems

Effective monitoring of PV power stations must be equipped not only with well-calibrated devices but also with a set of auxiliary systems. Such auxiliary systems must be integrated with measurement components and fully utilized [45]. A two-tier sensor network is used to monitor the PV system. The first tier of the network consists of sensor nodes, which monitor the voltage and temperature of each PV module. In contrast, the second tier consists of sensor nodes, which monitor the irradiance, ambient temperature, voltage, and current of each string. Additionally, the second-tier nodes merge their monitored data with the data obtained by the first-tier nodes and send it to the data center. Communication between the tiers is conducted via radio frequency wireless networks, with the second tier using ZigBee to transmit all collected data to the center. Data logger devices are directly connected to the internet or intermediate devices between the internet and the data logger [46] [47] [48]. A complete energy monitoring system can help users improve power generation efficiency by monitoring and analyzing PV system data in real time, as depicted in Fig. 5.

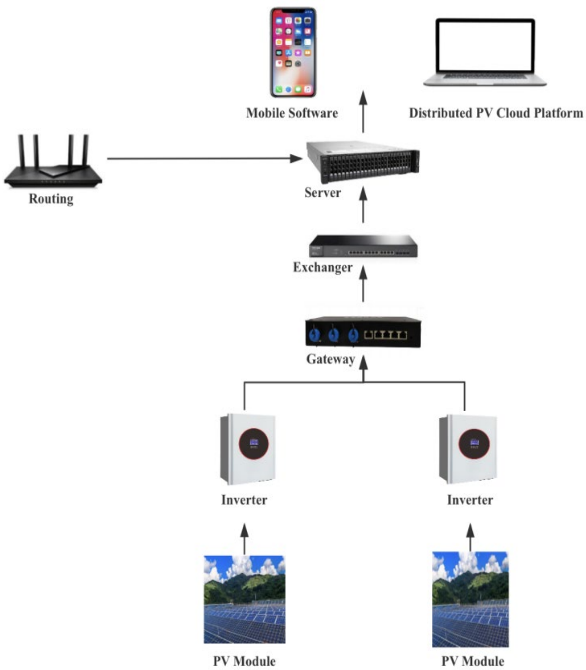

Figure 5. Sub-components of PV monitoring systems

B. Performance Factors in Photovoltaic (PV) Systems for Maximizing Power Generation

The integration of IoT with the energy yield prediction, based on historical data, weather forecasts, and other factors, helps optimize the operation of PV systems and plan grid power supply [49]. In addition, the inclusion of IoT is able to improve the system's efficiency. A high-efficiency PV system can generate more electricity, especially during peak hours. The integration of IoT technologies can significantly enhance the system reliability, stability, and durability of a PV system during extended operation under varying weather conditions. By enabling real-time monitoring, predictive maintenance, and data-driven decision-making, IoT contributes to consistent and steady electricity generation over the long term, thereby improving the overall performance and resilience of the system [50]. The complete energy monitoring process for an IoT-based PV system includes several stages, from data collection to analysis and control, as illustrated in Fig. 6.

