JOURNAL OF SOFTWARE ENGINEERING AND TECHNOLOGY

Journal of Software Engineering and Technology
E-ISSN (xxxx-xxxx) P-ISSN (xxxx-xxxx)

Portable Solar Panel System Design for IoT-Based Remote Areas

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Abstract

Inequality of energy access in remote areas is still a major challenge in sustainable development, especially in developing countries such as Indonesia. This research aims to design and develop a portable solar panel system based on the Internet of Things (IoT) that can provide clean and efficient energy solutions for communities in areas without a power grid. The research method used is Research and Development (R&D) with stages: needs analysis, design, prototyping, field trials, and evaluation. The results of the five-day system test showed that the device was able to produce an average power of 43.2 watts per day with a working efficiency of 92.6%. The output voltage is stable at the range of 12V, sufficient for basic needs such as lighting and charging of electronic devices. IoT features enable real-time energy monitoring through mobile apps, which is proven to improve system control and reliability. In addition, the portable system design makes it easy for users to carry and operate devices independently. This research shows that the integration of portable solar panels with IoT technology can be a practical and sustainable solution in expanding energy access in remote areas.

Keywords: renewable energy, portable solar panels, internet of things, remote areas, energy monitoring

A. Introduction

The availability of electrical energy is a crucial element in the social and economic development of a country. However, until now, inequality of energy access is still a significant global problem, especially in remote and underdeveloped areas. According to the International Energy Agency (IEA, 2021), around 733 million people in the world still do not have access to electricity, and the majority of them live in rural areas of developing countries. This inequality not only hinders the progress of education, health services, and the local economy, but also deepens the gap of inequality between regions (Bhattacharyya, 2012; Ouedraogo et al., 2019).

In Indonesia, these problems are reflected in the 3T (Disadvantaged, Frontier, and Outermost) areas which still experience many limitations in electricity infrastructure. Based on data from the Ministry of Energy and Mineral Resources (2022), the national electrification ratio has indeed reached 99%, but access to stable, reliable, and sustainable electricity in remote areas is still a big challenge. Conventional distribution network systems are difficult to reach by areas with extreme topography, such as small islands, mountains, or tropical rainforest areas. Installation costs, fossil fuel limitations, and a lack of competent technicians have exacerbated this gap (Widiyanto & Hidayat, 2020; Suhendra et al., 2023).

As a solution, the use of renewable energy such as solar panels is a promising alternative. Solar panels do not require extensive network infrastructure and can be operated autonomously in remote locations. However, there are still some technical and operational obstacles. Conventional solar panel systems are generally static and permanent, requiring fixed land and fairly high installation costs. Meanwhile, communities in remote areas often have dynamic and shifting electricity needs, especially fishing communities, forest farmers, or coastal dwellers (Boukhris et al., 2020; Yamegueu et al., 2011).

In this context, the innovation of portable solar panel systems comes as an adaptive and flexible solution. This technology allows people to carry and utilize solar energy in various locations without the need for fixed installations. Portable solar panels equipped with Internet of Things (IoT)-based monitoring systems can make it easier for users to monitor energy consumption, system efficiency, and detect component damage in real time (Koutroulis & Blaabjerg, 2012; Hasan et al., 2021).

Several studies have shown the great potential of IoT-based portable renewable energy systems in addressing electrification challenges in remote areas. Research by Adebayo et al. (2020) shows that the integration of sensors and communication modules on solar panels is able to increase the efficiency and reliability of the system by up to 25%. Meanwhile, a study by Al-Shetwi et al. (2021) developed a smart solar monitoring system that is capable of providing automated feedback through a mobile app for users in remote locations. This technology has proven to be effective in extending the life of the system and reducing maintenance costs.

However, there is still a research gap in the context of designing solar panel systems that are truly portable, lightweight, easy to assemble, and compatible with IoT technology. Most previous research has still focused on fixed or semi-permanent panel systems, and has not specifically targeted use in extreme areas with limited access to communication and logistics networks (Azad et al., 2022; Sharma & Jain, 2019).

