



Review

A Review of Monitoring Technologies for Solar PV Systems Using Data Processing Modules and Transmission Protocols: Progress, Challenges and Prospects

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Abstract: Solar photovoltaic (PV) is one of the prominent sustainable energy sources which shares a greater percentage of the energy generated from renewable resources. As the need for solar energy has risen tremendously in the last few decades, monitoring technologies have received considerable attention in relation to performance enhancement. Recently, the solar PV monitoring system has been integrated with a wireless platform that comprises data acquisition from various sensors and nodes through wireless data transmission. However, several issues could affect the performance of solar PV monitoring, such as large data management, signal interference, long-range data transmission, and security. Therefore, this paper comprehensively reviews the progress of several solar PV-based monitoring technologies focusing on various data processing modules and data transmission protocols. Each module and transmission protocol-based monitoring technology is investigated with regard to type, design, implementations, specifications, and limitations. The critical discussion and analysis are carried out with respect to configurations, parameters monitored, software, platform, achievements, and suggestions. Moreover, various key issues and challenges are explored to identify the existing research gaps. Finally, this review delivers selective proposals for future research works. All the highlighted insights of this review will hopefully lead to increased efforts toward the enhancement of the monitoring technologies in future sustainable solar PV applications.

Keywords: solar PV; wireless monitoring system; sensors; data processing board; data transmission protocols; data acquisition

1. Introduction

The depletion of fossil fuels and carbon emission issues have transformed power systems from conventional systems to renewable systems [1–3]. Moreover, the need for energy security and economic stability has increased, and hence more and more emphasis is now being given to the generation of renewable energy [4,5]. Among the renewable energy sources, solar energy is attractive and sustainable [6]. Solar Photovoltaic (PV) energy is considered a clean, attractive, and secure source of electricity generation [7,8]. The solar PV system promises a great future and is increasingly popular due to its simple installation, low maintenance cost, robustness, and zero fuel cost [9,10]. Solar power is abundant; thus, it could play a crucial role in fulfilling global energy requirements including heating, ventilation, and air-conditioning (HVAC) systems, domestic lighting, hot water systems, and other key applications [11]. The cost reduction in solar PV installation is due to several factors such as improved technology, economies of scale, supply chain

competitiveness, and the growing experience of developers [12,13]. At present, solar PV energy is the third-largest renewable source of energy generation after wind and hydro [14]. In the last two decades, the solar PV system has become one of the main sources for power generation [15,16]. In 2018, a unique milestone in the field of solar PV systems was achieved i.e., the 100 GW threshold of annual installations was crossed [17]. According to the Renewable Energy Market Report 2018 by the International Energy Agency (IEA), there will be a comprehensive growth in the generating capacity of solar PV systems from 572 GW to 720 GW between 2018 and 2023 [18]. Further, the global solar PV power capacity is expected to increase to more than 2840 GW by 2030, and to 8519 GW by 2050 [12].

Since the need for solar energy has risen around the globe, the development of an advanced monitoring method has become an urgent necessity. Due to various environmental factors such as soiling, temperature, irradiance etc., the operation and functionality of solar PV systems can be affected. Thus, the accuracy and performance of the solar PV system can be improved by employing an efficient solar PV monitoring system [19]. Monitoring is the process of observing and recording the parameters from the solar PV power plant in real-time. An efficient monitoring technology of the solar PV system improves the performance efficiency as it provides updated information and executes the preventive measures if any flaws are found. The monitoring method also notifies the users by an alert signal when unexpected events occur in a solar PV system [20]. The monitoring of the solar PV power plant is performed either at the module, string, or system level. The monitoring of the solar PV at the system level provides information about the system exclusively. The monitoring technology related to panels and strings helps in identifying the root cause of the problem precisely. Every panel and string needs to be monitored for the overall efficiency improvement of a solar PV power plant, as even a change in the output from a single panel can affect the efficiency of the entire system. Henceforth, numerous monitoring methods have been introduced in recent decades. There has been a change of trend from wired to wireless monitoring systems in the past decade [21].

In the past, the wired monitoring system was commonly used for transferring data through an RS232 cable or an RS485 cable [22,23]. However, as the solar PV system has expanded, real-time monitoring using conventional wired cables has resulted in additional significant costs. Moreover, the cables carrying the data are exposed to environmental conditions such as rain, humidity, temperature, etc. In contrast, the wireless monitoring system is less prone to environmental conditions compared to the wired monitoring system and can deliver faster decision-making in real-time. This is due to the exposure of sensors and nodes to the open environment installed for data acquisition and transmission. Furthermore, wireless monitoring technologies not only increase mobility and network security by implementing associated security protocols, but they also have a longer range, a high response time, and low maintenance costs. Nevertheless, various factors can cause a change in the output of the system, including a change from a sunny sky to a cloudy sky, the temperature of the panel, humidity, irradiance, the mounting angle, and the mismatch between the specification from the manufacturers and the actual PV output [24]. Therefore, further exploration is required to design an effective solar PV monitoring technology before the system can be implemented, considering the number of anticipated challenges.

Very few notable review articles have been published on solar PV monitoring technologies. Shariff et al. [25] emphasized different designs and topologies of solar PV monitoring systems. The different monitoring characteristics such as sampling time, mechanisms for data transfer, associated software etc., were highlighted in the work but the works did not outline the current progress in the field of monitoring with regards to module-based technology. Madeti and Singh [26] focused on examining solar PV systems in terms of the sensors employed, the controllers used, and data transmission techniques. Rahman et al. [27] discussed the architecture and features of various monitoring systems for solar PV power plants. Triki-Lahiani et al. [28] explained the various monitoring systems and concentrated on addressing the major failures in solar PV systems. All the above-highlighted reviews do not consider the insights of the technological implementation of

data transmission and data processing modules in the field of solar PV wireless monitoring systems in a comprehensive manner.

To bridge the existing research gaps, this review unveils new contributions with a detailed investigation of the monitoring technologies of the solar PV system. The review offers the following contributions:

- A comprehensive explanation of various data processing modules for solar PV monitoring systems is presented in terms of categories, specifications, design implementation, software platforms, results, and limitations.
- The categories of the various data transmission modules for wireless communication in solar PV monitoring systems are reported, highlighting topology, data transmission range, sampling rate, power consumption, and range.
- The existing issues and challenges for the monitoring technologies of solar PV applications are covered, emphasizing data handling, security, signal interference, energy efficiency, etc.
- Some constructive future recommendations are presented toward the development of an efficient and reliable solar PV monitoring system.

The paper is organized into eight sections. Section 2 presents the survey methodology of this review paper. Section 3 covers an overview of the solar PV monitoring system and the classification of the modules based on the data transmission and data processing boards. Sections 4 and 5 highlight the data processing technology and data transmission technology for monitoring solar PV systems, respectively. The current issues and challenges are discussed in Section 6. Section 7 presents the discussion and future perspectives. The concluding comments are outlined in Section 8.

2. Survey Methodology

There has been a growing interest among researchers to enhance the performance of solar PV monitoring systems using various technologies. In line with this matter, various data processing modules and data transmission protocols have been introduced in the last decade. Figure 1 denotes the number of papers published between 2010 and 2020. A sharp upward trend is visible in the number of articles accepted from 2010 to 2020 which implies the importance and potential deployment of various modules and communication protocols in solar PV applications. A total of 443 papers were published between 2010 and 2020. Among the total number of manuscripts, 43.57% of the articles were published in the first seven years (2010–2016). However, the number of articles published in the next four years (2017–2020) increased at a greater rate. In this period, 56.43% of the articles were published which is 12.86% higher than the previous seven years.

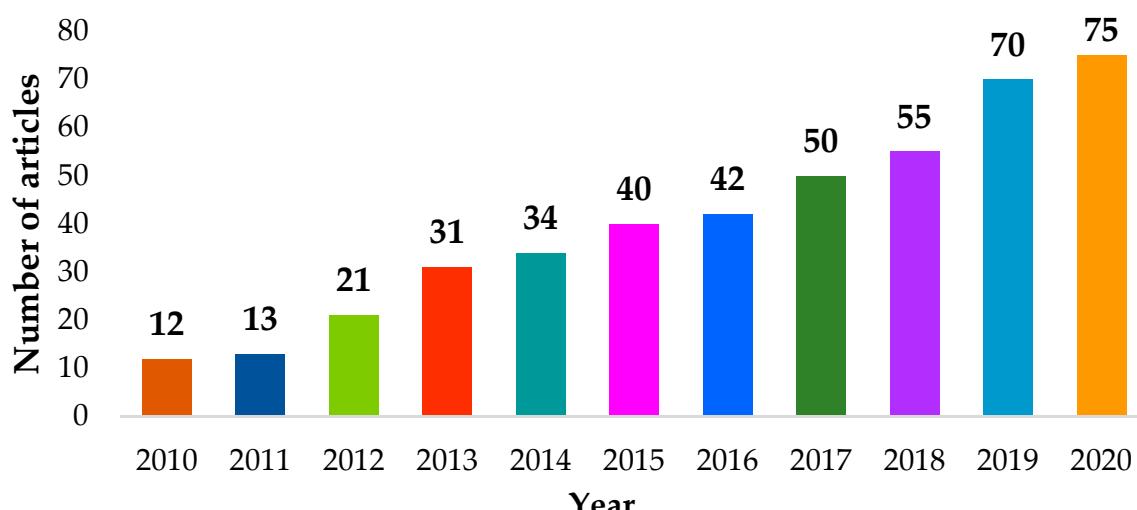


Figure 1. Research trend of solar PV monitoring systems from 2010 to 2020.

The goal of this review is to gather all the recent information, conduct an analysis, and provide a critical discussion of the monitoring technologies for solar PV systems. Firstly, Google scholar, IEEEExplore, MDPI, and ScienceDirect databases were utilized to explore the related work for this paper. Secondly, keywords, abstract, paper content, novelty, and the main topic of interest of the journal were applied to search for the relevant publications within the scope of this paper including solar PV, wireless monitoring systems, sensors, data processing board, and data transmission protocols. The final suitable works were investigated by assessing the impact factors, the review process, and the citations.

The outcome of the screening process can be categorized into four sections. Firstly, the review of solar PV monitoring systems based on data processing modules with its design features, implementation, comments or suggestions, and limitations is presented. Secondly, various data transmission protocols are studied for solar PV monitoring systems. Thirdly, the review investigates various issues and shortcomings of the monitoring technology for solar PV systems. Finally, the review delivers some selective future prospects for the further enhancement of solar PV monitoring systems. The review process can be divided into two phases as shown in Figure 2 and summarized as follows:

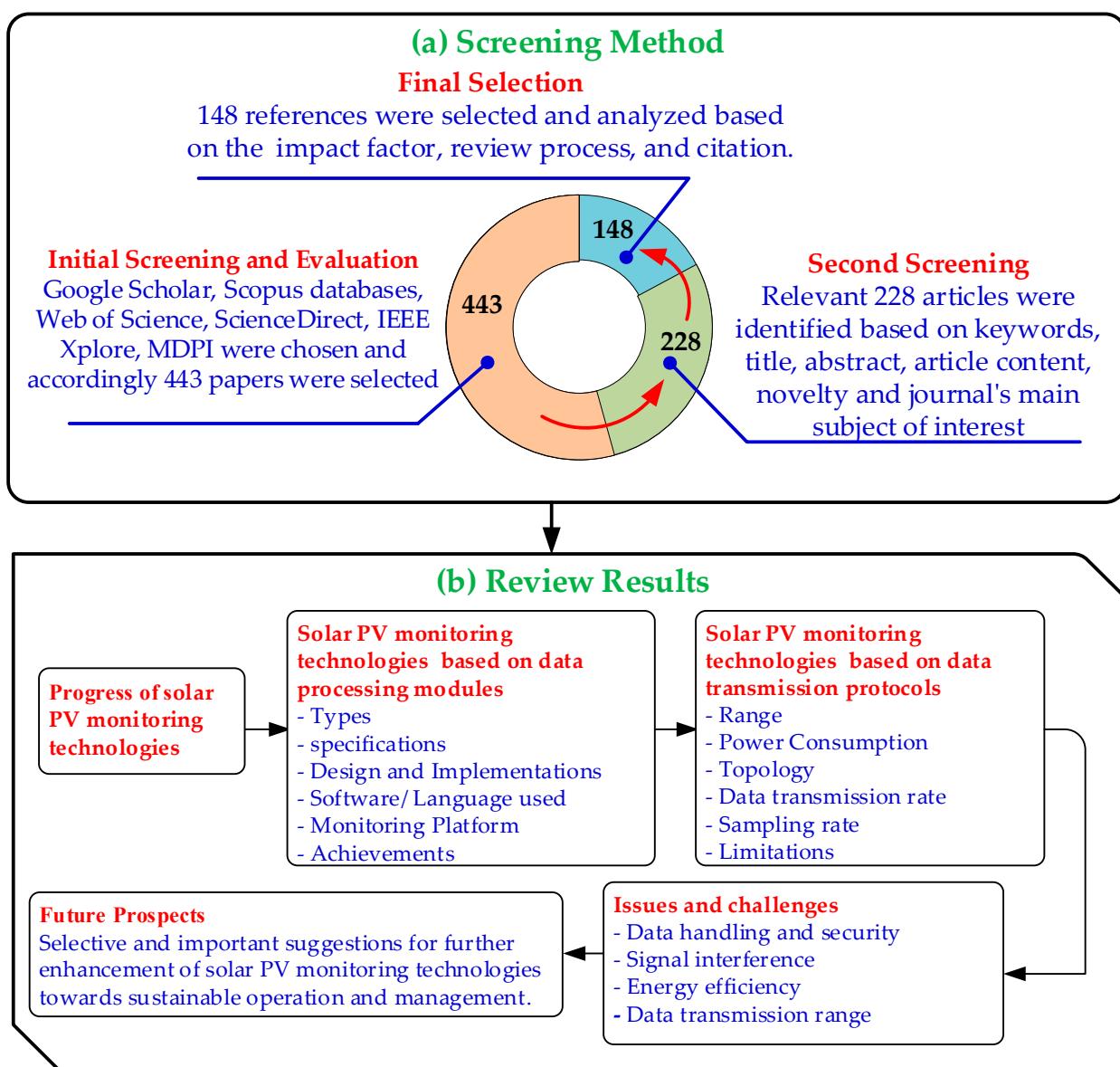


Figure 2. Schematic diagram of the survey methodology.