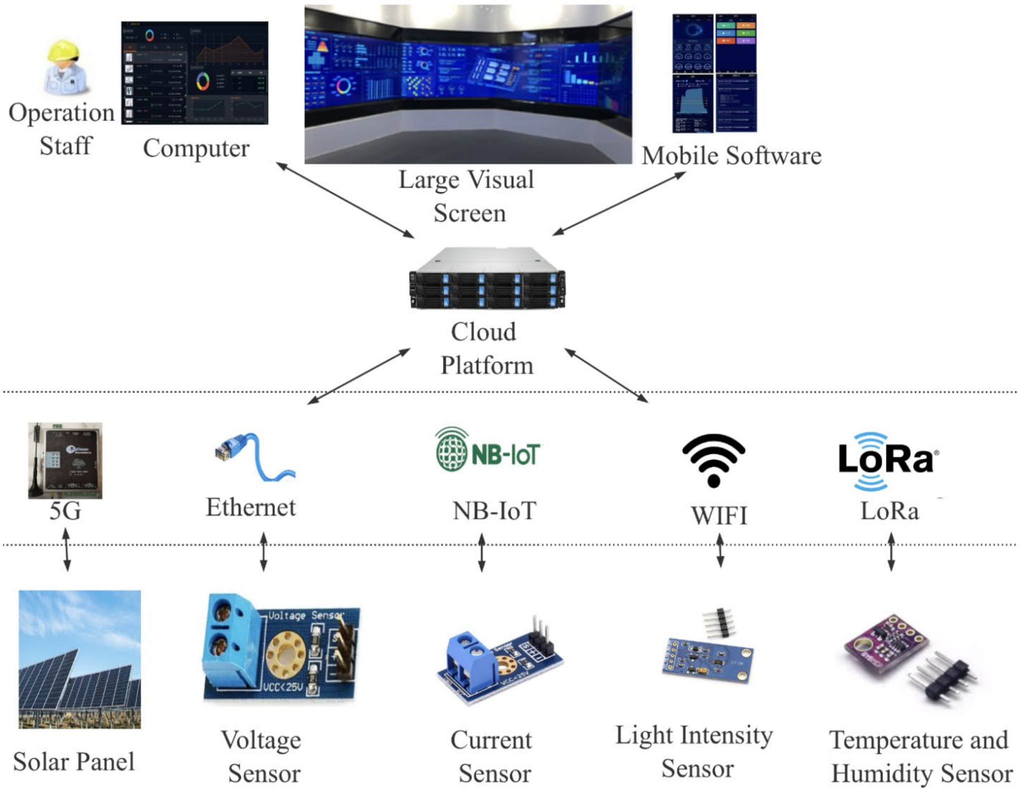

Figure 6. The complete energy monitoring process for an IoT-based PV system

The PV panels convert solar energy into electricity through the power converters. The gateway server collects and processes data from the converters, while the switch ensures connectivity among all components, facilitating data transmission and communication. The server stores and analyzes the data. With such a system, users can monitor the performance and operational status of the PV power generation system in real time, including real-time status updates, fault alerts, and important parameters such as electricity generation. This enables effective management and optimization of energy resources. Data collected by PV panels is sent to applications for data analysis and visualization, as discovered through statistical analysis and short-term or long-term forecasting research. Data can be collected through smart meters and sensors and can be stored and analyzed in factories. Data analysis is an important step in understanding energy consumption patterns, determining energy sources, and ultimately converting collected data into information. Data monitoring plays a key role in understanding the utilization of renewable energy. Sensor data is transmitted in real time to cloud databases via IoT applications, facilitating global data access through active internet connections. The real-time implementation of this system is integrated with cloud databases, featuring a secure login system that grants access only to authorized personnel. This security measure enhances user confidence. The system boasts an efficiency of up to 95%, ensuring the effective utilization of PV systems [51], [52].

IoT connectivity systems provide efficient monitoring and control capabilities for PV systems, surpassing manual inspection operations. The system aims to monitor various parameters, including voltage, current, temperature, and the amount of direct sunlight received by the solar panels [53]. Data captured by Arduino is transmitted via NodeMCU wireless communication transceivers to the internet. The data is uploaded to the open-source IoT cloud platform ThinkSpeak, which compiles sensor data and presents it to users for analysis when connected to the internet. The well-known popular optimization technique, the Particle Swarm Optimization (PSO) algorithm was inspired by the foraging behavior of birds [54] [55]. The main idea is to initialize a group of particles carrying interactive information randomly and then gradually search for the optimal solution by specific iterations, evaluating each particle based on its fitness. Subsequent iterations of particles are guided by the trajectory of the best-performing particles to find the optimal solution of the system. The PSO has advantages such as simplicity of implementation and fast convergence. It has been widely applied in various fields, including system optimization, pattern recognition, nonlinear optimization, scheduling, and control [56]. Moreover, the performance of PV system is affected by the lighting conditions, and PSO can be applied to the maximum power point tracking, by adjusting the working point of the PV cell array, so that it always works at the MPP, to improve the energy conversion efficiency of the PV system. Implementing voltage and current sensors is a costly and resource-intensive task. Time-based MPPT algorithms provide an alternative solution by observing the time required for capacitor charging and indirectly calculating power to avoid voltage and current sensors [57] [58]. Prediction Mode is the key method used for calculating expected energy consumption and can be categorized into two types. The first type is based on historical data, and the second type is based on driving factors. Both methods have drawbacks, such as accuracy, long intervals, inaccurate results when abnormal consumption patterns occur in a given period, inability to detect energy waste occurrences, and others [59] [60].