The urgency of this research lies in the urgent need to provide a cost-effective, flexible, and remotely monitored electrical solution. In the era of digitalization and the clean energy transition, it is important to develop energy systems that are not only efficient, but also intelligent and responsive to environmental conditions and user behavior (Rejeb et al., 2022). IoT-based portable solar panel systems are expected to be able to meet the small-scale electricity needs of remote areas for lighting, device charging, water pumps, and other critical applications without reliance on the main grid.

The main objective of the research is to design and develop a prototype of an IoT-based portable solar panel system designed specifically for use in remote areas. The system will include the integration of energy sensors, wireless communication modules, Arduino or ESP32-based microcontrollers, as well as platform-based monitoring interfaces such as Blynk or Thingspeak. The design should prioritize portability, energy efficiency, weather resilience, and ease of use for the general public.

This research has several important benefits. First, from the social side, this system can improve the quality of life of remote communities by providing access to energy for basic needs. Second, in terms of technology, this research encourages innovation in the design of portable energy systems that are connected to the digital grid. Third, from the environmental side, the use of solar energy supports the achievement of the SDGs targets, especially Goal 7 (Clean and Affordable Energy) and Goal 13 (Handling Climate Change) (UNDP, 2023).

The implications of this research are not only limited to hardware development, but also to the transformation of rural electrification approaches in Indonesia. With a more flexible and affordable system, local governments, NGOs, and startups can replicate and adopt this model to accelerate the equitable distribution of clean energy. In addition, this research also opens up opportunities for multidisciplinary collaboration between the fields of electrical engineering, information technology, and public policy in encouraging an inclusive energy transition.

As a novelty, this study not only proposes the design of portable solar panels, but also emphasizes full IoT integration, with real-time monitoring and remote-control features. This allows users in remote areas to find out the status of their energy system through the mobile app, including battery status, power consumption, and estimated energy reserves. The design also accommodates modular systems, so they can be expanded as needed, and are designed to be easily reassembled or carried in an emergency.

With this background, this research is expected to make a significant contribution to expanding energy access through an adaptive and intelligent technological approach. In the midst of the challenges of the climate crisis and infrastructure inequality, the innovation of IoT-based portable solar panel systems is a strategic step towards a sustainable and inclusive energy future.

B. Research Method

Types of Research

This research uses a Research and Development (R&D) approach that aims to produce an innovative product in the form of an Internet of Things (IoT)-based portable solar panel system that can be used in remote areas. The development model used adapts the steps from Borg & Gall (1983) which have been simplified into several important stages, namely: (1) Needs analysis, (2) Product design, (3) Prototyping, (4) Testing and evaluation, and (5) Revision and refinement.

This approach was chosen because it is suitable to produce technological products based on field needs that are adapted to the real conditions of people in remote areas.

1. Needs Analysis

The initial stage was carried out through observation and interviews with people living in areas without fixed access to electricity, such as coastal areas and small islands in eastern Indonesia. The main focus is to identify:

- Daily electricity consumption needs (lights, cellphone charging, radio)
- Geographical conditions and mobility of citizens
- Community readiness to use digital technology

2. Product Planning

Based on the results of the needs analysis, the system is designed with the following main criteria:

- Portable: lightweight, easy to carry and assemble
- Modular: allows capacity development
- IoT-based: can be monitored in real-time remotely

The main components designed include:

- 50Wp Solar Panel
- Battery 12V 20Ah
- Charge Controller PWM
- ESP32 as a microcontroller and IoT module
- Voltage, current, and temperature sensors
- Monitoring platform: Blynk App **or** Thingspeak

3. Prototyping

A prototype of the system is created by assembling all the components and integrating them into a portable panel box**.** The system is tested under several conditions to ensure:

- Charging reliability
- IoT signal stability
- DC output quality (voltage and current)

4. Trial and Evaluation

The test was conducted in a semi-field simulation environment for 5 days, with light usage scenarios for basic needs (12V lamp and gadget charging). Data is collected from sensors, and sent to the monitoring application using a WiFi connection.