2.1. Selection Process

- In the first search results, a total of 443 articles were found using various platforms including Google scholar, IEEEXplore, MDPI, and the ScienceDirect databases.
- In the second screening results, a total of 228 articles were selected based on the appropriate title, keywords, abstract, and content of the paper.
- In the third assessment results, the articles were analyzed based on impact factor, review process, and citation. Accordingly, a total of 148 references were finalized for the review paper consisting of journals, conferences proceedings, and recognized webpages.

2.2. Review Results

- Monitoring technologies for solar PV systems based on data processing modules were explained.
- Further, the monitoring technologies considering various data transmission protocols for solar PV application were discussed.
- Key issues and limitations of the solar PV monitoring system based on the presented technology were explored.
- Recommendations and future directions for the further improvement of the monitoring technology for solar PV systems were presented.

3. Overview and Taxonomy of Solar PV Monitoring System

The architecture of the solar PV monitoring system can be divided into three levels, namely, the data acquisition level, the data processing level, and the data display and storage level, as illustrated in Figure 3 [27]. In the data acquisition level, the data are collected from the various sensors such as voltage, current, temperature, humidity, irradiance, etc., and are then sent to the next stage using either the wired or the wireless system. In the next level, the data are stored temporarily in auxiliary devices such data loggers, processed, and sent to the last stage for the display of the results. In the last level, the data are received by the workstation and then the required actions are taken by the system to be configured accordingly. These data can be accessed from anywhere at any time via the internet.

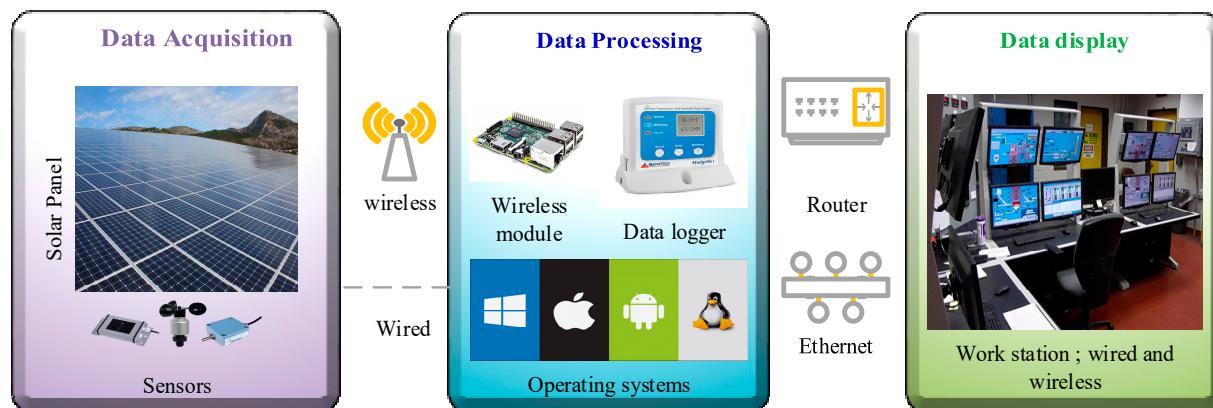


Figure 3. The basic architecture of a solar PV monitoring system.

A comprehensive review of solar PV monitoring system-based data processing modules and data transmission protocols has been carried out. The data transmission modules allow the acquisition, control, and management of connected devices and networks in a real-time environment. Furthermore, they act as middleware that connects with different devices through cloud computing technology. The solar-based monitoring system is comprised of a four-layer structure which consists of sensors (electrical and environmental) for gathering data such as panel voltage, current, temperature, humidity (small scale) etc., a network layer for the transmission of the data by utilizing various transmission protocols

such as ZigBee, Wi-Fi, Bluetooth, LoRa etc., a data processing layer for processing necessary data through various data processing modules such as Raspberry Pi and Arduino, and lastly, an application layer which acts as an interface between end devices and the network as depicted in Figure 4. Further, Fernandez et al. [29] explored the functionality of the various layers such as the sensor, transmission, data processing, and application layers. The authors revealed that the change in the execution of various layers is based on applications such as small scale or large-scale monitoring, and software-based or cloud-based monitoring. The classification of various electrical and environmental parameters based on large-scale and small-scale solar PV systems is presented in Table 1. Platforms such as BeagleBone, Arduino, Raspberry Pi, PLC, and the microcontroller chip have been reviewed in relation to the application of data transmission protocols, the parameters measured, the software used, the monitoring platform, and the related results. In addition, the monitoring system consists of several network protocols for communication to ensure the protection of data during transmission between connected devices [30]. Furthermore, issues relating to low range, low computational speed, low storage memory etc., motivates the requirement of the communication protocol for the monitoring system [31]. In this regard, communication protocols utilizing various wireless communication modules such as ZigBee, Wi-Fi (ESP8266 module), Bluetooth, GSM, and the LoRa module have been reviewed for monitoring solar PV systems.

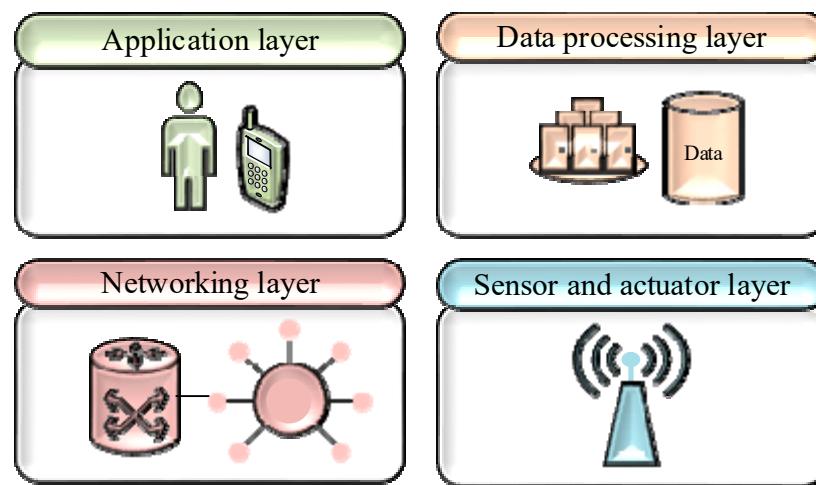


Figure 4. Primary layers for the development of a solar-based monitoring system.

Table 1. Classification of various electrical and environmental parameters monitored under large-scale and small-scale solar PV systems.

Solar PV System	Parameters	
	Environmental	Electrical
Large scale	Irradiance	Array output voltage
	Array Temperature	Array output current
	Speed of wind	Grid voltage
	Humidity	Current to and from grid
	Air pressure	Grid impedance
Small scale	Irradiance	Panel output voltage
	Panel Temperature	Panel output current
	Humidity	Inverter output voltage
		Inverter output current
		Load output voltage
		Load output current

Various state-of-the-art monitoring technologies for solar PV applications have been comprehensively studied based on the application of electronics modules required for data processing, data transmission protocols, and Artificial Intelligence (AI) techniques. Monitoring technology depending on various data processing boards has been explored. The advancements in solar PV monitoring systems in relation to BeagleBone [32], Arduino [33,34] Raspberry Pi [35,36], PLC [37], and microcontroller chips such as ATMEGA8 and ATMEGA16 [38] have been explained along with their limitations. Data transmission protocols such as ZigBee [39,40], GSM [41], Wi-Fi [42], Bluetooth [43], and LoRa [44] have also been studied with regard to the various aspects such as range, parameters to be monitored, program language, sampling time etc. The review of the monitoring technologies based on two distinct classes is presented in Figure 5.

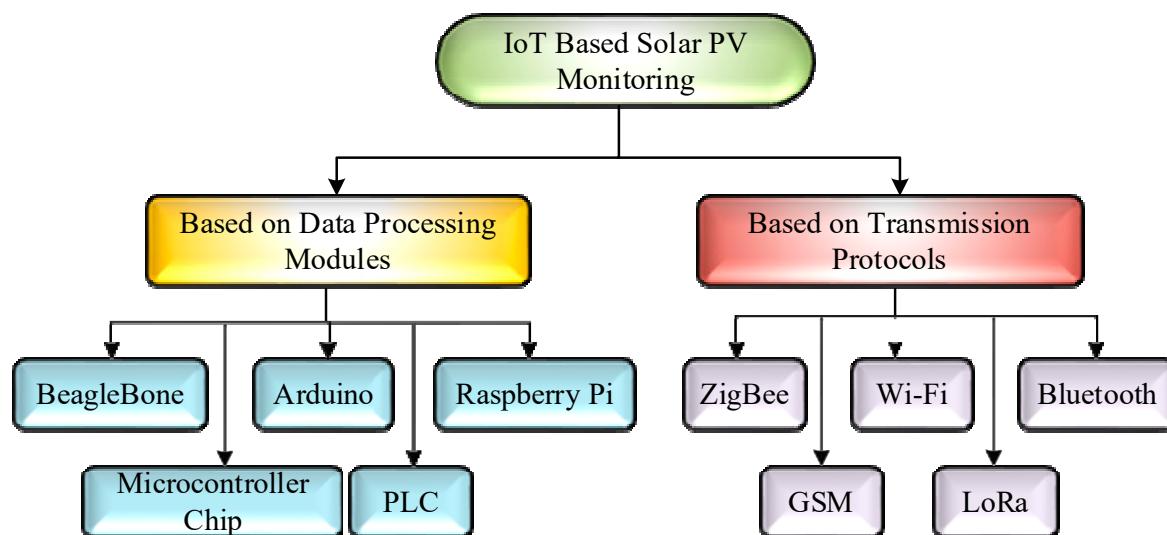


Figure 5. Classification of data processing technology and data transmission protocols for a solar PV monitoring system.

4. Progress of Data Processing Modules for Solar PV Monitoring System

A comprehensive review of various data processing modules for a solar PV monitoring system has been performed which gives an insight into its implementation, design, specifications, used software, and limitations.

4.1. BeagleBone-Based Module

The BeagleBone module is an open-source Linux platform and is also considered as microcomputer which was developed by Texas Instruments, digi-Key, and Newark element 14 in 2008 [45]. The board consists of several busses such as Serial Peripheral Interface (SPI), 12C and Control Area Network (CAN), analog inputs, general-purpose input-output pins, serial ports etc. [46]. It was developed to assist young students learning about open-source hardware and software. Furthermore, it is widely accepted worldwide due to various factors such as its network capabilities, remote control, time management, etc.

Ngo and Floriza proposed a BeagleBone module-based solar PV monitoring system for computing the energy generated as shown in Figure 6 [32]. The proposed system not only computes the energy generated from the solar PV system, but it also monitors its consumption by the respective households. In addition, the designed system was equipped with a web-based mobile application for analyzing the data in real-time. An algorithm was developed with a web-based application for calculating the monthly household energy consumption charge as well as the energy generated by the system. Furthermore, after analyzing the information provided by the web-based application software, it was easier to take the necessary steps to limit the consumption of energy and hence limiting the electricity cost. Solar PV in a household system was analyzed by the proposed design and

several electricity parameters such as voltage, current, output power, and energy were calculated. The extracted electrical parameters were transmitted by the sensors to the server and further to mobiles via the Short Messaging Service (SMS). The presented design consisted of sensors such as INA219 for measuring DC power and the CS5463 sensor for the measurement of AC power, the BeagleBone Black module, and the GSM module for the transmission of data to the server. A python script was scripted in BeagleBone Black module to communicate with different sensors. It was realized that the proposed model could be enhanced comprehensively by employing sophisticated data processing modules for handling complex data in the calculation of the energy tariff for different household utilities. Moreover, Okhorzina et al. [47] proposed a low range monitoring and control system by utilizing the BeagleBone module. The paper proposed a tracking and cooling system to eliminate the problem of the heating of solar panels. The designed system is comprised of a BeagleBone module which controls the overall working of the system in conjunction with the temperature sensors. An algorithm was prepared to control and monitor the heat of the solar PV system by utilizing a liquid cooling mechanism. It was observed that the algorithm proposed by the author needs more attention to control the cooling of the PV station as well as the functionality of the station which could enhance the performance of the system.