C. Weather Forecasting

As displayed in Fig. 7, weather forecasting is essential for IoT-based smart energy management systems for PV applications [61], as it enables efficient utilization of solar energy resources and enhances the reliability and performance of renewable energy systems.

Figure 7. Weather forecasting equipment [61]

By forecasting weather patterns, the system can anticipate changes in sunlight intensity and adjust the operation of PV systems accordingly. For instance, if clouds are predicted to cover the sky, the system may adjust the tilt angle of solar panels or activate backup power sources. Additionally, by integrating weather forecasting data into energy management algorithms, IoT-based systems can improve energy efficiency by ensuring that energy generation aligns with demand and minimizing energy wastage. For communication, using the limited LoRaWAN protocol on 8-bit Atmega1281 microcontrollers has become a popular choice [62]. Machine learning modules play a critical role in modern weather forecasting by enabling the analysis of large-scale atmospheric data, improving the accuracy of predictive models, and enhancing the detection of complex weather patterns [63]. These modules utilize techniques such as neural networks, decision trees, and ensemble methods to process real-time data from satellites, sensors, and historical records, thereby supporting more reliable short-term and long-term weather predictions. Weather sensors are used for real-time monitoring of weather conditions, including temperature, humidity, wind speed, wind direction, atmospheric pressure, and solar radiation. As illustrated in Fig. 8, these sensors can be installed near PV panels or in other locations to capture accurate weather data. Data acquisition devices are responsible for collecting real-time data from weather sensors and transmitting it to central servers or cloud-based storage systems. These devices are typically integrated with IoT gateways or edge devices to ensure reliable data transmission and processing. The user interface provides users with access to weather forecasts and related data. Users can use it to view real-time weather data, weather forecasts, and information about PV performance [64].