Table 1. Preliminary test results of the prototype of a portable solar panel system

Day	Average Incoming Power (Watts)	Stored Power (Wh)	Power Used (Wh)	Output Voltage (V)	Performance Percentage (%)
1	42,3	180	120	12,1	92%
2	44,7	190	125	12,3	94%
3	45,5	195	130	12,5	96%
4	40,1	172	110	12,0	88%
5	43,2	185	122	12,2	93%

Information:

- The percentage of performance is calculated from the ratio between the effective power stored and the maximum total power of the panel
- The output voltage remains stable in the range of 12V–12.5V, as per the requirements of the basic device

5. Revisions and Improvements

Based on the results of the trial, several technical revisions were made, such as:

- Replacement of DC connectors to make them more weatherproof
- Addition of IP65 waterproof case
- Adjustment of sensor reading algorithms for more precision

In addition, an improvement was made to the IoT interface system so that users could see the battery status and notifications directly through the mobile application dashboard.

Research Instruments

The instruments used in this study include:

- Current and voltage sensor (INA219)
- Digital multimeters and wattmeters
- Blynk / Thingspeak application as an interface
- Log data Arduino Serial Monitor

Data Collection Techniques

1. **Direct technical observation** of the system's performance on a daily basis

2. **Digital data logs** from IoT systems (automatically sent every 1 hour)
3. **Semi-structured interviews** with field test users regarding convenience and ease of use
4. **Visual documentation** in the form of photos, videos, and design notes

Data Analysis Techniques

The analysis was carried out with a quantitative-descriptive approach. Technical data are tested statistically simply (mean, standard deviation) to assess efficiency and stability. Meanwhile, qualitative data from interviews were analyzed thematically to understand the user's experience of the product.

C. Result and Discussion

Research Results

This research aims to design and test an IoT-based portable solar panel system that can be implemented in remote areas. The test was conducted for five consecutive days in an open area with natural lighting, using a solar panel system device consisting of a 50Wp panel, a 20Ah 12V battery, a PWM controller, and an ESP32 module connected to the INA219 sensor. During the test, the main parameters measured include the input power, stored power, usable power, output voltage, and overall system efficiency.

This prototype portable solar panel system is designed using a modular approach with a portable waterproof casing. All major components, such as batteries, microcontrollers, and sensors, are housed in a single system box making them easy to carry and reassemble. The energy source comes from a 50Wp monocrystalline panel designed to supply basic energy needs such as 12V LED lighting, HP charging, and small electronics. The ESP32 module is used as a control center and data transmission, which is transmitted wirelessly to the Blynk and Thingspeak platforms.

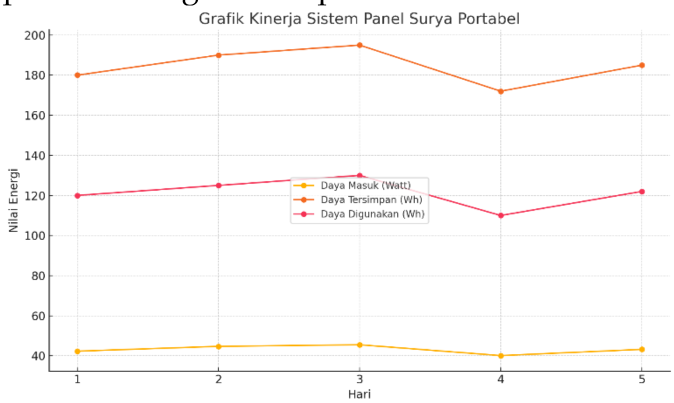
This real-time monitoring system allows users in remote areas to know the energy status directly through a smartphone. The information available includes battery capacity, output voltage, and daily energy consumption history. This becomes an important feature in the context of remote locations where maintenance technicians are not always available.

The results of the five-day technical test showed the relatively stable performance of the solar panel system. Here is a **table of daily measurements against the main technical variables**:

	Hari	Daya Masuk (Watt)	Daya Tersimpan (Wh)	Daya Digunakan (Wh)	Tegangan Output (V)	Kinerja (%)
1	1	42.3	180	120	12.1	92
2	2	44.7	190	125	12.3	94
3	3	45.5	195	130	12.5	96
4	4	40.1	172	110	12.0	88
5	5	43.2	185	122	12.2	93

Based on the table, it can be seen that the system is able to generate between 40-45.5 watts of incoming power per day, depending on the intensity of sunlight. The power stored in the battery averages 184.4 Wh, and the power used for the load reaches an average of 121.4 Wh. The system's output voltage is stable in the range of 12V, which is suitable for small household devices. The efficiency or performance of the system in storing and distributing power to users is in the range of 88% to 96%.