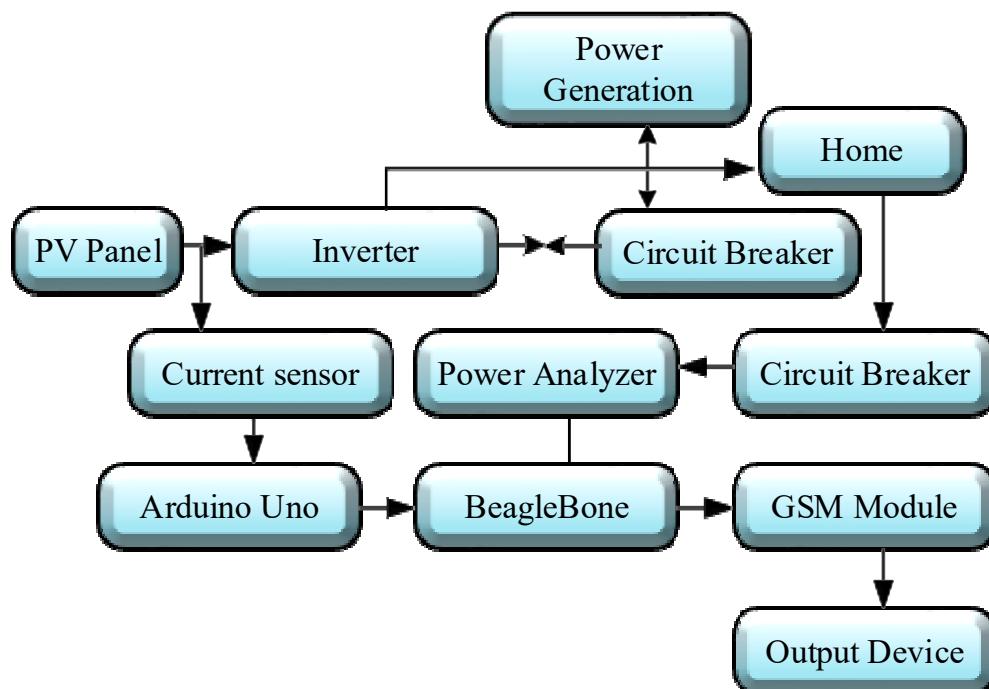


Figure 6. BeagleBone-based monitoring of solar PV systems.

Although the BeagleBone modules have various advantages such as compact size, low power consumption of up to 2 W, high processing power, open-source platform to play etc., their usage is limited by factors such as low numbers of Universal Serial Bus (USB) ports for connecting external devices, expensive cost, the lack of extensive community support, limited connectivity to Wi-Fi, Bluetooth, and lastly, limited color in HDMI resolutions [48].

4.2. Arduino Based Module

The Ivrea Interaction Design Institute invented Arduino technology which was intended for students with no background in the field of electronics hardware as well as programming [49]. Due to the easy availability of hardware design and software programming codes, Arduino is currently one of the most influential open-source hardwares to work with. Arduino IDE is used to program an Arduino board which is a simplified

version for C++. Furthermore, Arduino boards can read input from several sources as well as publish the output in various forms such as the switching on/off of the motor, writing a text online, and controlling light [50].

Allafi et al. [34] designed a monitoring system for standalone PV systems by utilizing low-cost Supervisory Control And Data Acquisition (SCADA) with Arduino Uno. The data was extracted by the current sensor ACS712 and a voltage sensor and sent to the Arduino Uno microcontroller which was further transmitted to the computer through a USB cable. Furthermore, the Modbus library was installed on Arduino to set up the communication between Arduino and SCADA. The main aim of the proposed system was to determine the MPPT efficiency of the system from the data extracted by the sensors. In addition to the proposed system, more functionality in terms of observing electrical as well as environmental parameters such as panel voltage, panel current, temperature, and humidity could be implemented for future research works. Furthermore, Vargas et al. [51] developed a low-cost data logger system for monitoring remote PV systems through Arduino Uno. The proposed design meets the necessary requirements laid down by the International Electro-Technical Commission (IEC). The low-cost data logger utilizing Arduino was capable of operating in remote locations with less network coverage and with minimum maintenance costs. To overcome the limitations of Arduino Uno, the author suggested improvements such as integrating the 12C bus with PCB, a Real-Time Clock (RTC), two external ADCs, SD flash memory, a visual interface, and a power consumption module to make the system compatible according to IEC standards. The temperature sensor DS18B20 along with the current sensor and voltage sensor were placed to extract the data and to send it to an improved data logger. The algorithm to operate Arduino was written in C/C++ with Arduino IDE. The test on the improved data logger was held for one month to test the efficiency in compliance with IEC standards. For further upgradation, the suggested model could be developed for a large coverage area with more data handling capabilities, and the complexity of the model could be reduced by using an easy programming language. Recently, Jamil et al. [52] presented an Arduino-based performance monitoring system for floating solar PV systems. In this approach, the main controller was regarded as Arduino Nano. Furthermore, electrical parameters such as voltage, current, and output power of solar PV modules of 10 W were monitored. Moreover, the monitoring of the module was performed on both the floating system as well as a land system. It was concluded that power output and efficiency were higher in the floating system compared to the land system. The presented system is simpler in implementation; hence, the system can be developed with high wattage monitoring capabilities. Gonzalen and Calderón [53] introduced a hybrid approach with PLC and Arduino to monitor the temperature of solar panels in Smart Grids/Micro-Grids applications. The acquisition and display of data were performed in combination with PLC and SCADA while the extraction and transmission of data were completed by the Arduino MEGA 2560 R3 platform. Although the extensive extraction of temperature was executed, the utilization of various other sensors for the extraction of electrical and environmental parameters could be considered in future works.

Although the technology of Arduino boards possesses several advantages such as low cost, adaptability to various operating systems such as Linux, Windows and Macintosh, easy and flexible programming environment, etc., it suffers from various limitations too. Firstly, it suffers from a limited bit resolution of up to 10 bits. Secondly, for complex and advanced research, more sophisticated platforms are chosen over Arduino boards as the latter is not capable of handling complex data consisting of several processes at once [54].

4.3. Raspberry Pi-Based Module

The Raspberry Pi module is a single-board computer with a low-cost package [33,55]. It is a device similar to a fully functional computer manufactured on a single printed circuit board. The size of Raspberry Pi is as small as a credit card but it has the capability of performing a task similar to a computer [56]. The Linux operating system is used to operate Raspberry Pi [57]. The ARM-based CPU embedded in Raspberry Pi draws less power

which eliminates the need for a heat sink [58]. The easy-to-use module of Raspberry Pi can be utilized for enabling wireless technology [59] and Arduino interaction [60]. Moreover, many variants of the operating system are supported by Raspberry Pi which only requires power to boot [61]. Due to its numerous advantages stated above, Raspberry Pi modules are now used in real-time monitoring schemes.

Pereira et al. developed a multi-user remote system-based Renewable Energy Monitoring System (REMS) using Raspberry Pi and the internet of things (IoT) concept as depicted in Figure 7 [62]. The REMS was updated by the Analogue Digital Converter Embedded System (ADCES) and the communication was established in Linux and cloud server profiles. The REMS server and online server database had a storage capacity of 84.44 MB and 2 GB, respectively. The data was stored at 1 sample/minute with the size of 150 bytes for 391 days. The experiment was performed on a 50 W load with the following specifications: model YL95P-17b 2/3, a maximum power of 95 Wp, 14.3% efficiency, an open-circuit voltage (V_{oc}) of 22.5 V, and a short circuit current (I_{sc}) of 5.59 A. The developed architecture did not have to unlock ports and/or firewall when using the multi-user cloud service. It was proposed that cryptography to secure data storage and database confidentiality should be implemented. The proposed model could be modified to record data from other types of analog or digital sensors as well as for other types of applications using renewable sources. In addition, the utilization of programming languages such as Basic C language and Linux is preferred.

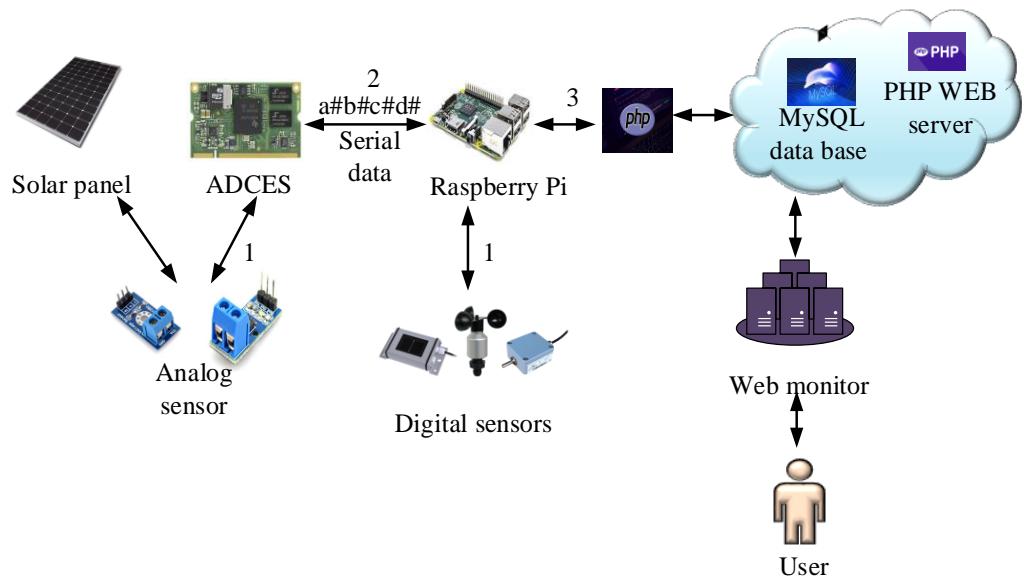


Figure 7. The block diagram of Raspberry Pi and IoT-based REMS.

The work by the authors in [35] proposed a Raspberry Pi-based solar PV monitoring system at the module level using the IEC 61724 standard as presented in Figure 8 [35]. The monitoring was performed at the module level which gave detailed information about the solar PV plant performance. The system not only monitors the electrical and environmental data, but it also evaluates PV module performance and identifies any abnormal behaviors. The variable parameters of the solar PV were monitored under the environment of LABVIEW. The design was implemented with a 5 kWp solar PV consisting of 18 PV modules where each module had a capacity of 310 Wp. The results showed that the error rate was estimated to be less than 2%. The introduced design could be altered to store the data on the cloud/internet for future reference so it can be accessed easily.

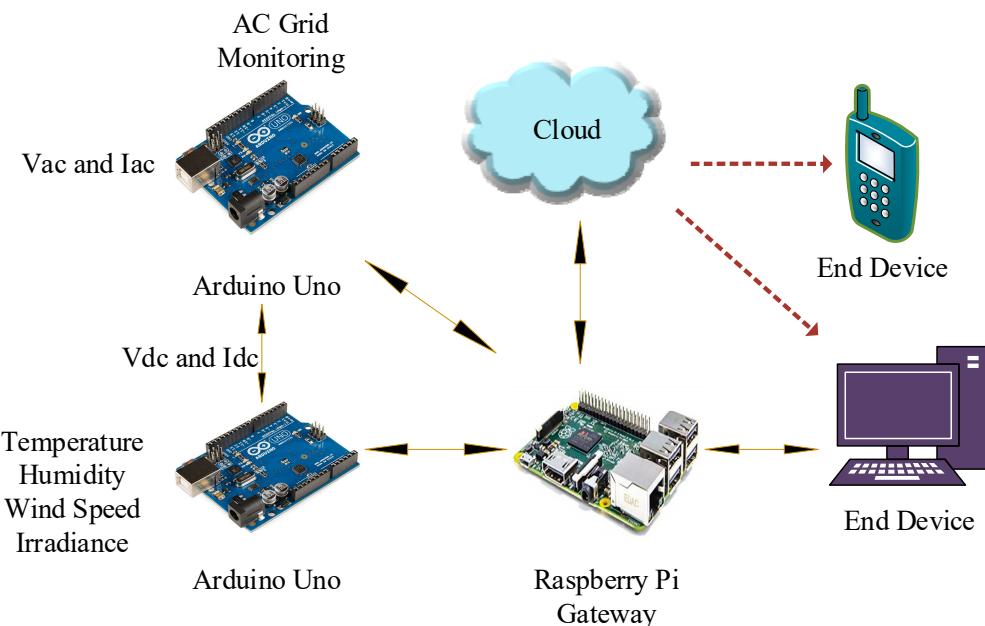


Figure 8. Presented diagram for a Raspberry Pi-based monitoring system.

