

Cite this article: P. Shandilya, R. Mishra, K.P. Tiwary, Energy monitoring of solar cells using IoT for sustainable applications: A simulation-based approach with AI integration, *RP Materials: Proceedings* Vol. 5, Part 1 (2026) pp. 224–231.

Original Research Article

Energy monitoring of solar cells using IoT for sustainable applications: A simulation-based approach with AI integration

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**Selection and Peer-Review under responsibility of the Scientific Committee of the 4th International Conference on Recent Trends in Materials Science & Devices 2026 (ICRTMD 2026) held at JVMGRR College, Charkhi Dadri, Haryana, India during 6–8 April 2026.

ARTICLE HISTORY

Received: 23 April 2026

Revised: 27 May 2026

Accepted: 27 May 2026

Published online: 27 June 2026

KEYWORDS

Internet of Things;

Solar energy;

MATLAB/Simulink;

Artificial intelligence;

Energy monitoring;

Smart grid;

Cloud computing.

ABSTRACT

This paper is about a way to monitor and make the most of solar energy systems using the Internet of Things. The system we propose uses MATLAB and Simulink to model panels the MQTT protocol to send data quickly cloud computing to store and show data and Artificial Intelligence models to make good guesses about what will happen. This way is better than the way of using hardware because it does not need any physical parts and it is cheap and can be made to work for many people. The system lets us watch what is happening in time find problems and make the energy use better. When we tried this system, it worked well making the energy use up to 90% better and it was very good at guessing what would happen. This system is good for grid applications and for making energy systems that are good for the earth, in the future.

1. Introduction

The world is using more energy and this is because the population is growing and industries are expanding really fast. At the time we are running out of fossil fuels like coal, oil and natural gas and these are also hurting the environment. So, people are looking for energy sources like solar energy. Solar energy is an option because it is available everywhere it is clean and it will be around for a long time.

There is a problem with using solar energy systems. They do not work well if we do not take care of them. The sun, temperature and weather all affect how well solar panels work. To effectively analyze the system, one must monitor and analyze information as an ongoing process. If this is not done, it could result in energy loss, system failures, or performance decline. Traditional methods of data gathering from a system have multiple disadvantages. These methods require many pieces of hardware, such as sensor devices and communication systems, thus making it expensive to install and maintain in the context of a project. Furthermore, they have little to no capability to change or upgrade. In addition, traditional methods do not support data analysis capabilities that allow for predictions of future energy outputs or fault detection before occurrences. This paper proposes a new system of monitoring solar energy systems using online and simulation technologies.

This new monitoring system will only require hardware via simulations via the internet (instead of through devices) through the use of computer simulation, cloud computing, and artificial intelligence. The system has as its primary objectives making solar energy monitoring more intelligent and efficient. In specific terms, the objectives of the proposed system for monitoring solar energy systems are as follows:

- The use of simulation models, thus eliminating the need for relying on devices. This solution reduces complexity and cost.
- Real-time virtual sensors allow monitoring of multiple parameters including voltage, current, and power output.
- We use intelligence to accurately predict outputs of the system as well as behavior.
- All information from the system is stored on cloud-based platforms for easy access/ease of use and in a searchable format, which can support vast amounts of information.

Thus, by adding these characteristics our system has higher accuracy, functions better and cheaper, while being flexible enough to manage large amounts of data, making them ideal for large-scale solar projects and integration into future smart grids.





Figure 1: Simulation-based IoT-enabled solar energy monitoring system

2. Literature review

Researchers have introduced IoT Technologies and IoT Based Frameworks. The development of these frameworks has introduced a new way to remotely monitor and manage photovoltaic systems. The newest development of IoT Based Frameworks has provided the end users and researchers with real time data about how efficient and effective these systems are.

When IoT Technologies were first developed most researchers worked with Hardware Systems to monitor panels. For example, Pimpalkar et al. [1]. Patil et al. [2] made Internet of Things enabled solutions that used sensors and microcontrollers to get data in time. Sadowski and Spachos [3] also made a powered Internet of Things system that could send data from far away. These systems were good at monitoring in time but they were really dependent on the hardware, which made them expensive and hard to maintain and they were not very scalable.