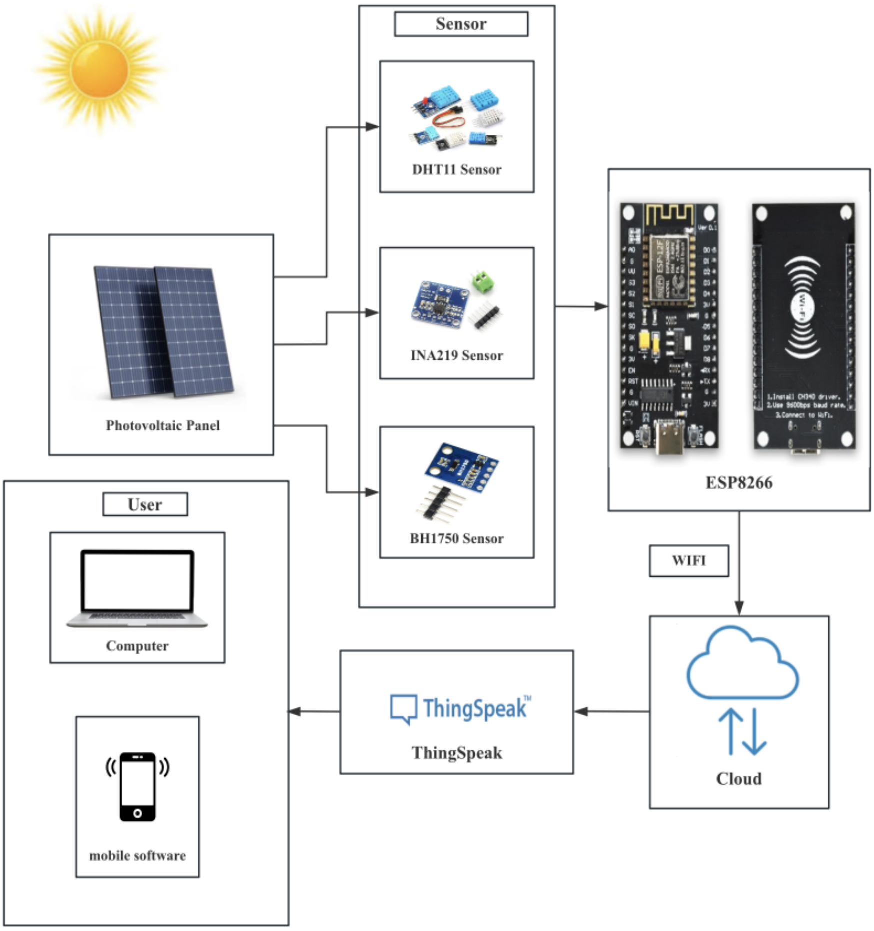

Figure 8. A general block diagram between various modules in an IoT-based PV system.

D. IoT-based PV Sensors

PV systems need to monitor various parameters to ensure their proper operation and optimize power generation. The commonly used types of sensors in PV systems for IoT applications include voltage sensors, current sensors, temperature sensors, and light sensors, as illustrated in Fig. 9 [65].

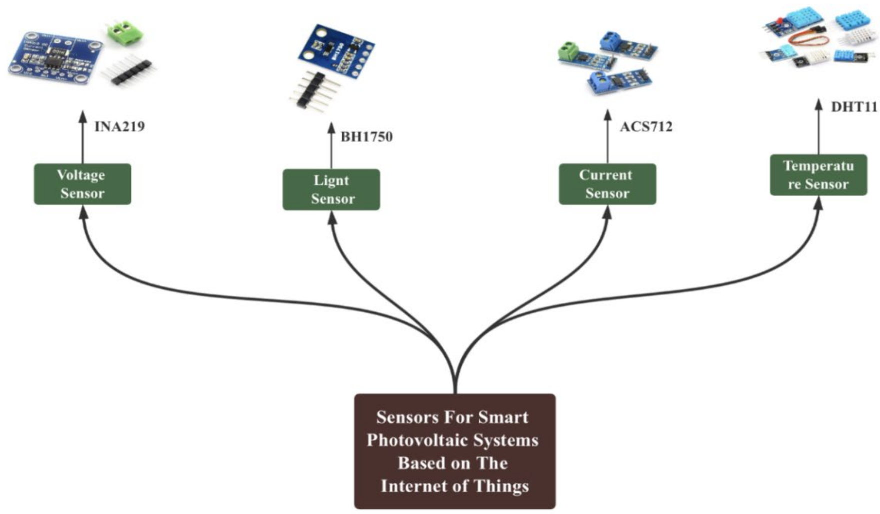

Figure 9. The commonly used types of sensors in PV systems

E. Various Communication Protocols used in IoT-based PV systems

Data collected by IoT sensors is wirelessly transmitted to a central monitoring platform using communication protocols such as Wi-Fi, Zigbee, Bluetooth, NB-IoT, LoRa, or cellular networks. Table 2 summarizes the features of various communication protocols used in Io-based PV systems.

Table 2. Features of various communication protocols used in IoT-based PV systems.

Communication Protocol	Transmission Rate	Signal Stability	Transmission Distance	Power Consumption	Obstacles Handling	Cost-Effectiveness
Wi-Fi	High	High	Moderate	High	Strong	Moderate
Zigbee	Moderate	Moderate	Short	Moderate	High	High
LoRa	Moderate	Moderate	Long	Very Low	Moderate	High
NB-IoT	Low	High	Long	Low	Strong	High
Bluetooth	High	High	Short	Moderate	Weak	Low
Cellular Networks	High	High	Very Long	High	Strong	Low

The communication protocols are chosen based on range, power needs, and data requirements. Wi-Fi offers high speed and stability but consumes more power. Zigbee is low-power and cost-effective for short-range setups. LoRa provides long-range, ultra-low power communication, ideal for remote areas. NB-IoT offers stable, long-range, low-power transmission for low data rates. Bluetooth is fast and low-cost but limited to short-range use.