Ranjit and Abbot [63] designed a cloud-based Raspberry Pi system for solar PV monitoring consisting of four thermocouples connected to the ADAFRUIT MAX31855 processor. Data recorded by the Raspberry Pi were transferred to the cloud system. It was proposed that technological implementation can assist in lowering the fatigue at the panels which could be easily detectable when any fatigue condition occurs. The methodology could be improved by the inclusion of a cryptographic method to secure the data comprehensively. Bikrat et al. [64] established a system with a Raspberry Pi3 card for the monitoring of a remote solar PV system using Bluetooth and Wi-Fi modules. Bluetooth protocol was implemented by transferring the data from the sensors to the Raspberry Pi module. Wi-Fi protocol was used to transfer data from the gateway to the supervision machine/cloud. The comparative analysis among different Raspberry Pi modules confirmed the superiority of the Raspberry Pi3 module over other modules. Further modifications such as flexibility in the operating system as well as the processing application could lead to future expansion.

Raspberry Pi is one of the most effective data processing modules in the field of monitoring systems. However, it does have some technical drawbacks such as, it does not have a Real-Time Clock (RTC) with a backup battery, and it has a high power consumption and weight [65]. Moreover, it lacks a Basic Input Output System (BIOS), and thus it always boots from an SD card. Besides, it does not have a built-in Analog to Digital (AD) converter and hence, an external component must be used for AD conversion [66].

4.4. PLC-Based Module

A programmable logic controller (PLC) or a programmable controller is part of a computer family applied in commercial and industrial applications [67,68]. PLC exhibits robust construction and operational features such as sequential control, ease of programming, timers and counters, easy-to-use hardware, and reliable controlling capabilities which are essential in automation and monitoring applications. PLC modules are reliable and efficient in the synchronization of methods, control applications, and automated systems. Furthermore, it observes the state of processes such as monitoring and relates the data acquired from various sensors [69]. The main operation of the PLC is to monitor and make a decision based on how the system is programmed and how the output is controlled. Moreover, a PLC-based system is implemented in various fields such as monitoring, control, and PV applications [70,71]. The basic PLC monitoring system is displayed in Figure 9 [66].

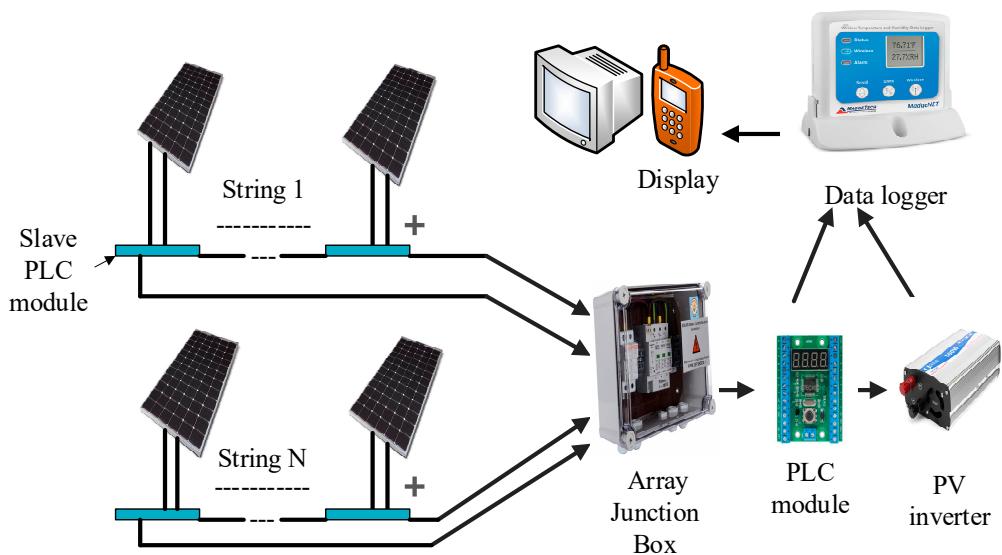


Figure 9. Configuration of a solar PV monitoring system implementing the PLC module.

Han et al. [72] proposed a PLC-based monitoring system to record each solar PV module parameter. The low-cost PLC module was applied on the 16-bit microcontroller unit (MCU) which generated a 100 kHz carrier. A 6.4 kW solar V plant consisting of 16 panels and an inverter rated at 10 kW were employed. The system operated at 49.4 V, 8.1 A, and 400 W of maximum power. Communication modules were not utilized in the proposed topology resulting in cost reductions in the system. The proposed monitoring system was integrated with the home network consisting of the home plug. Another concept in the field of the solar PV power plant is string monitoring with PLC which was proposed by Goto et al. [73]. The monitoring of each string in a solar PV plant consisted of 10–20 panels. The need for string monitoring was implemented due to factors such as aging solar panels and initial failure which degrades the output power of the solar power plant. The authors monitored 30 power stations with capacities ranging from 1 to 15 MW. A case study of a 1 MW solar plant consisting of 314 strings was investigated for 13 months from January 2015 to January 2016. It was observed that the proposed methodology for monitoring primarily focused on string monitoring. Hence, the methodology could be improved by incorporating the monitoring technique at array and module-level for low power generation applications. Mao et al. [69] introduced an intelligent solar PV module monitoring scheme based on a parallel resonant coupling unit. The proposed design used a DC bus and a communication channel to modulate the data into high frequencies for carrier communication. The presented scheme delivered high transmission efficiency and strong anti-interference ability with low costs. Kabalci and Kabalci [74] suggested a PLC-based solar PV monitoring method to develop a micro grid model on the MATLAB/Simulink environment. The system was designed using a DC-AC converter, three solar power plants with a maximum power point tracking (MPPT) system, a multilevel inverter for three-phase AC line voltage, with a 25 km transmission line and a PLC modem. It was stated that the proposed technique eliminated the need for additional monitoring costs since power lines carried the generated voltage as well as transferred the power drawn from the loads. The proposed block diagram of the PLC-based monitoring method is presented in Figure 10 [74]. The methodology of the proposed monitoring system could be further enhanced by simplifying the utilization of technology at the distribution level as well as the sub-distribution level too.

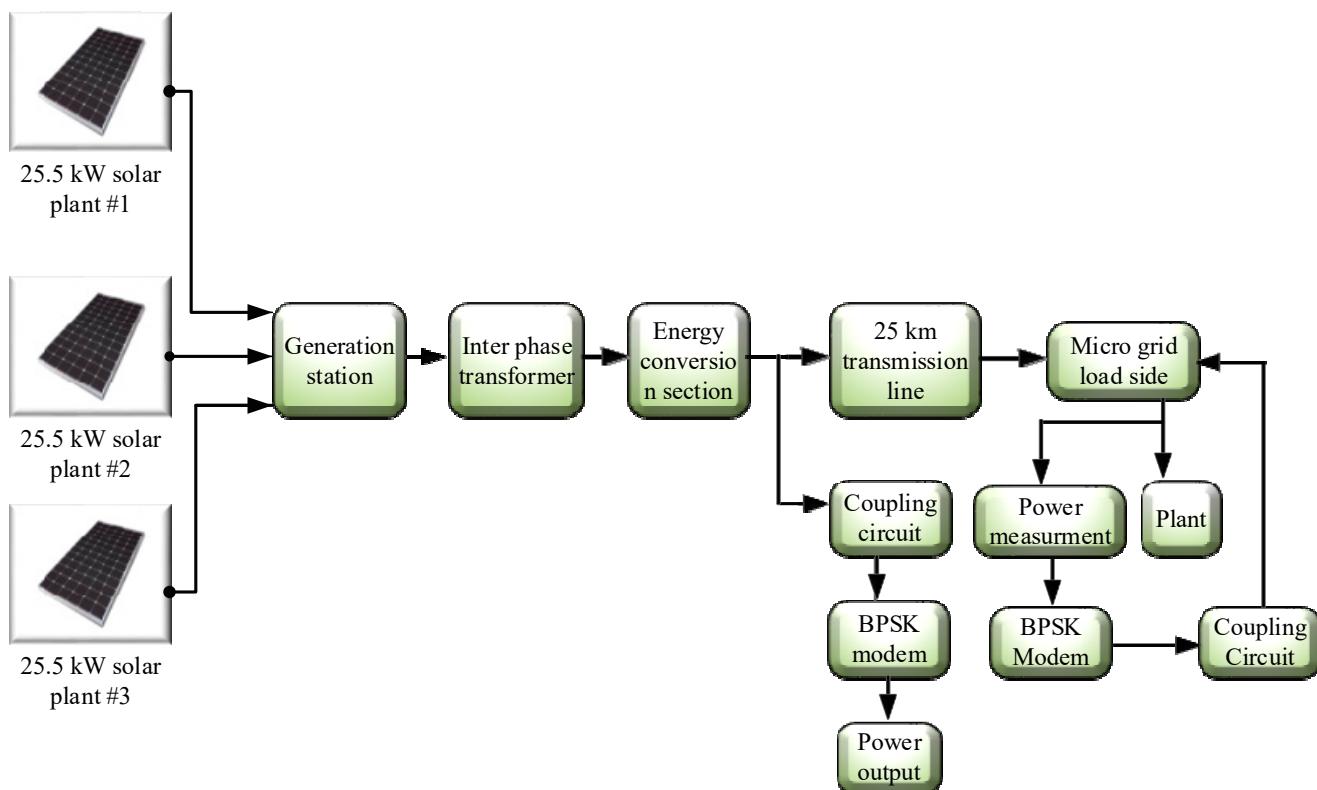


Figure 10. Proposed block diagram for a solar PV monitoring system implementing the PLC module.

PLC exhibits strong points in the progress of solar PV monitoring systems as it can deliver a better performance than other monitoring methods in terms of controlling outputs. In addition, PLC can last for 5–10 years and has low cooling costs since it does not generate much heat [75]. However, the outcome of PLC is not good enough when handling a large amount of data or complex data. Furthermore, the Pentium system, which is widely available today, outperforms even the fastest PLC. Moreover, debugging in PLC may become tedious as finding the fault is not very easy [76].

4.5. Microcontroller-Based Module

The microcontroller is an embedded computer system that has transformed the IoT [58,77,78]. Today, microcontrollers are extensively used in various fields [79] both in scientific research and industrial use [80]. The microcontroller module along with different interfaces is designed to monitor different parameters of solar PV power plants. The schematic circuit of a solar PV monitoring system with ATMEGA8 microcontroller is depicted in Figure 11.

Suryavanshi et al. [81] proposed a solar PV monitoring system based on AVR microcontroller ATMEGA16. The load and battery were connected to the solar panel through a relay. The microcontroller sensed the power requirement of the load and accordingly managed two PV cells to connect to the load. The relay system was employed to manage the direction of the power from the solar panel either to the load or to the battery. Further improvements with regard to the maintenance of the solar panels by monitoring the environmental parameters could be assessed to develop a more reliable wireless solar PV monitoring system. A sensor network for monitoring solar PV with microcontroller PIC181F4620 was designed by Ayesh et al. [82]. Microchip MiWi protocol was used to monitor individual panels. The proposed structure was built to monitor open-circuit voltage (V_{oc}), and short circuit currents (I_{sc}) under various conditions such as dust accumulation, cracks in the string, shading, and MPPT. It was claimed that the monitoring of other electrical parameters such as V_{pv} and I_{pv} must be

observed to effectively measure the power generated by the PV system under various conditions. Harmini and Nurhayati [83] developed a monitoring system for a standalone PV plant using an ATMEGA8 microcontroller through the ethernet. The accuracy of the panel output was determined by a voltage sensor and current sensor readings. It was concluded that the voltage sensors had an accuracy of about 99.3% and 95% for current sensors. Although the author implemented a real-time monitoring system by utilizing a visual basic system, it is necessary to integrate the technique with cloud-based monitoring to effectively utilize the monitored data for future reference.