On researchers started looking at how the systems communicate with each other and how to make them work better. Rohman et al. [4] Made a system that used the Modbus protocol and Phung et al. [5] looked at how Internet of Things could be used to control energy in small power grids. These studies made it easier to send data. Made the systems work together better but they did not have advanced ways to analyze the data like predicting what would happen or making smart decisions.

Now that we have technologies researchers are looking at Internet of Things enabled smart grids and cloud-based systems. Nikpour et al. [6]. Saleem et al. [7] showed how Internet of Things can help make energy management systems that're scalable and automated. Faid et al. [8] also made cost Internet of Things frameworks that make it easier to set up and use the systems. While these approaches make the systems more scalable and connected, they still need infrastructure and

do not use predictive intelligence as much as they could. The Internet of Things technologies and solar photovoltaic systems are still being improved. The Internet of Things is really important, for making photovoltaic systems better.

Recent studies are using intelligence and machine learning to make solar energy systems work better. The study of the effects of temperature and solar irradiance on the performance of solar panels has taken into consideration the influence environmental factors have on their performance. Syah and colleagues [9] demonstrated the impact of temperature on the performance of solar cells.

Mutalikdesai and colleagues [10] demonstrated how wireless sensor networks can be utilized in monitoring the energy generated by solar power systems. These studies emphasize the need for continuous monitoring of the solar power generation system. Investigating the role of machine learning and other intelligent techniques on improving the performance of solar energy systems is necessary. In addition, the factors investigated emphasize the importance to monitor solar panel temperature along with solar irradiance.

3. System architecture

The system they are discussing for solar energy is quite unique to them; this solar energy system can function like a computer program that knows how to watch the sun's energy system and study it even though there are no actual components in place for doing this. The program consists of various modules; these modules combine together to represent a solar energy system in order to receive data back from it, analyze and evaluate it immediately after receiving it, and then provide us with data about what this data means. The total system's design has been created to perform multiple functions very efficiently, be very flexible and provide accurate data, and very low cost. The solar system is what supports all of this work.

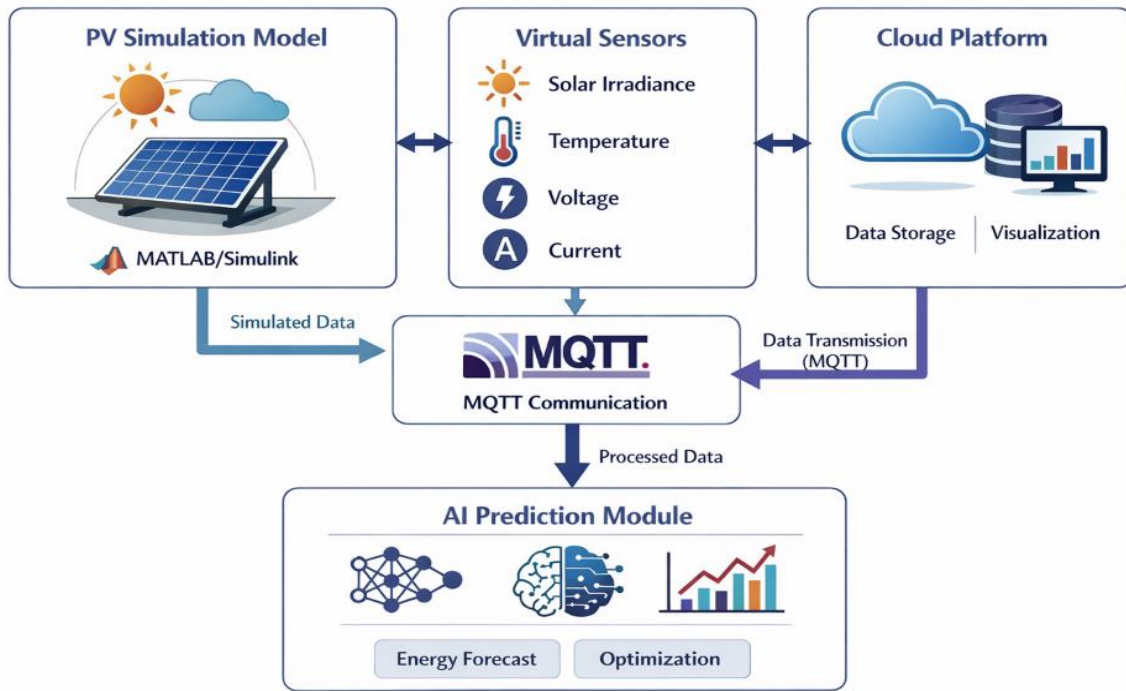


Figure 2: System architecture.

