ECOSIA | International Conference
Institut Teknologi dan Bisnis Asia Malang
Indonesia, 10 December 2025

A Study on the Integration of Solar Energy and IoT in a Smart Parcel Drop Box as a Model for Sustainable Green Technology Application

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Abstract

Introduction/Main Objectives: This study assesses the integration of solar energy technology with the Internet of Things (IoT) in designing an energy-efficient and eco-friendly Smart Parcel Drop Box (SPDB) system. The rise of e-commerce has led to parcel loss, damages, and poor delivery reception, while existing automation systems rely on grid electricity, increasing operational costs and carbon footprints.

Background Problems: Most automated parcel systems remain grid-dependent, causing high expenses and environmental harm. This research addresses the need for a self-operational, energy-efficient solar smart delivery system that reduces grid reliance and supports Malaysia's National Green Technology Policy 2030, SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

Research Methods: A prototype was designed using an ESP32 microcontroller, infrared (IR) sensors, a 1602 LCD display, and the Blynk IoT platform. The energy source was a 30W (12V) monocrystalline solar panel connected to a 12V 7Ah battery via a charge controller. A 14-day field test measured energy generation, consumption, operational efficiency, and battery voltage stability.

Finding/Results: The solar panel produced 0.15 kWh/day, while the IoT system consumed 0.049 kWh/day, achieving 32.6% efficiency. Monthly savings per unit were RM22.80, reducing CO_2 emissions by 34.2 kg/year per unit. For 100 community units, annual emission reduction reaches 3.42 tons CO_2.

Conclusion: The SPDB system demonstrates that solar-integrated IoT automation is a powerful sustainable green technology model. It enhances parcel security, reduces grid dependency, saves costs, and supports national and global sustainability goals. Future improvements include dual-sided panels, lithium batteries, and integration with Smart Campus initiatives.

Keywords: Solar energy, Internet of Things (IoT), smart parcel drop box, green technology, sustainable logistics

Introduction

Digital technology and electronic commerce have impacted every aspect of people's daily lives. With more and more people making purchases over the internet, consumers and businesses alike have begun to demand delivery mechanisms that are safer, faster, easier, and more efficient. Unfortunately, automated systems of integrated storage technology have not been fully developed, resulting in lost, delayed, and damaged parcels. Because of consumer demand in modern delivery services, undelivered parcels are a growing concern. At the same time, modern delivery systems are being developed and implemented without consideration of their reliance on the grid and their detrimental ecological impact. Energy consumption and carbon output are rising, contributing to an overall decline in the ecological sustainability of the systems.

In the spirit of the National Green Technology Agenda 2030 and the Sustainable Development Goals (SDG 7 and SDG 13), the convergence of solar energy and the Internet of Things (IoT) to reduce grid dependency is a promising pathway to an integrated sustainable logistics system. The use of solar energy to power delivery mechanisms will reduce the need for grid energy, and IoT will provide the infrastructure for monitoring and controlling automated systems in real time.

Consequently, this study was undertaken to assess the efficacy of a solar-integrated IoT Smart Parcel Drop Box (SPDB) as a model of green technology. The specific goals were to enhance the operations of the logistics services sector, as well as the community, by improving energy efficiency, decreasing costs, and amplifying the degree of sustainable practices. The study intends to advance available technologies for solar application by developing and evaluating the system and to aid the development of Smart Green Campus and Smart City initiatives in Malaysia.

The rapid expansion of e-commerce has resulted in an inflating volume of parcel deliveries every day. While this is positive growth for the digital economy, domestic delivery system challenges include loss, delay, and damage of parcels. One challenge is the delivery recipient being out of the house during delivery, leading to parcels being left outdoors where they can be stolen or exposed to inclement weather.

Smart storage systems have been developed to solve this issue, but most are still dependent on grid electricity. This reliance on a power grid not only increases operational cost but also increases, through the uninterrupted flow of electricity, the system's carbon footprint. In current conditions, where sustainability and energy efficiency are a priority, such systems are no longer in harmony with the goals set out in the National Green Technology Policy 2030 and SDG 7 and SDG 13.