Cellular networks provide wide coverage and reliability nevertheless requires significant operational and financial costs.

F. Various Communication Protocols used in IoT-based PV systems

Table 3 highlights recent advancements in IoT-based photovoltaic (PV) technologies, presenting a variety of innovative smart energy solutions designed to improve efficiency, reliability, and sustainability across different sectors. These developments range from affordable, compact monitoring systems to AI-powered forecasting, fault detection, and hybrid microgrid technologies, all focused on optimizing power generation, management, and storage. The technologies support a broad spectrum of applications, including smart homes, greenhouses, urban infrastructure, agriculture, and large-scale PV systems. By incorporating data analytics, wireless communication, and energy harvesting, these solutions help create more intelligent, sustainable, and resilient energy systems.

Table 3. Recent advancements of IoT-based photovoltaic (PV) technologies.

No	Purpose	Parameters	Components	Key Features	Area of Application
[1]	PV management using IoT devices for efficient energy monitoring	PV voltage and current, Temperature, Irradiance	Arduino Uno, Node MCU, XBee, Gateway, Ethernet module, Wireless module	Energy Monitoring, Management	Rooftop Housing
[3]	Distributed energy data collection for smart grid-level PV performance tracking	Power generation, Load consumption	Distributed PV stations, IoT devices, Data collector	Energy Management	Smart Grid
[5]	Compact PV applications in space-constrained environments	Power Efficiency, Open-circuit Voltage, Operating Frequency	GaAs-based PV cell, Chip inductor	Power Optimization	Compact Thin PV cell
[6]	Real-time PV monitoring for off-grid installations	PV Power, Battery Temperature, Irradiance	Battery, INA29 sensor, I2C, NodeMcu, ThingSpeak IoT platform, LM35	Energy Monitoring, Management	Off-Grid PV systems
[7]	Uses atmospheric sensors in large-scale PV systems	PV Power, Temperature, Humidity, Irradiance	Raspberry Pi, Atmospheric Sensors	Energy Monitoring	Large-scale PV systems
[8]	Early PV fault detection through data and communication modules	PV power	Communication module, Power supply, ZigBee modules	Energy Monitoring	PV Fault Diagnosis
[9]	Applies AI-based prediction and anomaly detection for	PV Power Generation, Atmospheric data, Device status	Cloud server, AI models	Power Optimization	Large-scale PV systems

No	Purpose	Parameters	Components	Key Features	Area of Application
	large-scale PV optimization				
[10]	Integrates wind and solar systems with IoT to optimize hybrid renewable energy	Wind speed, Wind direction, Atmospheric data, PV Power	Wind turbine, Sensors, and measurement devices, PV system	Energy Monitoring, Power Optimization	Smart Campus
[12]	Implements MPPT and control devices for PV optimization in grid systems	Irradiance, Ambient temperature, Wind speed, Battery state of charge	Inverters, Batteries, Charge controllers, Maximum power point trackers	Power Optimization	Grid-connected PV
[13]	Manages transient load effects in PV-connected smart grids through cloud-based data	PV Voltage, Power, Irradiance, Temperature	Bus, Cloud storage	Energy Management	Smart Grid
[14]	Develop a low-cost IoT PV monitoring system for small installations	PV, Battery Voltage, Load Voltage, Battery Current	Irradiance, Temperature sensor, Voltage sensor, Current sensor, Arduino, Raspberry Pi	Energy Monitoring	Small-scale PV systems
[15]	Enhances IoT data collection efficiency while reducing battery drain in PV-powered devices	System Efficiency, Frequency, Temperature	Solar cells, Batteries, Microcontrollers, Wireless communication modules	Energy Monitoring	PV-powered Devices
[16]	Combines sensors and IoT modules for energy usage reduction and grid stability in microgrids	Temperature, Pressure, Wind speed, Power consumption of appliances	XBee, Solar panels, Battery, Arduino microcontroller, Relay modules	Energy Monitoring	Microgrids
[21]	Focuses on powering medium-scale buildings using solar energy	Irradiance, Temperature, PV Power generation	Inverters, Temperature, Voltage, Current, Solar radiation sensor	Energy Monitoring	Medium-scale PV systems
[23]	Deploys a smart PV-based microgrid for real-time data exchange and improved control	PV Voltage, Current, Temperature, Humidity, Irradiance	Raspberry Pi, Arduino Mega 2560, Netgear GS308, Sensors, Lithium-ion battery	Energy Monitoring	Microgrids