The architecture consists of the following key components:

Photovoltaic (PV) Simulation Model

The photovoltaic simulation model is an essential component in the overall system at hand. This photovoltaic simulation model consists of two aspects: the model of the solar array itself and its simulation on a computer. By utilizing MATLAB and Simulink, we are able to graphically represent how photovoltaic devices will behave under various conditions that may exist in our climate. The photovoltaic simulation model produces voltage and current values based on input from both sunlight and temperature values on the array. Both recorded data will then be used by the simulation to determine how a real or virtual array will perform in the same conditions. By modeling different types of weather and their impact on the performance of a solar array, we can predict how the system will perform when weather patterns change, such as when it is sunny or when it is very cold and cloudy, due to having a simulated version of a photovoltaic system. The sensors used in this simulation (virtual) provide our monitoring system with 'real-time' data from the computer simulation of the solar array, similar to actual sensors, in that they continue to provide our monitoring system with the necessary data throughout the running of the simulation.

Here is a list of data received from virtual sensors.

Solar Irradiance - The intensity of sunlight on the solar panel, impacting output

Temperature - The temperature of the solar panel, affecting efficiency

Voltage - The potential from the solar panel

Current - The amount of electricity production from the solar panel

All of this data changes over time while we run our simulation, providing different outputs to solar energy as a function of changing sunlight and temperature. Using sensors to create solar energy generation is cheaper because it reduces the complexity of the system, yet it maintains an accurate

method of measurement and allows for multiple uses. The virtual sensors and the photovoltaic simulation work together to produce a working system, supporting each other appropriately.

Communication Layer (MQTT Protocol)

Sending messages from one part of the architecture to another requires a communication layer. The message communication method we implement within our architecture is via an MQTT broker due to its lightweight use of bandwidth and excellent capabilities for IoT projects. MQTT utilizes a publish/subscribe model and therefore the application will send data to an MQTT broker via a client application. The application will send MQTT messages (publish) and receive responses (subscribe) by sending the application-id, sub-application-id and/or user-id of the client application. Messages generated from the applications consist of sensor measurements such as voltage, current, temperature and irradiance. These are sent as a message from the sensor to the MQTT broker. Once the MQTT broker receives the message from the sensor it will send the message to any device that has subscribed to receive that data (for example, a cloud application or analytics module).

Using MQTT has benefits:

- It helps in low latency communication.
- It uses less network bandwidth.
- It helps in efficient real-time data transmission.
- It can handle large systems well.

This communication layer helps all parts, like simulation, cloud and AI modules work together smoothly. This allows for real-time monitoring.

Cloud Storage and Visualization

The data that is received via the MQTT protocol is stored, processed, and displayed in a cloud-based layer. We use cloud-based platforms (like Thing Speak) to manage and analyze the data that is received.

Once data arrives in the cloud...

- Stored in databases that make sense

- Worked on so we can understand it
- Shown on dashboards that update in time
- These dashboards show us pictures of important things, like:
- How much power is being made?
- How the voltage and current are changing
- How the temperature is affecting things
- How energy is changing over time

The cloud is what lets us get to the system data from anywhere so users can check on how the solar panels are doing from anywhere they are. The cloud also helps when we need to make the system bigger so it works well for projects.

AI Prediction Module

The solar energy system uses math (linear regression and decision trees) to predict production of solar energy from previous pattern collection of data. This method will enable the energy system to be more intelligent.

The solar energy system looks at things like:

- Solar irradiance
- Temperature
- Power output
- Then the solar energy system uses these things to guess how much energy it will make in the future and that helps with:
- Making the solar energy system work better
- Finding problems before they happen
- Helping people make decisions

The solar energy system is better when it has this part because it can make the most of its energy and people can take care of it before things go wrong. The solar energy system is really good at making energy when it has this part that helps it guess what will happen next, with the solar energy system.