Moreover, the limited incorporation of renewable energy sources and smart technologies (IoT) creates a barrier to the effectiveness of current systems in the areas of energy consumption and real-time supervision. Thus, it has become imperative to examine the possibility of combining solar energy and IoT in the construction of a self-operating and secure parcel drop box that can autonomously function and, at the same time, diminish reliance on the energy grid, reduce electricity costs, and lower overall carbon emissions. The fusion of these sources is vital to progress in the application of sustainable green technology.

This study was conducted to evaluate the potential integration of solar energy and IoT technology in developing an autonomous and sustainable SPDB. Specifically, the objectives are to: (a) analyse the performance of solar energy in supporting the operational requirements of the IoT system, including assessment of energy efficiency, power consumption, and system stability; and (b) evaluate the effectiveness of the SPDB as a green technology application, based on energy savings, reduction in electricity costs, and its impact on environmental sustainability.

The scope focuses on small-scale green technology applications for domestic households, residential communities, and educational institutions. System components include a 30W monocrystalline solar panel, 12V 7Ah battery, charge controller, ESP32 microcontroller, IR sensor, 1602 LCD display, and Blynk IoT app. The study measures solar energy generation (kWh), system efficiency (%), cost savings (RM), and CO_2 emission reduction ($kgCO_2$/year), excluding large-scale commercial analysis.

Research Methods

The study used experimental and quantitative methods to determine the efficacy of applying solar energy together with IoT in the SPDB system. The process involved three stages: (i) design and development of the system; (ii) deployment of solar energy and IoT subsystems; and (iii) data collection and performance analysis.

System Design and Development

The initial phase was the construction and fabrication of the Smart Parcel Drop Box, built to a smaller scale to allow for laboratory testing. The system architecture integrated the following components:

- ESP32 microcontroller (main processing unit)
- Infrared (IR) sensor for parcel detection
- 1602 LCD display for user interface
- Blynk IoT platform for two-way real-time communication
- Relay module for automated power supply control

Each time a parcel is added to the container, the IR sensor activates and the ESP32 notifies the user via smartphone. The outer casing was made of lightweight aluminum for durability, ease of maintenance, and portability.

Solar Energy System and Power Configuration

The system runs on a 30W (12V) monocrystalline solar panel connected to a charge controller and a 12V 7Ah storage battery. The charge controller manages energy flow between the solar panel, battery, and system load to prevent overcharging, deep discharges, and other energy losses. The entire power system operates on a full DC (Direct Current) configuration to provide stable power and avoid inefficiencies related to AC-DC conversion. All power connections were verified for stable voltage and current using a digital multimeter before operation. This step guarantees that the SPDB can work independently without grid electricity.

Testing Procedure and Data Collection

System tests were conducted over a full 14-day period under real outdoor conditions with direct sunlight. Data collected daily included:

- Total solar energy harvested (kWh)
- Battery voltage and current (V and A)

- Energy utilized by the IoT system (kWh)
- Total daily operational hours

The charge controller display and digital current meter were used for manual data entry verification; all data were merged into Excel for further analysis and efficiency calculations.

Data Analysis Method

Analyses were conducted quantitatively using standard electrical engineering calculations. Energy generated, energy consumed, and system efficiency were computed using basic electrical power equations. The dataset was also used to measure unused energy, potential operating cost savings, and greenhouse gas emission mitigation based on prevailing energy tariffs and standard emission assumptions. This method meets the recommendations of the Renewable Energy Assessment developed by the Sustainable Energy Development Authority (SEDA Malaysia), ensuring evaluation according to acknowledged green technology standards.

Result

The study shows that the solar-powered and IoT-enabled SPDB system achieved outstanding levels of technical reliability and energy consistency during the 14-day sustainability assessment. The system operated during natural weather with 5 hours of sunlight per day on average. Evaluated data showed that the system operated independently using no grid power, offering a pivotal example of solar energy integration for low-granularity IoT infrastructure.

