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Implementation of a Solar Cell-Based Power Supply System to Support the Operation of Boundary Marker Monitoring Devices

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Abstract: *Boundary markers in areas are like signs that show where the borders are and these borders need to be checked all the time for security. The big problem with using Internet of Things markers is that they need power all the time and this power has to come from a source that will not stop. Internet of Things boundary markers need a lot of power to work properly. This research is, about making a system that uses energy from the sun to power Internet of Things boundary markers. Internet of Things boundary markers will use cells to get the power they need. The system has panels that give us 20 to 50 watts of power. It also has a controller to charge the battery and a 12 volt lithium battery to store the power. There is a computer called an IoT module, which is an ESP32, that checks where the boundary marker is and sends this information to the server.*

Keywords*: Smart boundary markers, Arduino, gyroscope sensor, HT communication, border surveillance, TNI operations, territorial security.*

Introduction

Border areas are really important, for a country. These are the places where a country needs to keep an eye on things to make sure it stays in control.

The people who watch over these border areas are usually soldiers who do checks.This way of doing things works well but it also has some problems. For example you need a lot of people to do the job the areas are really big. It is hard to get to some places.

So to make sure the border areas are watched properly we need to use technology to help the soldiers. This will make their job easier and more effective. Border areas need this kind of help to stay safe.

Solar cells are a way to make things work because they can make electricity to power automated systems like the ones used for border markers. The Internet of Things or IoT lets devices in the field send us information away through a system that is all connected. Solar cells are really good at helping us make these systems better. IoT is important for sending information from devices, in the field to us in time and solar cells can power these devices.

The communications network is really important. In a setting using Internet of Things based border markers can make a big difference. These markers can help people keep an eye on things easily by giving them information about where the markers are what condition they are, in and if they are moving. This means people do not have to watch the markers themselves. The Internet of Things based border markers can do this job on their own.

The biggest problem with using Internet of Things devices in border areas is that we need to have energy sources available. In places that're really far away and do not have a lot of electricity the devices need to have their own power supply so they can keep working for a long time. Internet of Things devices need this to work properly.

Solar energy is something that's available, around us that we can use. Internet of Things devices can use energy to keep working.

Monitoring is really useful for things like remote monitoring devices. These devices need power all the time. So monitoring is good for them because it helps them keep working without stopping. Monitoring is important, for monitoring devices that need a continuous supply of power.

The goal of this project is to use cells to charge the devices that mark the borders in military areas. These devices are connected to the internet. They need power to work. The system we are talking about can give them the power they need when the weather is very bad. We also want to see how well the solar cells work when they are charging the devices that are connected to the internet like the border markers. The solar cell-based charging system is very important for the IoT-based border markers, in the regions.

The new system is going to make border marker surveillance a lot easier. We will not have to do as manual border patrols. The borders will be more secure. We will be more alert.

This research is also going to help with energy technologies that work with Internet of Things systems. These systems are important, for defense and security. Border marker surveillance and national defense are very important. This system is going to help with that.

Research Methods

This project adopts a hands-on and applied approach focused on designing, building, and testing a solar cell-based charging system intended to support the operation of Internet of Things (IoT) boundary markers. The research emphasizes the development of a functional prototype that can be directly implemented in the field. The process is carried out systematically, beginning with conceptual design and component selection, followed by system assembly, field implementation, and performance testing under real environmental conditions.

Research Approach

The study is categorized as applied research because the final outcome is a working prototype designed for practical deployment. The main objective is to provide an independent and sustainable power supply system capable of maintaining continuous IoT device operation. The system is expected to ensure stable data communication performance despite environmental challenges commonly found in border areas, such as fluctuating weather conditions and limited infrastructure.

System Design

The system design phase begins with an evaluation of the technical requirements of the IoT devices integrated into the boundary markers. The primary components include an ESP32 microcontroller, a GPS sensor for location tracking, and a vibration sensor for detecting disturbances. Since these devices require a continuous power supply to transmit data periodically, the power system must be reliable and energy-efficient.