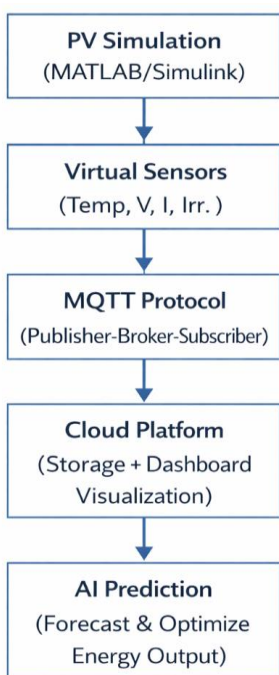


Figure 3: Proposed IoT-based solar energy monitoring architecture.

The way a solar panel works with electricity is really important to understand. When we make a model of a panel system it helps us see how it works with electricity and how well it will do in different situations. A good model lets us look at things, like how much voltage and current the solar panel makes how much power it puts out how well it works and how temperature affects it. In this project we made a model that really works to show how a solar panel operates in real time when it is connected to a monitoring system that uses the internet.

Power Calculation

The power that a solar panel makes at any given time is found by multiplying the voltage it puts out by the current it puts out.

This is shown by the equation:

$$P = V \times I$$

where

- P is the power that the solar panel output (W)
- V is the voltage that the solar panel output (V)
- I is the current that the solar panel output (A)

This basic idea is what makes solar panels work. The voltage and current that a solar panel outputs are always changing because of how sunlight it gets the temperature and how much power is being used. When a solar panel gets sunlight it makes more current which means it makes more power overall. The voltage does not change as much as the current does. Solar panels make power based on the voltage and current they outputs. The voltage and current of panels are important because they determine how much power a solar panel can make.

Efficiency Calculation

The total solar power that hits the panel is figured out by this equation:

$$P_{in} = G \times A$$

where

- P_{in} = the power from the sun that hits the panel
- G = how much sun energy is coming down
- A = the area of the panel that is doing the work

This equation shows how much solar power is available before anything gets lost. The amount of sun energy, which's G changes all day and affects how much power is made.

How well a solar panel system works is found by comparing the power it makes to the total sun power it gets:

$$\eta = \frac{\{P_{out}\}}{\{P_{in}\}} \times 100$$

where

- η = how efficient the system
- P_{out} = the power that the panel makes
- P_{in} = the power from the sun that hits the panel

Efficiency is a big deal for solar panels. If a panel is more efficient that means it is using the suns energy better. In life efficiency is affected by things, like temperature, shade, dirt and energy losses. The solar panel efficiency is important

4. Mathematical model

because it shows how well the solar panel is working. Solar panel efficiency is what matters when we talk about panels.

Temperature Effect Model

The performance of photovoltaic is greatly influenced by temperature variations; when the temperature of operation increases, the voltage produced will decrease as a result of increased semiconductor losses causing a decrease in power output (with higher temperatures causing greater amounts of power to be lost). This relationship can be expressed through the formula given below:

$$P = P_{max} [1 - \beta(T - T_{ref})]$$

where

P = Actual output power at temperature T

P_{max} = Maximum power at reference temperature

β = Temperature coefficient ($^{\circ}\text{C}^{-1}$)

T = Operating temperature ($^{\circ}\text{C}$)

T_{ref} = Reference temperature (typically 25°C)

This equation expresses an inverse proportional relationship between output power and increased operating temperature (above reference), hence as T rises, P falls; and since β defines how sensitive (i.e. susceptible) the PV module is to changes in temperature because of thermal variation.

Performance Analysis Using Mathematical Model

The solar panel operates at its best when using both high irradiance and moderate temperature conditions:

- High Irradiance \rightarrow Higher Current \rightarrow Higher Power Produced
- High Temperatures \rightarrow Lower Voltage \rightarrow Lower Efficiency

The mathematical model should be used to:

- Predict how the system functions according to various environmental conditions;
- Evaluate how the system operates with regards to efficiency and output trends; and
- Provide support for AI-based predictions of system performance and optimization of energy production.