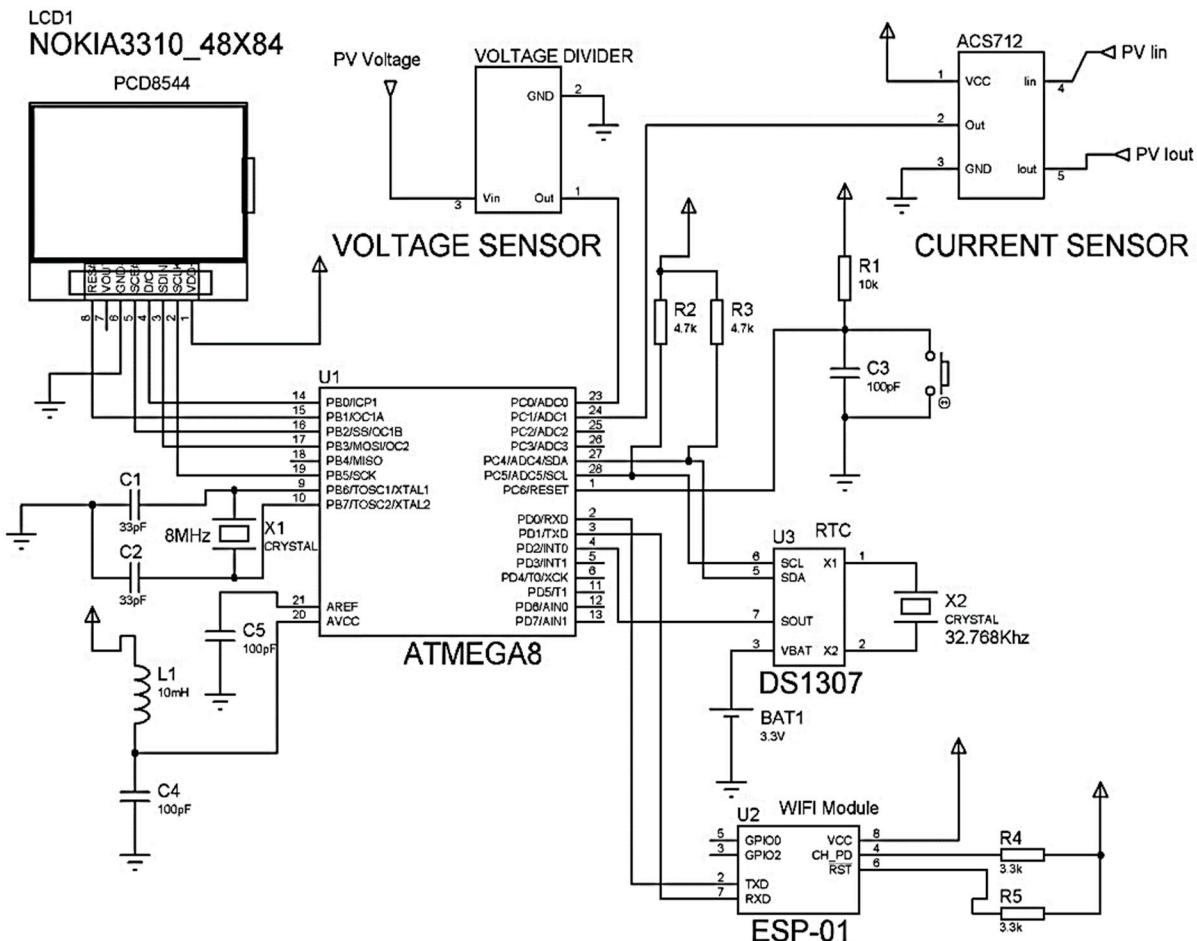


Figure 11. Circuit diagram of a Microcontroller-based monitoring method for a solar PV system.

Although the microprocessor is considered as the basic building block in many fields, it has some drawbacks, such as a lack of memory isolation and real-time performance. Moreover, the power consumption of the system on the chip increases due to the high-density integration of the embedded components [79]. The microcontroller is prone to unlimited physical access from attackers investigating its design and functionality [78]. Furthermore, due to its low storage capabilities and lack of real-time performance, microcontroller-based systems are less effective in the present scenario.

Table 2 provides a detailed specification between the various data processing modules utilized in solar PV systems.

Table 2. Comparison for the specification of various data processing modules.

	Arduino Uno	Raspberry Pi3	PLC (FX1N-14MR)	BeagleBone	ATMEGA 16
Communication protocol	4x SPI, 2x I2C, PCM/I2S, 2x UART	1x SPI, 2x I2C, PCM/I2S, 1x UART	Ladder logic, Ethernet, RS-232, RS-422 and RS-485 modules	4x UART, 2x SPI, 2x I2C, 2x CAN BUS	Serial, 12C, SPI
Size of Board	69 × 53 mm	85 × 56 mm	110 × 95 × 17 mm	86 × 56 mm	As per Requirement
Speed of Clock RAM	16 MHz 16 MHz	1.2 GHz 1 GB LPDDR2	140–180 MHz -	1.0 GHz 512 MB DDR3	0–16 MHz 1 KB SRAM
Supply Voltage	5 V	5 V	24 V	5 V	2.7–5.5 V
GPIO pins	14	26	14	69	32
Storage Memory	32 KB	Micro SD	8 MB	4 GB, micro-SD	16 KB Flash memory, 512 Byte EEPROM
USB port	-	4 × USB 2.0 Broadcom BCM2837,	-	1 × USB	-
Processor	ATmega328P	ARM Cortex-A53 64-b Quad Core	SLC 5/03 CPU	AM335x ARM Cortex-A8	8 bit processor
Power consumption	98.53 mA @ 9 V	400 mA @ 5.1 V	400 mA (Approx)	500 mA	1.1 mA @ 3 V
Weight (Approx)	30 g	45 g	120 g	39.68 g	20 g
Cost (Approx)	USD 30	USD 25–35	USD 45	USD 30	USD 3 (Approx)

5. Progress of Data Transmission Protocols for Wireless Communication in Solar PV Monitoring Systems

In this section, a comprehensive review of the data transmission protocols for solar PV monitoring systems is presented, emphasizing their implementations, design, specification, results, and limitations.

5.1. ZigBee-Based Module

The ZigBee technology was developed in alliance with IEEE and ZigBee based on 802.15.4 standards [84]. IEEE is responsible for developing its physical layer, its media storage control layer, and its data link layer while the ZigBee alliance took charge in the development of its logic network, its data transmission encryption mechanism, the application interface specification, and the communication interface between the system protocols. ZigBee modules are driven by low power and can be employed for short-range monitoring in a wireless sensor network [85,86]. ZigBee is a simple and lightweight wireless network module that uses Radio Frequency (RF) to support the network within sensors. The transmission range of ZigBee may vary from 40 m indoors to 120 m outdoors in the line of sight. ZigBee operates at a 2.4 GHz frequency with a transmission rate of up to 250 kbps [87]. ZigBee uses a ready collision prevention mechanism and a MAC layer to avoid data collisions. The ZigBee module receives the transmitted data and then replies with a confirmation message which greatly increases the reliability of data transmission in a system [88].

Batista et al. [89] presented an overview of ZigBee devices and modules with regard to smart grid infrastructure and the importance of smart metering. The paper discussed four cases of ZigBee technology implementation to detect the interference of the signals at a water treatment plant, a distribution company, a control house of a wind farm, and a home energy system. Although the experiments were performed at several locations to evaluate the performance of ZigBee, the methodology was only limited to the examination of interference of various blockages with no real-time data. Hence, real-time monitoring data should be integrated for further research works. Papageorgas et al. [90] developed a ZigBee-based solar PV monitoring system for a single wire Local Interconnected Network (LIN) bus. The authors also proposed a web-based application to optimize the electrical power output from the solar plant. A three-tier architecture was proposed for the monitoring and characterization systems where the characterization module of the PV solar panel was placed in the first level, the PV cluster gateway was positioned in the second level, and the PV park coordinator and the web-based communication technologies with remote

monitoring and control computers were located in the final level. The proposed algorithm to monitor the condition of solar panels could further be improved with the addition of environmental parameters such as humidity and temperature. Shariff et al. [88] utilized point to point topology for data transmission with a web-based monitoring interface to develop a ZigBee-based solar PV monitoring system. The proposed system utilizing ZigBee modules was implemented with a web-based function as illustrated in Figure 12 [88]. The test was conducted on 1.25 kW solar panels to extract 600 data points for calculating the AC voltage with a sampling rate of 60 milliseconds. Further research with regard to the measurement of efficiency and stability could be performed. In addition, the methodology could be utilized to identify the faults which could significantly increase the performance and efficiency of the solar PV monitoring system.

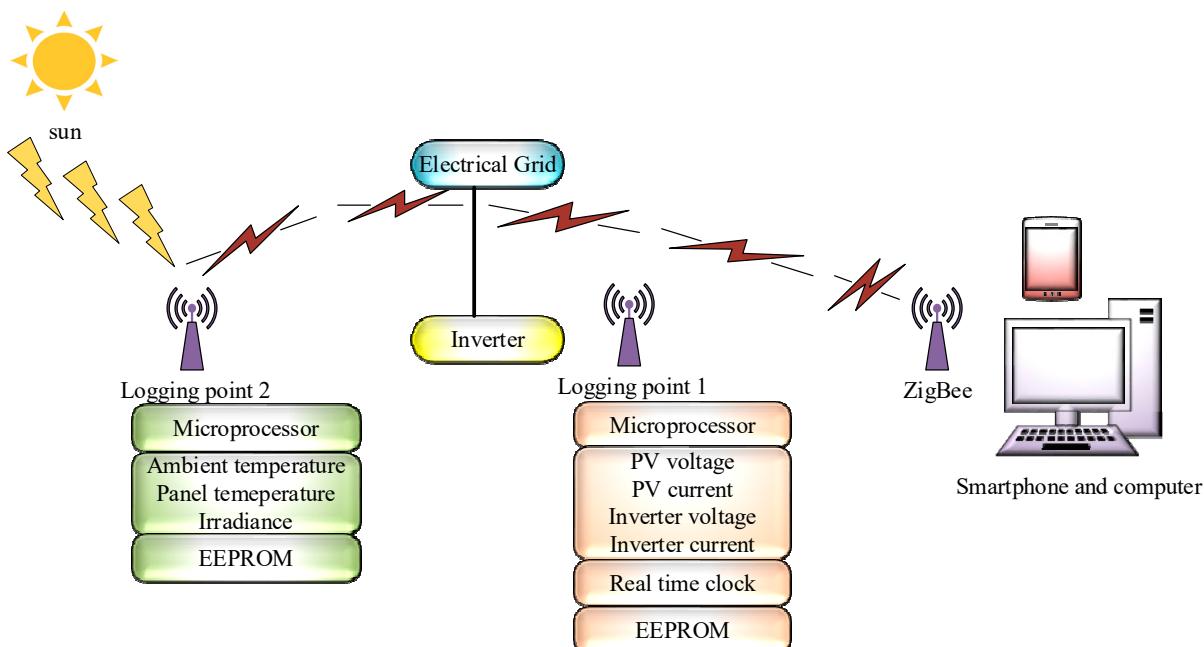


Figure 12. The overall setup of the ZigBee-based grid-connected photovoltaic system.

Li et al. [91] suggested a method using a ZigBee module for solar PV array online monitoring and fault diagnosis. The system was evaluated using 2522 sample data. The fault diagnosis accuracy of the PV power plant was estimated to be 98.58%. More electrical and environmental parameters could be considered in future work to observe the faults effectively. Liu [92] developed a solar PV system using ZigBee technology for PV module performance monitoring. Furthermore, a feed-forward compensation of network voltage was proposed to reduce the voltage fluctuation of the grid-connected current. The paper also proposed a method to reduce Total Harmonic Distortion (THD) in the grid-connected current through a simulation analysis. The algorithm developed by the authors could be further improved by involving a cloud-based system for real-time monitoring. Sabry et al. [93] developed a ZigBee-based low-cost solar PV monitoring system equipped with driving software for recording PV system parameters. The paper proposed a prototype system for a high voltage series-connected PV array in the range of (100–310) V and 3A as the maximum current with a sampling frequency of up to 14 samples/seconds. It is suggested that the proposed model under various conditions/interferences is examined to validate the performance of the system comprehensively. Singh and Chawla [94] designed a solar PV monitoring system located in a remote location using ZigBee. The proposed system used the Python language to store the data in the Structured Query Language (SQL) database. Further research could be carried out by implementing the methodology at several locations. Cihan and Koseoglu [95] applied ZigBee topology as well to transfer data

to observe the panel angle to determine the maximum efficiency. The results indicated that the efficiency of the panel will be negatively affected if there is an increase in temperature of 3–5 °C after 20 °C. The suggested methodology could be implemented with a higher communication distance in order to read the values of current and voltage by utilizing sensors.

Although ZigBee modules have countless practical applications, they have some negative points due to the non-conventional protocol design, complexity, the bandwidth constraints of the communication channel, and the signal processing techniques [96]. The protocol of ZigBee is inadequate for a large sensor network consisting of several large-scale clusters [97]. Moreover, the security aspect of ZigBee is weak and is prone to cyber-attacks which can be hacked or breached by professional hackers. The RF features in ZigBee are limited, creating a disruption of the signal by any obstacle. Furthermore, some other issues relating to ZigBee are signal interference, discrete communication, low range, and loss of signals in lifts, basements etc.