No	Purpose	Parameters	Components	Key Features	Area of Application
[25]	Aims to reduce O&M costs by improving PV system performance through data sensing	PV Current, Voltage, Temperature, Humidity, Irradiance	Current, Voltage Sensor, Inverter, Routers	Energy Monitoring	Smart Grids
[27]	Self-powered IoT device architecture with environmental awareness for energy harvesting	Battery current and voltage, Environmental data	ESP32, Lux meter	Energy Management	Ambient light harvesting
[28]	Focuses on downsizing PV panels for cost-effective and reliable wireless systems	Irradiance, Temperature, Power Consumption, Data Rate	PV Panel, Battery, GPS, Microcontroller, Communication Module	Energy Management	Wireless communicati on systems
[29]	Implements dual-axis sun tracking to boost energy generation in sunny regions	PV Voltage, Current, Irradiance, Light intensity, Temperature	Microprocessor, Motor, Gearbox, Sensor	Energy Monitoring. Power Optimization	Sunlight Tracking
[30]	Supports green street lighting through luminance sensors and IoT-enabled control	Luminance, System fault maintenance and management	Sensor, Actuators, LED light controller, Master control unit	Energy Management	Street lighting Application
[33]	Promotes sustainable IoT agriculture using solar-powered sensors and wireless communication	Batteries, Wireless communicatio n modules	Digital technology, Microcontroller, RFID, Wireless Sensor, ZigBee	Energy Monitoring	PV for Agricultures
[34]	Optimizes battery capacity to lower emissions and improve PV efficiency	PV power, Energy	PV panels, Battery	Power Optimization	Residential PV systems
[41]	Proposes the affordable, real-time LoRa-based PV monitoring system for small setups	PV Voltage, Current, Power, and Meteorologica l variables	Halted Wi-Fi LoRa32, PV microsystem consisting of 19 polysilicon (Si-p)	Energy Monitoring	Small and medium-sized PV systems

No	Purpose	Parameters	Components	Key Features	Area of Application
[42]	Enhances HMG performance in remote areas using optimization algorithms	Power, Battery state of charge, Power consumption of loads	Batteries, Inverters, Converters	HMG, Whale optimization algorithm Energy Management	Microgrids
[50]	Enables wireless charging and autonomy for IoT devices using PV and rectifiers	PV generator output voltage, Battery voltage	Dual Battery green energy collection rack, Antenna arrays, Batteries, Rectifiers	Energy Management	Wireless Charging
[52]	Moves toward digitized PV management with smart sensors and ESP32-based control	PV Voltage, Current, Temperature, Irradiation	Hall effect sensor, Resistance divider, ESP32 microcontroller, Antenna	Energy Monitoring	Large-scale PV power plants
[55]	Develops a new model to estimate maximum indoor PV power output accurately	Output current, Output voltage	Multimeter, Rheostat, Temperature Sensor, Digital illuminometer, PV modules, MATLAB	Energy Management	Energy harvesting systems
[56]	Focuses on efficient EV charging via optimized solar and battery pack integration	Power, Grid power consumption, Solar irradiation	Solar panels, Battery charging station, Controller	Power Optimization	Electric vehicle charging stations
[60]	Applies bilevel optimization to reduce energy losses and grid dependency in microgrids	Voltage, Current, State of charge	Microgrid controller, Transformers	Energy Management	Microgrids
[64]	Improves PV forecasting accuracy and reduces emissions using IoT sensors	Temperature, Wind speed, Humidity, Power, Current, Voltage	Smart meters, Solar controllers, Data loggers, Sensors	Energy Monitoring	Grid-connected PV Systems
[65]	Leverages AI & IoT for PV protection and reliability, preventing system failures	Voltage, Power, and Temperature	PV power station, PV array accumulator Battery converter inverter	Power Optimization Artificial Intelligence and Deep Learning Algorithm	Large-scale PV systems