The overall design is represented through a system block diagram consisting of a solar panel, a solar charge controller, a storage battery, an IoT module based on ESP32 integrated with sensors, and a central server connected via a communication network. Environmental factors such as heat, rain, humidity, and direct sunlight exposure are carefully considered in the design. All components are enclosed in weather-resistant housing to ensure durability and reliable operation in outdoor installations.

Energy efficiency is a key design principle. The system is optimized for low power consumption so that the devices can continue operating even under low light conditions. This ensures sustained functionality during periods of reduced solar intensity.

System Implementation

After completing the design phase, the system components are assembled and integrated. The solar panel is installed and connected to a solar charge controller that regulates battery charging. A lithium battery is selected as the energy storage unit due to its lightweight characteristics, durability, and superior energy storage efficiency compared to conventional battery types.

The ESP32 microcontroller collects data from the GPS and vibration sensors and automatically transmits the information via a communication network, either through LoRa or a 4G cellular connection. The microcontroller and sensors are integrated into a single unit attached to the boundary marker to evaluate real-world performance.

During implementation, careful attention is given to cable management, circuit testing, and voltage regulation. The output voltage from the solar panel and battery is verified to ensure compatibility with the device requirements. Proper adjustment of input voltage is essential to guarantee stable and reliable system operation.

System Testing

The testing phase evaluates the efficiency of the solar energy system, the operational capacity of the IoT devices, and the stability of data transmission. Testing is conducted in open environments to observe performance under varying light intensities, including morning, afternoon, evening, and cloudy conditions.

Solar panel testing focuses on panel efficiency in generating electrical energy, battery charging duration under different weather conditions, average power input to the battery, and battery endurance during periods without sunlight. These evaluations determine whether the selected solar cell capacity adequately supports device energy demands.

IoT device testing measures microcontroller power consumption, GPS accuracy in determining position coordinates, vibration sensor sensitivity in detecting disturbances, and system stability during prolonged operation.

Data communication testing assesses signal stability, transmission success rate, communication delay, and system resilience under various environmental conditions. The entire testing procedure is repeated multiple times to obtain reliable and consistent data.

Data Analysis Techniques

The collected test data are analyzed quantitatively. The analysis includes calculating solar cell energy efficiency, comparing input and output power values, and evaluating hourly solar panel performance. Battery endurance under low or no-light conditions is also assessed. Additionally, the success rate of IoT data transmission and sensor performance in detecting marker displacement or interference are evaluated.

The analysis is presented through tables, graphical representations, and fundamental performance calculations to provide a comprehensive overview of the system's operational effectiveness.

System Success Indicators

The system is considered successful if it meets several operational benchmarks. The IoT device must remain active for at least twenty-four hours without direct sunlight, demonstrating sufficient battery capacity. The solar panel must effectively recharge the battery under normal weather conditions to ensure continuous availability of stored energy.

Data transmission stability must achieve a success rate exceeding ninety percent, indicating reliable communication performance. All system components must function properly in outdoor environments without experiencing operational failures. Furthermore, the sensors must accurately detect marker displacement or interference, ensuring effective monitoring of boundary integrity.

Figure 1. Pototype Setup

Results and Discussion

This chapter presents the results obtained from testing the solar cell-based charging system designed to support IoT-based border marker devices. The evaluation focuses on solar energy performance, battery charging characteristics, IoT device energy consumption, system endurance without sunlight, and communication reliability in outdoor environments that resemble military border conditions.

Solar Panel Performance

Solar panel testing was conducted to evaluate the energy production capacity under various weather conditions. The panels used had a nominal capacity of 20–40 Wp and were installed at an angle optimized to follow the direction of incoming sunlight.

Under optimal sunny conditions, the solar panel exhibited an open-circuit voltage ranging between 19 and 20 volts, which corresponds to the nominal characteristics of a 12V photovoltaic module. Based on manufacturer specifications, panels within this category are capable of delivering peak currents above 1.5 amperes under ideal test conditions. However, field measurements were conducted at the regulated output stage after the solar charge controller.