5.2. Wi-Fi-Based Module

Wi-Fi technology is based on the 802.11 family standard which is implemented to develop a wireless local area network (WLAN) [98]. The Wi-Fi-based monitoring system depends on a Wi-Fi module commonly using ESP8266 for data transmission. This tool can read current changes up to 5A with an error reading of 2.5% in the ammeter and voltages up to 30 V with an error reading of 0.073% in the voltmeter. The range of the Wi-Fi module can reach up to 100 m with the data rate between 11 Mb/s and 54 Mb/s. However, the Wi-Fi module consumes more power in transmitting data than other data transmission modules.

Pramono et al. [99] introduced a method to monitor and protect the solar PV system with low power communication using an ESP 8266 Wi-Fi module. A total of three nodes consisting of a 12 V DC motor, LED lights, and LED lamps were observed with an average error of 2.4% for the current sensor and 0.073% for the voltage sensor recorded. The proposed work needs further improvements to elevate the efficiency as well as to decrease the transmission time of the data. Allafi and Iqbal [42] proposed a method based on an ESP32 module to monitor the electrical parameters of the solar panel and battery. The designed system used low-cost sensors, an ESP32 Wi-Fi module, and an SD-card reader. A total of 12 solar modules each at 130 W was tested. The work consisted of low power applications which could be improved comprehensively for high power applications such as 1 kW. In addition to the above methodology, environmental parameters should be considered for future works in terms of panel conditions. Moreover, the presented technology proves insufficient for supporting any intelligent decisions or notifications. Rouibah et al. [100] designed a low-cost monitoring system utilizing a Wi-Fi module ESP8266 for maximum power point tracking (MPPT) in a solar PV plant. The system consisted of two electronic boards, a data acquisition sensing board, and a DC-DC boost converter. Besides, a website was also designed to store and display the monitored data in real-time. The block diagram of the proposed monitoring system is displayed in Figure 13 [100]. Further improvements related to fault detection as well as remote sensing could be implemented with the integration of a failure system to send the information related to sensor failure. Gusa et al. [101] proposed a Wi-Fi-based solar PV monitoring system using a Wi-Fi module for data transmission to monitor solar panel parameters such as voltage, current, and temperature. The monitoring of the parameters was completed in real-time. The results showed that the average errors of voltage and current were 0.96% and 5.6%, respectively. The methodology observed is simple and could be comprehensively improved for a wide range of applications such as fault detection, measurement of efficiency, as well as panel condition. Aghenta and Iqbal [102] proposed an open source SCADA architecture to develop an efficient monitoring system and a robust supervisory control system. The developed structure consisted of various components such as sensors, ESP32 Thing Micro-Controller (RTU), a Thinger.IO local server IoT platform, a Raspberry Pi

Micro-Controller and a local Wi-Fi Router. The ESP32 Thing Micro-Controller (RTU) is used to collect the electrical data from various sensors and then transfers the obtained sensor data to the Thinger.IO local server IoT platform through a Wi-Fi network for data storage, remote control, and real-time monitoring. The proposed SCADA system was tested using 260 W and a 12 V Solar PV System to monitor the voltage, current, and power remotely.

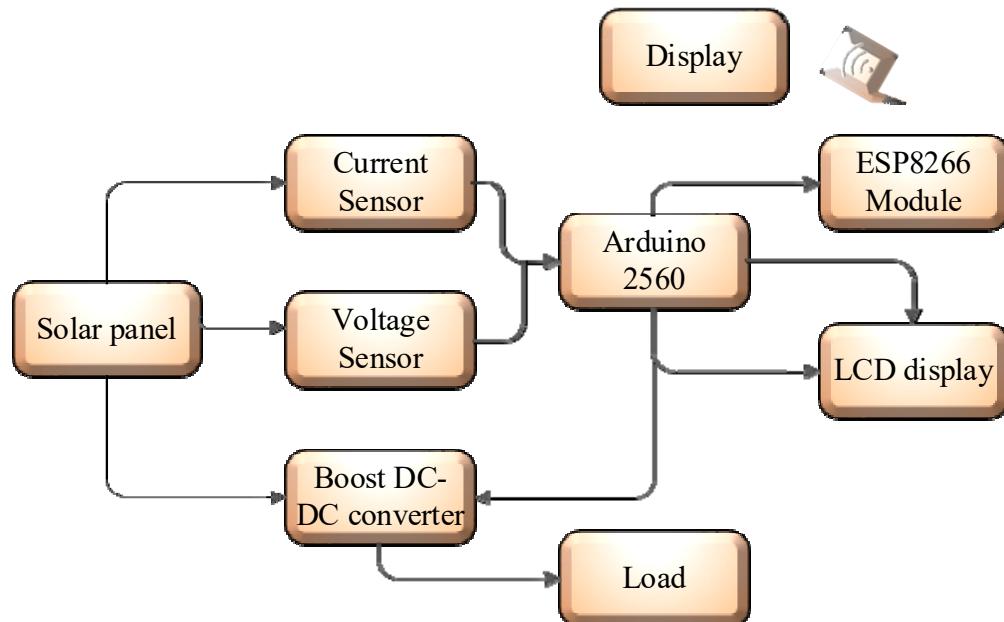


Figure 13. Schematic diagram of the monitoring scheme using an ESP8266 module.

Some issues relating to monitoring using Wi-Fi are as follows:

- The deployment of unauthorized devices without undergoing security review possesses could result in a threat for the insertion attack;
- Bypassing access points by clients makes them prone to external threats as well as threats against each other;
- Interception and monitoring of traffic across a LAN. The attacker needs to be within the range of an access point (approximately 300 feet for 802.11b standard);
- Acquisition of the frequency by illegitimate traffic thus preventing the legitimate traffic reaching clients or the access point.

5.3. Bluetooth-Based Module

Bluetooth is a wireless technology for exchanging data over short distances. Bluetooth functions are executed using an IEEE standard of 802.15.4 and Low-Rate Wireless Personal Area Networks (LR WPANs). It is an emerging platform and one of the most popular modes of transmission for sending data from one device to another [103]. Radio interference is removed in Bluetooth technology and replaced by a Speed Frequency Hopping (SFH) technique which allows devices to make complete access of the radio spectrum. Users have access to data transfer among various devices by forming an ad hoc network [104]. The transmitting power can be increased for sending the data up to 100 m in Bluetooth technology [105].

Sarabia et al. [106] designed a portable solar PV system for measuring the data of the generated PV power using Bluetooth communication protocols. The INA219 sensor was used to monitor the current, voltage, and power as well as execute the 12C communication protocol. The 12C protocol consists of two communication cables: serial data (SDA) and serial clock (SCA), which allows up to 127 slave devices to be connected. The latencies generated by masters of many slaves during the transmission of data from each slave can be taken into consideration. Wenxing [105] presented a solar PV monitoring system based

on Bluetooth technology for a photovoltaics substation. The proposed monitoring system was combined with an older automation system to develop a new system for a solar PV substation. The presented methodology could be improved by integrating the proposed algorithm with the safety and economics of the substation which could lead to an increase in the overall efficiency of the system. Le et al. [38] proposed a Bluetooth-based solar PV monitoring, evaluation, and fault detection system. The proposed system was designed to monitor the voltage, current, temperature, and irradiance of the solar panel. The results were displayed in MATLAB/Simulink platform. The experimental test was performed on a 1 kWp solar panel with a sampling time of 1 min. A fault detection parameter was proposed by observing the readings of the simulated results and then comparing them with the theoretical data obtained from the panels. All data visualization, simulation, and fault detection were completed on a common platform of MATLAB Simulink. Mohapatra et al. [107] introduced a solar PV monitoring system using Bluetooth module HC-05 to transmit data. The data were monitored by the user through the Bluetooth Terminal Application. The paper also focused on the distribution of power using a relay. The relay was switched ON/OFF by the control signal from the Arduino Uno to distribute the power properly. As per the review of the methodology, the complexity of the system could be minimized by utilizing some of the advanced microcontrollers (AVR and ARM architectures) in conjunction with the Wi-Fi transmission protocols which would provide a higher transmission range.

Bluetooth offers various advantages but also comes with several disadvantages, including factors such as authorization, encryption, and authentication [104]. One of the main concerns about the security of Bluetooth is the pairing process [108]. Attackers can imitate users, end connections between the devices, and modify data [109]. Furthermore, it has a limited operational range of up to 100 m. Moreover, it suffers from high power requirements and exhibits slow data transmission compared to other monitoring technologies [110]. In the case of monitoring environmental parameters, transmitting a large amount of data at short intervals would require a multi-hop routing protocol which could access larger areas by using other nodes in the network as relays to reach the destination node [111].

5.4. GSM-Based Module

The Global System for Mobile (GSM) is generally used for the mobile correspondence framework. The GSM framework is built by utilizing Time Division Multiple Access (TDMA) [112]. The GSM framework is portable with a wide coverage area and has a high consistency [41]. The framework is characterized by distinctive components and the routes in which they communicate to empower the general framework operation. The operation of the GSM includes the communication between a mobile phone and a Public Switch Telephone Network (PSTN). The first GSM framework was propelled in the mid-1990s [113].

Belghith and Sbita [114] designed solar PV remote monitoring and control systems with GSM technology and LABVIEW to monitor the parameters and other factors. The system consisted of sensors connected in a star topology and a PIC18F4550 board with an inbuilt 8 KB of flash memory, 368 bytes of Random-Access Memory (RAM) and 256 of Electrically Erasable Programmable Read-Only Memory (EEPROM). The microcontroller programming code was edited with mikroC PRO. The proposed technique could be further enhanced by storing the data in the cloud, detecting the faulty panel by fault detection techniques, and expanding the coverage area. Ahmad et al. [91] developed a solar power monitoring and control system based on the GSM network for rural areas. The information was transferred to the targeted mobile station through a GSM interface using a Short Messaging Service (SMS). It is suggested that future work focuses on data security which could secure the data sent via Short Message Service (SMS). Lelutiu and Georgescu [115] presented a GSM-based solar PV monitoring system to control the orientation of the solar panels all year round. The test board consisted of the solar panel, two lead-acid batteries

rated at 6 V, ab ATMEGA328 board, a Steca-Solsum 6.6 F/12, 24 V/6A solar PV panel charge controller, and a two bipolar stepper motor with a torque of 0.23 Nm rated at 12 V. The system was able to follow the sun tracker through the GSM network. The suggested work could be enhanced by obtaining the electrical as well as the environmental parameters to observe the panel condition in conjunction with the control of the orientation of the panel. In their recent work, Xia et al. [116] developed a 4G communication platform to monitor electrical parameters such as voltage and current. Further, the monitoring technology was integrated with a cloud server for the display and monitoring of the extracted data. Further, the presented work designed a feature extraction and a classification model for analysing the health status of the inverter. A probabilistic neural network (PNN) model was designed with the 660 sets of faulty data for training the model from the PV inverter obtained online at 2–8 kW.

GSM technology has taken a leap in terms of technological advancements with higher numbers of antennas, low error rates, low costs, wide area coverage and monitoring 24/7 [117]. Despite the advancements achieved, GSM lags behind in some issues relating to the sending of the message, such as the interruption of the data and connection problems with emails when many people use the same bandwidth [118]. Furthermore, Subscriber Identification Module (SIM) card cloning may lead to fraud, resulting in the theft of data [119]. The proposed method was used to examine the solar power transferred to the batteries and the temperature conditions for that moment of time.

5.5. LoRa-Based Module

Semtech [120] introduced a spread spectrum modulation technique known as LoRa (long-range) derived from Chirp Spread Spectrum (CSS). LoRa is a low-power wide-area network (LPWAN) technology that is specifically designed for IoT [121,122]. In recent years, LoRa has gained significant attention amongst both industrial and research communities [123]. This method aims at being usable in long-lived battery-powered devices, where energy consumption is of paramount importance [124]. A typical LoRa network is a star-of-stars topology, which includes three different levels of devices, as illustrated in Figure 14 [116].