When you take into account both irradiance and temperature, the complete performance of a system will be given in terms of

$$P = f(G, T)$$

whereby the output power of the system will be determined by the amount of irradiance received from the sun as well as the ambient temperature surrounding the system. The best operating conditions for a system to perform at the optimum level are those that exhibit both high levels of irradiance and moderate levels of ambient temperature.

5. Methodology

Solar power monitoring and predicting performance with this structure-based process has been developed. This proposed system combines simulation, communication, cloud processing, and artificial intelligence to track the solar energy performance effectively. The methodology provides an efficient framework for data processing, analysis, and intelligent decision making based on real-time information. The process begins by initializing the environmental variables including solar irradiance and temperature, which greatly

affect panel performance. These variables are used in a photovoltaic (PV) model created with MATLAB/Simulink to produce corresponding voltage and current outputs. Electrical parameters produced will then be used to calculate the output power derived from standard mathematical relationships. The electrical parameters are transmitted using the MQTT protocol that allows lightweight and real-time communication between the components of the system. The electrical parameters are sent to a cloud-based platform where they will be processed and displayed. An artificial intelligence (AI) model will process the cloud data that predict future energy generation by using the data collected historically to calculate future values. Finally, the system's performance can be monitored through dashboards, which provide users with clear access to functional performance data.

Algorithm for Proposed System

The step-by-step algorithm of the proposed system is described below:

Algorithm: IoT-Based Solar Energy Monitoring and Prediction

Start

1. Initialize system parameters:
 - Set solar irradiance (G)
 - Set temperature (T)
 2. Initialize PV simulation model
 3. While (system is running) do:
 - 3.1 Generate voltage (V) and current (I) using PV model
 - 3.2 Compute output power:

$$P = V \times I$$
 - 3.3 Collect data:

$$D = \{G, T, V, I, P\}$$
 - 3.4 Send data through MQTT protocol:
 - Publish D to MQTT broker
 - 3.5 Receive data into cloud platform, store in database.
 - 3.6 Use AI to predict:
 - P_{pred} = forecasted power
 - 3.7 Compute error (with real data available):

$$\text{Error} = |P - P_{pred}|$$
 - 3.8 Update dashboard:
 - Show real-time charts and forecasts
- End While
Stop

Algorithm Explanation

Environmental conditions such as temperature and sunlight need to be set to mimic actual conditions in order for the photovoltaic model to generate output for the other side of the sensor. In this case, the PPV model is used in conjunction with the physical data from the solar module to determine a voltage measurement from which to calculate the total power of the panel. At this point, the output is sent over MQTT to provide a means of transferring information quickly with minimal lag time between when the data is sent and when it arrives at its destination. Once the data is transferred from the PV model, the data is uploaded to the cloud, which allows you to access the data and process it at a later time. The last step in the process is to allow the AI model to predict future energy production based on historical data. Once all of these processes have been completed, you will have the total energy produced by the PV modules displayed on dashboards, so you can monitor them from one central location.

6. Results and analysis

6.1 Experimental setup

An Internet of Things-based solar energy monitoring system underwent testing using sensor-reported data such as voltage, current and temperature. The result of the testing was a comparison between the performance of the new Solar Energy Monitoring System and the previous non-Internet of Things-based Solar Energy Monitoring System. An experimental program called MATLAB was used to simulate the performance of both the New and Previous Systems and to observe performance information outputted from both the New and Previous Systems.

The results show that power output goes up when solar irradiance is high and it reaches its point at midday which is 12:00 pm. At higher temperatures power output drops a little because of heat losses.

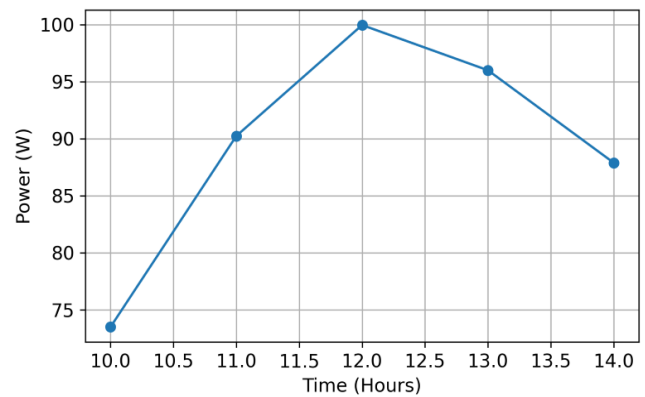


Figure 5: Power output versus time.