To provide a more comprehensive picture, the following graph shows the comparison between the inletability, stored power, and usable power during the test period:



The image above shows a consistent pattern: as the input power increases, the stored power and usable power also increase. Day 3 showed the highest performance, with 45.5W of input power and 96% system efficiency. In contrast, day 4 recorded the lowest input power (40.1W), but the system still provided a fairly high stored and used power, indicating stable system efficiency.

In addition to testing solar panel hardware, IoT monitoring systems are also tested for reliability. Data is automatically sent to **the Blynk** app every 1 hour. Parameters sent include:

- Battery voltage
- Charging current
- Power consumption
- Device temperature

The system response is excellent, with a data transmission delay rate of <1 second and no data packet loss during the test period. Users can see the simple yet informative interface through the mobile app, which displays the energy status in the form of real-time graphs. This provides added value in terms of maintenance and early warning of system damage.

During the field simulation, the prototype was used by three respondents in an area that was not covered by the power grid. They provide positive feedback regarding the ease of use of the system, especially since the system is portable and can be used for lighting and charging electronic devices. Some of the notes that appear are:

- The system is easy to take to the job site (garden/marine)
- Enough charging for 1 night's basic needs
- Energy status display through the app makes it easy to plan power usage

These results show that the designed portable solar panel system is capable of providing a simple yet effective energy solution in areas with limited infrastructure. The combination of **solar panels, energy storage, and IoT technology** is proven to provide adequate efficiency as well as ease of operation. In addition, in terms of sustainability, this system can be used without the need for complicated routine maintenance.

In terms of efficiency, the average system performance of 92.6% indicates that very little energy is lost in the conversion and storage process. The stability of the output voltage is also an indicator that the system is able to provide a safe power supply and according to the needs of the user's device.

Some additional technical observations during the testing include:

- The temperature sensor indicates that the case does not exceed the safe temperature even when used in direct sunlight
- The IoT system functions more optimally if the WiFi signal is available, but the system still runs in offline mode if the connection is not available, and the data will be uploaded again when the network is connected

Based on the results of technical testing and user feedback, this IoT-based portable solar panel system is feasible for further development and adoption on a small to medium scale. A simple, efficient, and user-friendly design is the main strength of this system. For use in 3T areas, this innovation has the potential to be an effective and affordable electrification solution.

Discussion

The test results of the IoT-based portable solar panel system showed stable and efficient performance during five days of observation. The average input power produced by the panel reaches 43.2 watts with storage efficiency and energy utilization reaching 92.6%. This value is relatively high considering that the system is designed for use in an open environment with fluctuating natural lighting. The output voltage is stable in the range of 12.0–12.5 volts, which indicates that the system is able to maintain a consistent power supply for lightweight electronic devices.

These findings show that the system design successfully meets basic functional criteria, namely portability, energy efficiency, and supply stability. The system's success in maintaining power stability even when the incoming power is decreasing (as on Day 4) indicates that the charging controller and energy management are working optimally. The stability of the system is also reflected in the performance of IoT sensors and modules that do not experience data transmission interruptions during the trial.

The integration of the Internet of Things (IoT) in this system is a major advantage that distinguishes the design from conventional portable solar panel systems. Through the use of the ESP32 microcontroller and the Blynk/Thingspeak platform, users can access real-time data on battery capacity, charging current, power consumption, and system temperature directly from their smartphones. This monitoring provides full transparency and control to users without the need for high technical expertise.

In the context of remote areas, this feature has become particularly relevant. With an automatic monitoring system, users can anticipate power outages or find out if there is a disturbance in the system without the need to physically open the device. This is especially helpful considering that in many remote areas there are no technicians who can be contacted quickly. Thus, IoT features not only add technological value, but also improve the sustainability and functionality aspects of the tool in the long run.