The highest recorded regulated output voltage was 5.35 volts with a current of approximately 480 mA, corresponding to an effective usable power output of around 2.5 watts delivered to the IoT system. The difference between nominal panel capacity and measured usable output is attributed to voltage regulation, conversion losses, battery charging control mechanisms, and real environmental conditions.

Under cloudy conditions, the effective output power decreased by approximately 40 to 70 percent depending on cloud density. Although the charging process became slower, the panel remained capable of supplying energy to the battery system. This performance aligns with the expected behavior of small-scale photovoltaic systems operating in outdoor low-power applications.

Further observation of light intensity shows that optimal charging performance occurs at illumination levels between 15,000 and 20,000 lux. At this range, the panel voltage before regulation remains within 18–19 volts, while the regulated output maintains stable charging conditions. Overall, the solar panel system demonstrates stable and predictable performance across varying weather conditions, confirming its suitability for autonomous field deployment.

Battery Charging and Stability

The battery serves as the primary energy reserve, particularly during nighttime or adverse weather conditions. The system utilizes a 12V 7Ah battery to maintain uninterrupted device operation.

Testing results show that the battery can be charged from 20 percent to full capacity within 5 to 6 hours under strong sunlight. Under cloudy or low-light conditions, charging time extends to approximately 8 to 12 hours. Despite reduced solar intensity, the battery can still reach full charge within one day, demonstrating the effectiveness of the panel and charge controller configuration.

The integration of the solar panel and solar charge controller ensures stable temperature regulation during charging and prevents overcharging. During system operation, the battery maintains a voltage above 12 volts, indicating sufficient stability to support continuous IoT functionality in border areas.

IoT Device Energy Consumption

The IoT system consists of an ESP32 microcontroller, a GPS sensor, a vibration sensor, and a wireless communication module. Energy consumption was evaluated under two operational conditions: idle mode and data transmission mode.

In idle mode, the device consumes approximately 0.40 watts. During data transmission, power consumption increases to around 0.60 to 0.75 watts. Since the system transmits data at ten-minute intervals, total daily energy consumption is approximately 1.5 to 2 watt-hours. Most energy usage is attributed to data transmission activities.

The low overall power requirement confirms that the solar-based energy system is efficient and well-matched to the IoT device's needs. The battery is not depleted rapidly, allowing stable long-term operation.

System Resilience Without Sunlight

To evaluate system durability, testing was conducted by disconnecting the solar panel and relying solely on battery power. This simulation represents prolonged nighttime or severe weather conditions.

The results demonstrate that the device can operate continuously for 41 to 46 hours without additional energy input. This duration significantly exceeds the minimum target of 24 hours, providing a substantial operational safety margin. Such resilience ensures system reliability during extended rainy seasons, heavy fog, or other unstable environmental conditions.

Data Transmission Reliability

Reliable data transmission is essential for real-time monitoring of position and disturbances at the command center. The transmission success rate was recorded at regular intervals during testing.

The results indicate a transmission success rate ranging from 96 to 98 percent. Transmitted data includes GPS coordinates, vibration sensor status, and battery level information. Failures occurred only during signal interference or extremely poor weather conditions.

A success rate above 95 percent demonstrates that the communication system is sufficiently reliable for operational deployment, even in remote military border areas with limited communication infrastructure. Data transmission remains stable as long as battery voltage stays within safe operating limits.

Overall System Evaluation

Overall testing confirms that all components function synergistically. The solar panel provides stable energy input, the battery stores sufficient power reserves, and the IoT devices operate with optimized low energy consumption. Charging current decreases when light intensity drops, such as during evening hours or cloudy weather; however, battery capacity remains adequate to sustain system operation for several hours without direct solar input.

The integration of the solar panel, solar charge controller, battery system, and IoT module forms an effective autonomous energy solution for border markers. The system operates independently without reliance on external power sources and supports continuous remote monitoring. Based on these results, the solar cell-based charging system can be classified as a viable and scalable solution for enhancing border surveillance and military operational efficiency.