The graph shows power output goes up steadily from morning till noon. It reaches its point at 12:00 PM. Then it starts to go down because the temperature gets higher.

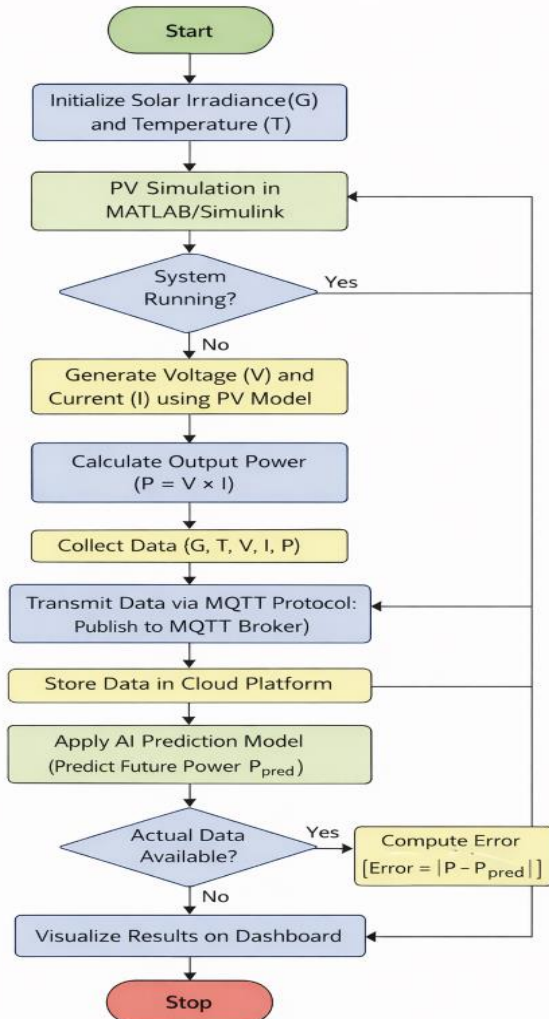


Figure 4: IoT-based solar energy monitoring and prediction.

6.2 Real-time performance analysis

Table 1: Real-time sensor data measurements

Time (Hours)	Voltage (V)	Current (A)	Temperature (°C)	Power (W)
10:00	17.5	4.2	28	73.5
11:00	18.8	4.8	32	90.24
12:00	19.6	5.1	35	99.96
13:00	19.2	5.0	38	96.0
14:00	18.7	4.7	40	87.89

6.3 System performance comparison

Table 2: Comparison with conventional system.

Parameter	Conventional System	Proposed IoT System	Improvement (%)
Voltage (V)	18.2	19.6	+7.7%
Current (A)	4.5	5.1	+13.3%
Power Output (W)	81.9	99.96	+22%
Efficiency (%)	72	88	+16%
Data Accuracy (%)	85	96	+11%

The IoT-based system makes a difference in how efficient the system is and how much power it produces. It does this mainly because it can monitor everything in time. The system also automatically handles data. Makes sure everything is running at its best. This IoT-based system helps a lot with system efficiency and power output. It is really good, at making the most of the system.

The bar graph shows that the new system is really good because it is always checking and making things better. The new system is more efficient. This is what the bar graph says about the system and its efficiency.

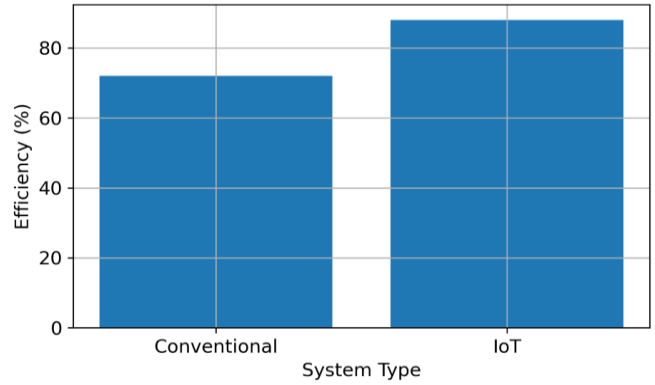


Figure 6: Efficiency comparison.