No	Purpose	Parameters	Components	Key Features	Area of Application
[66]	Tests an IoT-enabled energy manager in hybrid microgrids using real-time PV data	PV Voltage and current	Solar PV panels, Raspberry-Pi processor, Energy meters	Energy Management	Small-scale PV systems
[74]	Offers an open-source PV monitoring platform for grid-connected systems	PV Voltage, Current, Power, Power grid loss, Solar radiation, and Environment temperature	PV panel, MPTT Tracker, Inverter, Metering, Weather station, Battery	Energy Monitoring, Energy Management	Grid-connected PV systems
[75]	Evaluates MPPT algorithms in IoT PV systems for wearable and low-power devices	PV Voltage, Current, System Efficiency	Solar PV cell, DC-DC converter, Voltage regulator, Sensing unit, Signal-conditioning unit, Communication unit	Power Optimization MPPT	Wearable Devices
[76]	Demonstrates the use of fuel cells as backup for PV-based IoT energy systems	PV Voltage, PV Current, Output power of the battery, Temperature	Raspberry Pi, Battery, Fuel cell,	Energy Monitoring	Small-scale PV systems
[77]	Explores diverse energy sources and IoT components for smart city deployment	Power, Efficiency, Voltage, and Current	Sensors, Microcontrollers, Batteries, Communication modules	Energy Management	Smart Cities
[78]	Applies ML methods to enhance PV reliability and avoid power failures in small setups	PV Voltage, Current, Temperature, Radiation, Humidity, Stress	Node MCU v2 ESP8266, Weather Shield, Machine Learning method	Power Optimization	Small-scale PV systems
[79]	Optimizes indoor PV for IoT using various light source	Spectral irradiance, Voltage, Current, Power, Efficiency	Illuminance meters, Spectrometer Organic photovoltaic modules	Energy Management	Indoor PV

No	Purpose	Parameters	Components	Key Features	Area of Application
[80]	Improves PV system flexibility and cost-efficiency in smart grid	Power PV systems, Power consumption of loads, Battery SOC	Residential PV-battery systems, Energy management systems	Power Optimization	Smart Grids
[81]	Integrates PV with the grid to boost operational performance via Arduino-LoRa-based systems	Voltage, Current, Sunlight, Temperature, Humidity	Arduino Uno, LoRa, 12Vbattery, Sensor, Resistor, Potentiometer, LCD, LED, Lamp bulb	Power Optimization Energy Monitoring	Smart Grids
[82]	Reduces energy conversion losses using ESP-based modules for grid PV	PV Voltage, Current, Power, Battery SOC	PZEM module, Intelligent relay, ESP8266	Energy Management	Grid-connected solar PV systems
[83]	Considers economic factors in maximizing rooftop PV energy output	Irradiance, PV temperature, Wind speed	PV modules, Inverters	Power optimization	Rooftop PV systems
[84]	Manages solar energy with a boost converter for longer IoT device life	Solar cell voltage, Solar cell current	Solar cell, Battery, Boost converter	Energy Management	Self-powered IoT devices