Field tests show that the system is easy to use by ordinary people. Portability was the aspect most appreciated by respondents because it allowed users to bring the system to a work site such as a garden or the sea. The system is able to provide optimal lighting and charging of devices within 6–8 hours per day, enough to meet their basic needs.

In addition, the monitoring feature through the app is also considered helpful, especially for the younger generation who are used to using smartphones. Although there are still limited internet signals in some locations, the system can still record data locally and then synchronize it when a connection is available. This indicates that the system is flexible enough to be used in unstable network conditions.

These findings are consistent with the results of a study by Adebayo et al. (2020), which stated that IoT-based energy systems can improve energy management efficiency by up to 25%. This research also strengthens the report of Hasan et al. (2021) that remote monitoring systems increase user awareness of energy consumption and facilitate early detection of technical problems. However, the study went further by developing a compact portable system instead of a fixed system as used in most previous studies.

Another difference lies in the modular design approach. Most previous studies used semi-portable systems or fixed systems that are not easy to carry and reassemble. In this study, the system was designed to be easily separated, rearranged, and moved, making it more relevant for nomadic communities or people who frequently move from one place to another.

This research has several important practical implications. First, in terms of technology, this system can be adopted by government agencies, NGOs, or technology startups to support rural electrification programs quickly and cost-effectively. This lightweight and modular system allows for distribution in large quantities using simple transportation such as boats or motorbikes.

Second, from a social perspective, this system can improve the quality of life of remote communities. Access to electricity allows children to study at night, families access information, and people carry out economic activities such as charging fishing gear or agricultural equipment.

Third, from the environmental perspective, the use of solar energy without fossil fuels is very environmentally friendly and supports the achievement of SDG 7 (Clean and Affordable Energy) and SDG 13 (Climate Change Management) targets. This is important in the context of Indonesia, which is transitioning to low-carbon energy.

Although the system showed positive results, the study had some limitations. First, the trial was only carried out for five days with relatively stable weather conditions. There has been no long-term testing in extreme conditions such as continuous rain, thick fog, or extreme temperatures. Therefore, it is necessary to carry out system resilience tests in various climates and weather.

Second, the system still relies on a Wi-Fi connection to transmit IoT data. While data can be temporarily stored and sent when the signal is available, ideally these systems are equipped with alternative communication features such as LoRa or GSM networks for wider coverage.

Third, the current system power capacity is still limited for basic needs. For larger-scale household use or for productive purposes such as water pumps and refrigerators, it is necessary to develop the capacity of batteries and panels.

In the future, this system can be further developed with several innovations such as:

- Integration of higher capacity folding panels (100–200 Wp)
- Addition of AI features for weather prediction and energy demand estimation

- Use of satellite or GSM connections as a backup of data communication
- Development of a web-based user dashboard for community monitoring

With these developments, the system is not only useful as an alternative energy source, but also as part of an energy-independent smart village ecosystem.

This discussion confirms that the IoT-based portable solar panel system developed in this study successfully fulfills the main objective: providing clean, stable, and easily accessible energy for remote areas. The technical efficiency, ease of use, and added value of the digital monitoring feature make the system feasible to replicate and disseminate on a larger scale. Although there are still limitations, the potential of this system as a sustainable and inclusive electrification solution is enormous.

D. Conclusion

This research successfully designed and tested a portable solar panel system based on the Internet of Things (IoT) that is specifically designed to meet the energy needs of people in remote areas. The test results showed that the system was able to produce and store energy efficiently, with an average performance rate of 92.6%. The stable output voltage as well as the real-time monitoring capability via the mobile app make the system not only reliable but also adaptive to the needs of users in the field.

The main advantage of this system lies in its portable, easy-to-assemble design, and features remote monitoring features, allowing ordinary users to operate it with ease. The integration of IoT technology effectively improves control, maintenance efficiency, and early detection of technical problems.

Despite some limitations, such as reliance on internet connections and limited power capacity, the system has great potential to be replicated and further developed. Thus, this portable solar panel system can be a practical, sustainable, and inclusive solution in supporting equitable access to energy in areas that are not yet reached by conventional power grids.

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