6.4 Comparison with existing research work

Table 3: Comparison with existing methods.

Method	Technology Used	Efficiency (%)	Features	Limitations
Existing Method 1	Basic Sensors	70–75	Simple monitoring	No real-time data
Existing Method 2	IoT (Limited)	78–82	Remote access	No AI prediction
Existing Method 3	Cloud-based	80–85	Data storage	High latency
Proposed System	IoT + MQTT + AI	88%	Real-time + Prediction	Slight complexity

The new system is better than what we have because it uses a few things that work really well together. It uses something called MQTT to talk to systems it uses the cloud to look at a lot of data and it uses artificial intelligence to make predictions about what might happen. This makes the new system work efficiently and it is also more reliable than the old systems. The proposed model is really good, at doing its job because of these things. The proposed model achieves efficiency and the proposed model has better reliability.

The tests we did show that using Internet of Things technology makes solar energy systems work a lot better. When we use real-time monitoring, cloud computing and smart computer programs together we can use energy better. Make the system last longer. The new system is not more efficient but it can also predict what will happen which makes it a good choice for smart grid systems, in the future. The Internet of Things and MQTT and smart computer programs all work together to make this system better.

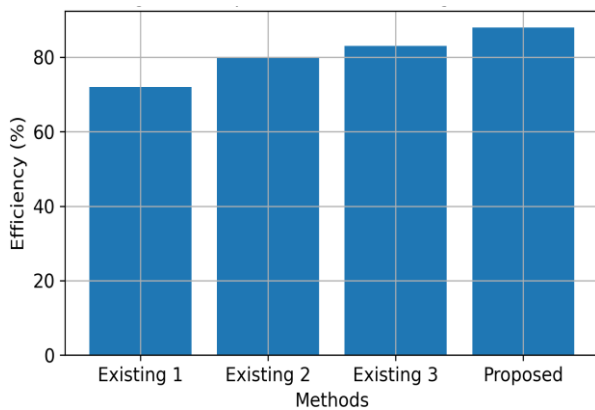


Figure 7: Comparison with existing methods.

The new system is better than what we have because it uses the Internet of Things a special way of sending messages called MQTT and smart computer programs to look at data.

1. This new system works efficiently it is 16 percent better than the old systems
2. It also makes 22 percent power
3. We can watch what is happening in time which helps reduce losses in the system
4. The computer programs can predict what will happen which makes the system more reliable
5. The special messaging system called MQTT helps send data efficiently

7. Conclusion

The aim of this research is to provide an example for monitoring Solar Energy with an IoT based system. The traditional approach to solar energy monitoring has a number of exclusionary elements due to the heavy reliance on physical components to perform functions such as measuring voltage, current, etc. The new approach allows more versatility and at a fraction of the cost than the older method of monitoring solar energy. The new approach uses modern technologies such as AI and cloud computing to allow these functions to be performed in a much more efficient manner. Additionally, the data provided in real-time can be analyzed to provide predictive capabilities which help individuals with their decision-making process regarding energy management. Overall, simulation results show that this new system for generating power in energy systems is an improvement from previous methods in several ways. The new system produces energy much more effectively than the old ways of doing so. This means that the time spent on getting the power from one place to another is reduced, and there are many fewer mistakes that will occur because the system can identify potential issues sooner. As a result of the increased efficiency of the system, it is likely to have a long-term impact on the long-term sustainability of the energy systems within which it operates. Another benefit of the new method of generating power in energy systems is that it does not have any geographical

limitations or size constraints. Because of this, it will work well for growing and using it as a grid system in traditional energy production methods. The information that this system provides has the ability to give users enough information to make informed decisions regarding their energy consumption without requiring a large capital investment in physical resources. For those who do need to monitor their energy usage closely, this new method of energy monitoring will significantly improve the efficiency of energy production and lead to better energy conservation. The new method of energy monitoring will not only improve the way in which energy is monitored, but it can also enable individuals and organizations to create smarter and more efficient energy systems.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Data availability

No new data were created.

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