Table 3 reveals several important research contributions in the integration of IoT technologies with PV systems. First, it demonstrates how various IoT components such as sensors, microcontrollers, and communication protocols are effectively combined to enable real-time monitoring, fault detection, and energy management in a wide range of PV applications. IoT can also extend the lifespan of batteries by harnessing PV technology, potentially eliminating the need for batteries in some cases. Wireless communication technologies such as 5G, Wi-Fi, ZigBee, and LPWAN facilitate data transmission and system monitoring. IoT enhances PV system efficiency through predictive maintenance, remote access, and fault detection, although challenges like data privacy, security, and the lack of standardized protocols remain. Second, the table highlights the versatility of IoT-enabled PV systems, showing their adaptability across different sectors including smart grids, microgrids, rooftop installations, off-grid systems, agriculture, and electric vehicle charging stations. Third, it emphasizes the growing use of artificial intelligence (AI), machine learning, and predictive analytics alongside IoT to optimize power generation and improve system reliability, pushing forward the development of autonomous and intelligent energy systems. Fourth, the table showcases innovative approaches to enhance energy efficiency, reduce operational and maintenance costs, and promote sustainability through techniques such as self-powered IoT devices and hybrid renewable energy systems. Finally, by presenting a wide variety of technologies and applications, the table also implicitly identifies key challenges such as ensuring reliable data communication, integrating sensors effectively, and scaling systems while providing examples of practical solutions to these issues. Collectively, these contributions advance the understanding and development of scalable, efficient, and intelligent PV systems powered by IoT technologies.

The integration of IoT with PV systems offers transformative potential for advancing smart energy management in the era of the Fourth Industrial Revolution (4IR). Future research should focus on enhancing real-time data processing through AI and machine learning to enable predictive maintenance, fault detection, and autonomous energy optimization. This will improve system efficiency, reduce downtime, and support intelligent decision-making with minimal human intervention. To support scalability, the development of standardized communication protocols and robust cybersecurity measures is essential. Ensuring interoperability and data integrity across diverse IoT devices will enable secure, seamless integration into larger energy networks. Equally important is the advancement of low-power and self-sustaining IoT devices. Leveraging PV energy to power sensors and communication units will facilitate widespread deployment, especially in remote or off-grid areas, reducing operational costs and maintenance. Integration with smart grids and energy markets represents another key direction. IoT-enabled PV systems can support dynamic load management, demand response, and even peer-to-peer energy trading, contributing to more flexible and decentralized energy systems. Further, combining PV with other renewables in hybrid systems, managed by IoT platforms, can enhance energy reliability and resource optimization. Coordinated control across sources will ensure efficient energy use under varying environmental and demand conditions. Finally, user-friendly energy interfaces and supportive policies are needed to accelerate adoption. Simplified monitoring platforms and clear regulatory frameworks will bridge the gap between technological advancement and real-world implementation. Collectively, these directions point toward the development of intelligent, efficient, and scalable PV systems that are central to a sustainable energy future.

5. Conclusion

The integration of photovoltaic (PV) systems with Internet of Things (IoT) technologies represents a transformative advancement in the fields of renewable energy and smart energy system management. By leveraging the synergy of hardware, software, and real-time communication technologies, IoT-enabled PV systems provide reliable, continuous access to operational data, thereby enhancing the responsiveness and precision of energy management strategies. Solar energy, as a sustainable and environmentally benign power source, offers a stable and autonomous energy supply for IoT devices, eliminating dependency on traditional grid infrastructure and facilitating deployment in remote or off-grid environments. The convergence of solar energy and IoT fosters mutual reinforcement. IoT platforms enhance the monitoring, analysis, and control capabilities of PV systems, while PV technology ensures uninterrupted energy provision for distributed IoT networks. In the industrial sector, such integration supports the development of intelligent building energy management systems, optimizing energy consumption and reducing carbon footprints. In agriculture, PV-powered IoT systems enable precise control over environmental parameters and resource inputs such as irrigation and fertilization thereby improving crop yield, quality, and sustainability. Overall, the deployment of IoT-based PV systems contributes significantly to improving the operational efficiency, reliability, and scalability of modern power infrastructure. Furthermore, it promotes the large-scale adoption of renewable energy technologies, aligning with global initiatives for environmental protection, smarter energy management systems, and sustainable development.

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7. References

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