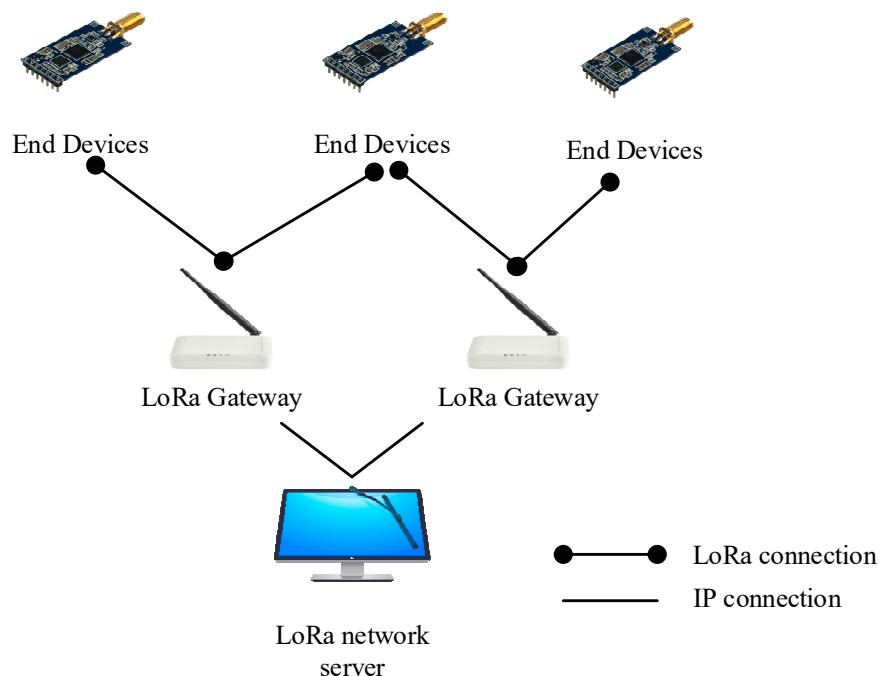


Figure 14. Star topology based on LoRa Network Architecture.

Shuda et al. [125] proposed a LoRa-based solar PV monitoring system. A LoRa module was selected for its long-range and low power characteristics. Different parameters such as module voltage, current, backside temperature, ambient temperature, and irradiance were measured. The test was conducted using a 250 Wp monocrystalline PV module and measurements were recorded accordingly. The results demonstrated that a range of 9.27 km was achieved with a Spreading Factor (SF) of 12 and a bandwidth of 125 KHz. The concept of SF dominates in LoRa based technology as it works on chirp (bits per second) protocol requiring a fixed amplitude and modulation for the transmission of data. Lower SF relates to the transmission of more chirp per second and vice versa. A graph was plotted showing the elevation profile between the transmitter node A and the receiver node B as displayed in Figure 15 [125]. The elevation profile suggests that the successful transmission and measurement of data packets is achievable at 10 km from the sensor node to the receiver node even without the line of sight. Although an extended range was achieved in transmitting the data from one point to another, the work could be extended for a large solar PV system. In addition, SF should be carefully selected to transmit the data with a high transmission rate.

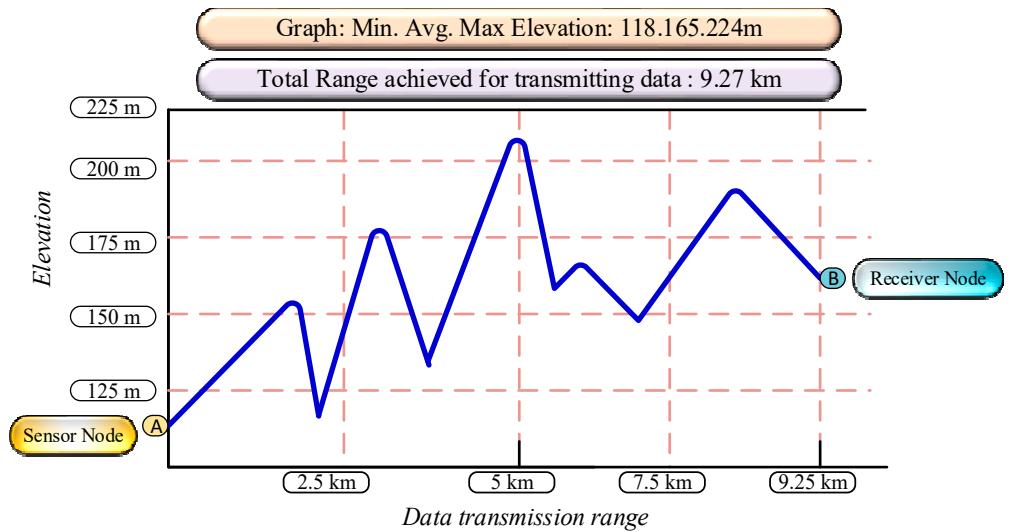


Figure 15. Elevation profile for data transmission for a LORA-based module.

Choi et al. [126] designed a monitoring system for renewable energy (solar and wind) using LoRa technology. The LoRa network used a sub 1 GHz frequency for long-distance data transmission. A low-powered LoRa network was implemented by applying an end-to-end modem without using a base station. The MongoDB database was employed to store a large amount of data received from the LoRa modem and a web server was designed using the JavaScript, PHP, apache, and CSS languages. The proposed system could be evaluated based on the efficiency of the solar PV plant and optimization could also be performed. Paredes et al. [106] proposed a low-cost LoRa-based solar PV monitoring system that communicated with solar photovoltaics plants located in remote locations. The proposed topology was designed using a 5 kW solar panel. The recorded data were stored in a packet size of 38 bytes with a transmission power of 14 dBm and SF metric ranging from 10 to 12. The presented work could be extended by observing the fault in the panel, array, or string by the utilization of a fault detection mechanism.

LoRa is regarded as having low power and a long-range transmission of data packets. Nevertheless, it has some operational restrictions, such as network size, which is limited by duty cycle [127]. Although the performance of Low Range Wide Area Network (Lora WAN) is determined by the Physical Layer (PHY)/ Media access Control (MAC) layer which identifies the devices connected in the network, the duty-cycle regulations in the industrial, scientific, and medical (ISM) frequency bands turn out to be key limiting factors [128].

There is an increase in packet loss when the number of end nodes in the network is increased [129]. Moreover, large SFs are required for longer communication but time on air and off period duration also increase in proportion with SFs. Large SFs are implemented more than small SFs for long-distance communication resulting in a low transfer rate and a high Packet Error Rate (PER) [130]. The time on-air utilized by data (bytes) to be transmitted and received with different SFs is shown in Table 3. For example, if 10 bytes of data were sent with SF = 7, it would take around 0.1 s, whereas if the SF is increased to 11, it would take 0.5 s for the same byte of data to be transferred.

Table 3. Time on air utilized by data packets at different SFs.

MAC Payload Size (in Bytes)	SF = 7	SF = 9	SF = 8	SF = 10	SF = 11	SF = 12
10	0.1	0.1	0.1	0.25	0.5	1
20	0.1	0.1	0.18	0.3	0.7	1.4
30	0.2	0.1	0.3	0.48	0.8	1.5
40	0.2	0.1	0.35	0.51	1	1.8
50	0.22	0.2	0.39	0.6	1.2	2.2

The comparison of the specifications for data transmission protocols used in solar PV monitoring systems is presented in Table 4. Bluetooth, Wi-Fi, and ZigBee constitute short range data transmission modules whereas GSM and LoRa comprise long-range data transmission modules.

Table 4. Comparison of various specifications of data transmission modules.

Module Implemented	Range	Power Consumption	Topology	Data Transmission Rate	Sampling Rate
Bluetooth	100 m	10–500 mW	Point to point	1 Mbps	44.1 kHz
Wi-Fi	Short range modules	1 W	Star	11 Mbps	20 MHz
ZigBee	150 m	1 mW	Mesh	250 kbps	8 MHz
GSM	300 m	1–5 W	Star	270.8 kbps	8 kHz
LoRa	Long Range module	10–30 km	Star, Mesh	5469–293 bps	500 kHz

The data transmission rate for Wi-Fi is variable and depends on protocols and frequency utilized. The value of 11 Mbps here refers to 802.11b protocol with 2.4 GHz frequency.

A comprehensive comparative study for the different data processing modules and the data transmission protocols for solar PV monitoring systems is tabulated in Table 5.

Table 5. Comparative analysis of solar PV monitoring system with various data processing and data transmission modules.

Data Processing Modules	Data Transmission Protocol	Measured Parameters										Software/Language Used	Monitoring Platform	Peak Power of Monitored PV Module/Plants	Achievements	Related Reference
		V_{pv}	I_{pv}	V_{ac}	I_{ac}	G	T	V_{oc}	I_{oc}	V_{sc}	I_{sc}					
BeagleBone	SIM900D GSM shield	✓	✓									Arduino Based	Web Application	245 W	Monitoring, forecasting of monthly bill	[32]
BeagleBone	-					✓						Not Mentioned	LED Display	-	Monitoring and Control of Panel	[47]
Arduino	Modbus library	✓	✓	✓								Arduino IDE	Reliance SCADA	1.56 kW	Application of Reliance SCADA for low-cost application	[34]
Arduino	-	✓	✓									Arduino IDE	Arduino Application	10 w	Minimizing biased reading by utilizing DAQ	[52]
Raspberry Pi	Wi-Fi Dongle USB	✓	✓		✓	✓						C and Linux	Cloud service	50 W	Multi-user remote monitoring	[62]
Raspberry Pi	RFM69HW 433 MHz Wireless Transceiver	✓	✓		✓	✓						LABVIEW	Web Server	250 W and 5 kW	Monitoring, Cost Reduction	[35]
PLC	Wi-Fi Dongle/Ethernet	✓	✓			✓						Not Mentioned	Data Logger/Smart App. Cloud	6.4 kW	Module Monitoring, No communication modem for PLC module	[72]
PLC	Ethernet (100BASE-TX)/Modbus							✓				Not Mentioned	System/Host System	1–15 MW	String monitoring	[73]
PIC181F4620 Microcontroller	Microchip MiWi protocol					✓	✓	✓	✓			Not Mentioned	WSN measuring unit	-	Monitoring, Detection, and localization of bypass event	[82]
Microcontroller	Wi-Fi/Ethernet WIZ 107 SR	✓	✓									Visual Basic	Monitoring Application	-	Monitoring	[83]
Microcontroller	ZigBee	✓	✓	✓	✓	✓	✓					C and NetBeans	PC Based Application	1.25 kW	Monitoring, improvement for low cost PV system	[88]
ATMega328P microcontroller	ZigBee	✓	✓									C#	PC Based Application	5 W	Monitoring, Significance of temperature on panel output	[95]
Not Mentioned	ZigBee	✓	✓		✓	✓						MATLAB	MATLAB	150 W	Monitoring, Checking the range of electrical power generation	[93]
Arduino Mega 2560	ESP8266 Wi-Fi module	✓	✓	✓	✓							C++/CSS, HTML and JavaScript.	Website Based	120 W	Improving monitoring, performance, and maintenance of system	[100]
Microcontroller ESP32	ESP32 Wi-Fi module	✓	✓									Arduino IDE/HTML	SD Card/Web page	1.3 kW	Development of low-cost web-based Monitoring system	[42]

Table 5. *Cont.*

Data Processing Modules	Data Transmission Protocol	Measured Parameters										Software/Language Used	Monitoring Platform	Peak Power of Monitored PV Module/Plants	Achievements	Related Reference
		V_{pv}	I_{pv}	V_{ac}	I_{ac}	G	T	V_{oc}	I_{oc}	V_{sc}	I_{sc}					
Arduino Uno	Bluetooth module HC-05	✓	✓									LabVIEW	LabVIEW interface	-	Monitoring, Low cost, Implementing 12C protocol	[106]
STM32F4DISCOVERY board	Bluetooth module	✓	✓			✓						MATLAB	MATLAB Platform	87 W	Monitoring, Fault Detection in Panel	[38]
PIC16F877 Microcontroller	GSM Module	✓	✓			✓	✓					LabVIEW/ISIS soft-ware/mikroC PRO	LabVIEW Platform	-	Monitoring, Replacement of manually module checking	[114]
PIC16F877 Microcontroller	GSM module	✓	✓			✓						Visual Basic/C	Web-Based application	-	Solar power monitoring and control	[131]
Raspberry Pi 3	LoRa Module	✓	✓			✓	✓					MySQL database	Mobile Receiver unit	250 W and 100 W	Monitoring and range measurement test	[125]
Raspberry Pi	Hope RMF95 LoRa Module	✓	✓			✓						LMIC library	TTN web Based application	5 kW	Module-level monitoring	[132]

V_{pv} is panel voltage; I_{pv} is panel current; V_{ac} is inverter voltage; I_{ac} is inverter current; G is irradiance; T is panel temperature; V_{oc} is open circuit voltage of panel; I_{oc} is open circuit current of panel; V_{sc} is short circuit voltage of panel; I_{sc} is short circuit current of panel; I_{st} is string current; D is Duty cycle.

Based on the abovementioned reviews, some guidelines need to be taken into consideration to select an appropriate technology for solar PV monitoring systems. The guidelines are presented in Table 6.

Table 6. Guidelines for the selection of appropriate technology for solar PV monitoring systems.