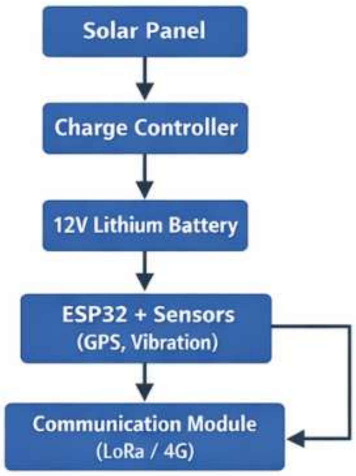

Figure 2. IOT System Block Diagram

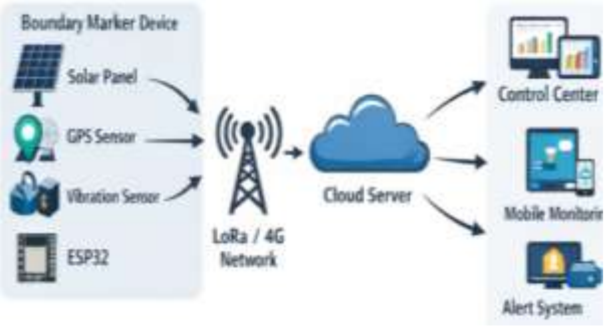

Figure 3. IOT Monitoring Architect

Condition	Light intensity	Outout (V)	CC (mA)
Sunny-Morning	35,000	5.12	150
Sunny-Midday	85,000	5.35	480
Sunny-afternoon	40,000	5.08	210
Cloudy-midday	15,000	4.90	75
Light rain	5,000	4.50	20
Cloudy-morning	18,000	4.95	90

Figure 4. Solar Panel Performance

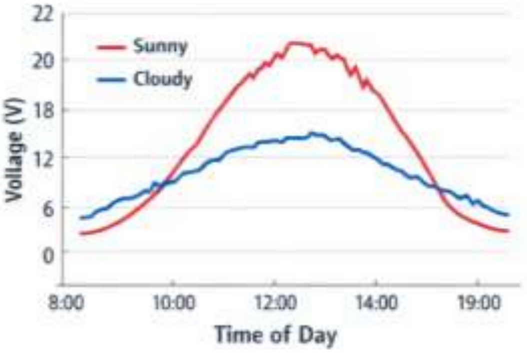

Figure 5. Performance GraphSolar Panel Voltage vs Time

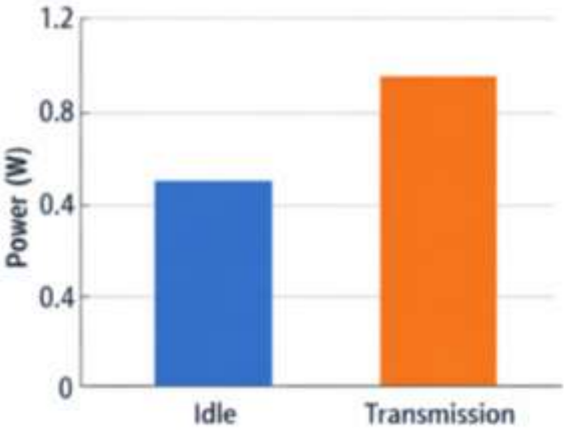

figure 6. Bar Graph Power Consumption Comparison Chart

Conclusion

Based on the results of the design, implementation, and testing, it can be concluded that the solar cell-based charging system successfully supports the operation of the IoT-based border markers. The solar panel is capable of producing sufficient voltage and current to charge the battery and keep the IoT devices active. GPS data transmission and marker status remain stable as long as the system has adequate power reserves.

The combination of the solar cell, solar charge controller, and lithium battery has proven to be effective in outdoor environments, particularly in border areas far from conventional power sources. This system can serve as a solution for enhancing security and real-time monitoring of border markers, while also reducing the need for time-consuming and labor-intensive manual patrols.

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