Technical Specifications	Rating	Technology	Remark
Storage/memory	In kB	Microcontroller/Arduino	Consideration has to be taken whether data needs to be stored locally or sent to the cloud.
	Internal storage + micro SD slot	BeagleBone/Raspberry Pi	
	In MB	PLC	
Supply Voltage	2.7–5.5 V	Microcontroller	For the development of an efficient solar PV monitoring system, the technology chosen must match the available power supply
	5 V	BeagleBone/ Raspberry Pi/ Arduino	
	24 V	PLC	
Range	<300 m	ZigBee/ Wi-Fi/ Bluetooth	The range of data transmission depends on the distance to the remote control center.
	upto 30 km	GSM/ LoRa	
Data transmission rate	In kbps	ZigBee/GSM	The rate of data transmission must be considered according to the requirements of the system.
	In Mbps	Wi-Fi/ Bluetooth	
	In bps	LoRa	

Therefore, the information discussed above will act as guidelines in selecting an appropriate solar PV monitoring system.

6. Key Issues and Challenges

The main aim of the monitoring system for the PV power plant is to transmit the data in a reliable, secure, and efficient manner. However, several issues significantly affect the performance of various monitoring technologies in terms of efficiency, security, range, data processing capability, sampling rate, and signal interference. Some of the identified key issues and challenges are discussed in the following subsections.

6.1. Data Handling

With the increase in the size of utility solar power plants, there is an enormous amount of data that is very difficult to monitor using conventional technologies and data processing modules. Although Arduino is cost-effective, it lacks powerful capabilities to acquire complex data and hence should be replaced by a powerful data processing platform for complex analysis [133]. In addition, PLC modules are also not good at handling large amounts of data generated by large-scale solar power plants. Raspberry Pi can handle large and complex data but lacks a real-time clock. Hence, it is a necessity to develop a powerful module that can acquire a large amount of data in real-time.

6.2. Security

Security is an important aspect of wireless monitoring schemes [134]. The data transmitted from the sensor node to the central station node may be affected [127]. The functionality of the system could be compromised due to the existence of weak security protocols. Security against any cyber-attack and physical tampering should be employed in all the layers including authentication for legitimate users and end-to-end encryption to provide privacy and confidentiality. Moreover, only authorized persons should be allowed to perform a certain task while complying with security protocols [135]. The data transmission modules are prone to external tampering; thus, they pose huge security issues.

When an unknown device is included in a ZigBee network, unprotected data can be sent from the device, hence affecting the whole network. The data in a Wi-Fi network can easily be captured within some ranges. The attackers in a Bluetooth system can interfere and steal encryption keys, thus accessing the data between the devices. Although LoRa provides end-to-end security through several steps such as application and network key, the network key can be extracted if an attacker gains physical access to the device [136].

6.3. Signal Interference

Interference issues can cause severe problems in the data monitoring of a solar PV system. The network may be affected by interference from other modes of communication. This results in the poor functioning of the modules, a slow rate of data transfer, poor signal strength and discontinuous connections. Signal interference in GSM reduces the quality of the service thereby increasing the loss of revenue [137]. Furthermore, interference in Raspberry Pi occurs by radio frequency from High-Definition Multimedia Interface (HDMI) cable due to the dropping off of Wi-Fi signals.

6.4. Energy Efficiency

The solar PV monitoring system consists of multiple nodes of transmitters. The energy efficiency issues are related to the lifetime of the node battery [138]. Any failure of the node battery results in the low life of the network, thus disturbing real-time communication. This hampers the extraction of data from different nodes which could affect the performance of the whole system. Hence, it is essential to develop an energy-efficient communication protocol [139]. Moreover, the utilization of multiple paths allows better energy efficiency for real-time communication in the monitoring system.

6.5. Operating System and Programming Language

Data processing platforms utilize different operating systems as well as programming languages to operate according to the system requirements. BeagleBone and Raspberry Pi support Linux as an operating system thereby making the module cost-efficient [140,141]. However, Linux is not a user-friendly operating system. Arduino operates on an Arduino-based programming language but due to its limited library resources, high computational efficiency in advanced research is not achieved [142]. PLC on the other hand utilizes OS 9 and VxWorks as its operating system while it is programmed by Ladder Logic, Function Block Diagram (FBD), Structured Text (ST), Instruction List (IL) and Sequential Function Chart (SFC). These programming languages require an expert as the written program is hard to debug, it consists of difficult syntax, and is difficult to edit online [143].

6.6. Data Transmission Range

One of the current issues relating to the solar PV system is an increase in the size of utility-scale solar PV plants. These large-scale solar PV plants cannot be monitored by low-range data transmission modules such as Bluetooth, Wi-Fi, and ZigBee. The range of Bluetooth modules is around 100 m while for Wi-Fi and ZigBee the range is around 150 m and 300 m, respectively, which makes these modules unable to monitor the data from a solar power plant where the distance between the two farthest PV panels may be in km. Moreover, the implementation of GSM is not possible for the solar power plants located in distant places due to the issue of network coverage. LoRa is being considered an important platform in transmitting data over long ranges but it suffers from a low transfer rate and a high PER as the distance is increased.

6.7. Environmental Impact

The performance of various data processing and data transmission modules may be affected by environmental factors such as temperature, humidity, irradiance, dust etc., which need to be addressed carefully while installing the boards in the open environment. For instance, the deposition of dust decreases the intensity of the light captured by the solar

panel, thus reducing the solar PV output. Ramli et al. [144] performed an experimental investigation using an ARM Cortex-M4 microcontroller STM32F407 as a standalone digital controller to study the effect of dust accumulation on solar PV output. The results indicated a decrease in solar PV power by 10.8% over the course of four weeks. Hence, careful assessment should be performed related to environmental factors of a particular location before the installation of the devices. For instance, it has been suggested that Raspberry Pi should be operated in a predefined range as mentioned by the developer. Once the operation exceeds the threshold limit, a warning icon showing a red half-filled thermometer will be displayed, and the ARM cores will be progressively throttled back.

6.8. Transmission Module Precision

The influence of unnecessary electromagnetic and radio signals affects the operating environment of sensing, monitoring, and control systems. Further, the efficiency and accuracy of the installed transmission modules can be hampered due to the occurrence of unwanted signals in the form of electromagnetic and radio signals. Hence, the development of compatible shield/modules integrated with data transmission boards such as ZigBee, Wi-Fi, Bluetooth, GSM, and LoRa modules is essential. This would assist in the prevention of unwanted interference and remove the mismatching of standardized signals.

6.9. Solar Cell Technology

The efficiency of the solar PV monitoring system depends on the type of solar cell technology. Further, the monitoring capabilities of the sensors attached depend on the data extracted from the solar cell in terms of irradiance, temperature, current, and voltage which are linked to solar cell efficiency. In recent times, very few works have monitored the efficiency of various solar cell technologies such as mono crystalline, third-generation PV cells, and perovskite solar cells [145–147]. The authors in [148] compared the efficiency of various solar cell technologies such as poly-crystalline silicon (pcSi), mono-crystalline silicon (mc-Si), thin-film copper indium disulfide (CIS), amorphous silicon (a-Si), and heterojunction incorporating thin film (HIT). The lowest efficiency was recorded for CIS while the highest efficiency was reported for pcSi technology. Hence, it is necessary to select a suitable solar cell technology to achieve optimal efficiency.

7. Discussion and Future Perspectives

By reviewing the different solar PV monitoring systems with regard to their application and advantages and disadvantages, it has been found in the context of data processing modules that BeagleBone is a powerful platform, but its usage is limited by a smaller number of external connections, and the fact that it is expensive and has a limited color resolution for HDMI. Arduino comes with user-friendly capabilities that are adaptable to several operating systems but it lacks a limited bit resolution and powerful module capabilities for processing complex data. Raspberry Pi is an effective module in the field of monitoring, but it lacks an RTC with a battery backup and BIOS. On the other hand, PLC has excellent outcomes in controlling data and can work for 5–10 years with a low cooling cost, yet it is incompatible with handling a large amount of data. Even though microcontrollers are reusable and energy-efficient, they have programming complexities that require a skilled person. Microprocessor-based prototypes are efficient and serve as a base in model development but are unsuited for new users as the programming languages, such as C/C++, require an expert programmer.

In terms of transmission protocol modules, ZigBee has a low cost and a low power consumption. However, it suffers from signal interference and the loss of signals. Wi-Fi can transfer data at high speed, but it has an issue relating to low coverage area. Bluetooth exhibits easily upgradable characteristics and low power consumption. Nonetheless, it has a shortcoming in terms of authorization, authentication, and encryption. GSM comes with a low error rate with wide area coverage. Nevertheless, it experiences data interruption and data connection problems. LoRa is considered to be powerful module for long-range

data transmission, but it is not suitable to send large payloads (limited to 100 bytes). Furthermore, the protocol does not allow for the continuous sending of data packets due to rules in relation to the frequency band it utilizes.

The review provides some useful suggestions to design an efficient solar PV monitoring system for future research works which are highlighted below.

Data transmission modules such as ZigBee and Wi-Fi have short-range transmissions. Nonetheless, the occurrence of signal interference is prevalent when the device is employed with other data transmission protocols. Thus, more exploration is required to eliminate the problems of signal interference for short-distance transmission.

- Although data transmission modules are utilized to transmit data from sensor node to receiver node, the acquired data needs to be secured from external tampering. Therefore, careful attention is necessary to examine the security aspects of the data transmission modules in terms of theft of data, privatization, authentication of the third party, etc. Further, the implementation of NB-IoT technology could result in better scalability, quality of service, and security compared to unlicensed LPWA networks such as LoRa/Sigfox.
- As the size of the solar PV systems is increasing, the complexity of handling several aspects such as data handling, security, efficiency, and transmission range needs to be studied. Hence the necessity for an efficient and reliable state-of-the-art wireless monitoring system to be developed. A new combination of sensor nodes with gateway devices could be designed.
- The implementation of state-of-the-art technologies related to 5G and Bluetooth low energy can be utilized in solar PV monitoring systems due to several benefits such as low power consumption, greater transmission speed, greater capacity of remote execution with a greater number of attached devices and lower latency.
- Several simulation platforms have been developed for the verification of the data received in solar PV monitoring systems. The accuracy of the validation of the data varies with different simulation platforms. Due to the advancements of the solar PV system worldwide, a validation of the data acquired from the sensor nodes is required. Thus, a common simulation platform is essential which could be interfaced with data transmission modules for the evaluation of the data received from the simulation results.
- For the development of a reliable, robust, and efficient wireless solar PV monitoring system, the validation of the data under different environmental conditions should be observed. Therefore, the monitoring system should be tested in changing environmental settings to evaluate the robustness and overall efficiency of the system.
- One of the critical issues related to the energy efficiency of the sensor nodes is the transmission of the data. Any failure of the node battery results in the low life of the network, thus disturbing real-time communication. Therefore, further research works are required to design modules for a long-duration operation without interruptions in sending the data.
- The data acquired from the solar panel can be affected by the degradation of the solar panel as well as dust, humidity, irradiance, and temperature. Therefore, an in-depth study is required to develop a low-cost intelligent real-time PV monitoring system to identify the degradation.
- The development of open-source platforms and software with regard to data processing modules such as Arduino, Raspberry Pi, etc. affects the availability of information in the internet as well as in the cost of acquisition, programming, and modification of devices. Further, the application of open-source platforms will accelerate the development of low-cost programmable devices for innumerable tasks in various applications such as Science, Technology, Engineering and Mathematics (STEM) in the coming years. Additionally, the development of open-source modules would lead to a reduction in the gap between the prototyping and the product development of PV panels due to fault conditions.

- The implementation of IoT based wireless solar PV monitoring systems consisting of sophisticated sensors, data processing boards, and communication protocols could be developed to achieve an efficient, accurate, and robust monitoring system for the solar PV environment.

8. Conclusions

The review outlined a comprehensive exploration of various solar PV monitoring technologies based on the application of various data processing modules and transmission protocols. In line with this, the review presented an overview of the monitoring system, classification, detailed description, and limitations of solar PV monitoring systems. As a first contribution, a comprehensive exploration of different data processing modules for solar PV monitoring systems is presented with regard to the monitoring platform, structure, specifications, shortcomings, and contributions. As a second contribution, the various data transmission modules have been investigated highlighting the types, configuration, data transmission rate, sampling rate, power consumption, strength, and weakness. As a third contribution, the current issues and challenges of the existing technologies for solar PV application were covered emphasizing data handling, security, signal interference, energy efficiency, transmission range, environmental impact, and efficiency. As a fourth contribution, some productive future suggestions have been provided to develop an improved monitoring system that will lead toward sustainable operations and management in solar PV applications.

The critical analysis, discussion, issues, and recommendations will prove fruitful in sustainable development with regard to clean energy, emission reduction and economic prosperity. Further, the development of an advanced solar PV monitoring system could provide guidelines and encourage solar PV industries and researchers to perform further research on IoT-based monitoring systems for large-scale solar PV applications. Additionally, this review could assist in selecting the appropriate monitoring technology for the improvement of efficiency, accuracy, and robustness of solar PV systems towards increasing green technology and achieving decarbonization goals by 2050.

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