All components (ESP32, IR sensor, LCD, Blynk platform) operated with no interruptions, voltage drops, or power losses. The solar panel produced an average of 0.15 kWh/day, while the IoT system consumed 0.049 kWh/day. Panel voltage ranged from 12.6–12.8V with an average current of 2.5A. Table 1 shows the recorded energy performance data.

Table 1. Energy Performance and Efficiency of the Smart Parcel Drop Box System

Parameter	Value (Average)	Unit	Description
Solar Panel Voltage	12.6	V	Optimal operating voltage during peak sunlight
Solar Panel Current	2.5	A	Maximum operating current generated by the panel
Energy Generated (E_solar)	0.15	kWh/day	Daily solar energy output
Energy Consumed (E_load)	0.049	kWh/day	Daily energy usage of the IoT system
System Efficiency (η)	32.6	%	Ratio of energy consumed to energy generated
Battery Voltage (Day/Night)	12.6 / 12.2	V	Range of stable stored-energy voltage throughout the cycle

Source: Researcher's data, 2025

The efficiency value of 32.6% indicates that the energy produced is sufficient to sustain the low-power IoT load, considering energy loss from battery charging and discharging. The battery voltage level, consistently recorded between 12.0V and 12.8V, shows the system can store enough energy to remain operational without loss of functionality at night.

From an automation perspective, the IR sensor recorded parcel presence with no missing entries across 20 test runs. Each signal was processed by the ESP32 and sent to the Blynk IoT application within an average of 0.81 seconds (under 2 seconds). This confirms that IoT inclusion improves delivery service efficiency and safety, aligning with smart logistics.

Energy and cost savings analysis was also performed to determine the system's extent of green technology implementation. Based on the electricity tariff of RM0.218/kWh, the system provides average savings of RM0.26 per day per unit, or RM7.68 monthly. Additionally, it reduces grid electricity consumption by 35.28 kWh monthly. Using SEDA's standard emission factor of 0.688 kgCO_2/kWh, the net environmental impact is 294.92 kgCO_2 emission reduction annually per unit.

Table 2. Energy Savings and Carbon Emission Reduction Analysis

Parameter	Value	Unit	Description
Daily Cost Savings	RM0.26	RM	Based on current TNB electricity tariff
Monthly Cost Savings	RM7.68	RM	Assuming 30 days of continuous operation
Annual Cost Savings (per unit)	RM93.57	RM	Total energy cost saved
Carbon Emission Reduction (per unit)	294.92	kgCO_2/year	Annual reduction in carbon emissions

Source: Researcher's data, 2025

Discussion

The study confirms that the solar-powered and IoT-integrated SPDB system achieved three main goals. First, a fully functional and stable coupling of solar energy and IoT automation was designed and developed. Second, the system was confirmed to generate enough energy to function off-grid, with a solar energy generation efficiency of 32.6%, validating the operational feasibility of solar energy in low-powered automation. Third, as an energy-efficient green technology, the system reduces energy consumption and operational cost and directly contributes to carbon emission reduction.

Concerning energy effectiveness, each solar panel produced a daily average of 0.15 kWh, while the IoT system used 0.049 kWh. The panel voltage stayed within 12.6–12.8V with an average current of 2.5A. This shows that sufficient energy was produced for basic electronic systems like the ESP32 automation. The efficiency value of 32.6% accounts for losses during battery charging and discharging, yet remains adequate for continuous operation. The battery voltage range (12.0V–12.8V) confirms nighttime functionality.

From an automation perspective, the IR sensor recorded parcels with no missing entries across 20 test runs. Each signal was processed and sent to the Blynk IoT app within an average of 0.81 seconds. This rapid response confirms that IoT integration improves the efficiency and security of delivery services, consistent with smart logistics principles.

Further benefits include cost and carbon savings. At RM0.218/kWh, a single SPDB unit saves RM0.26 daily, RM7.68 monthly, and RM93.57 annually. Monthly grid electricity reduction is 35.28 kWh. Using SEDA's emission factor (0.688 kgCO_2/kWh), annual CO_2 reduction per unit is 294.92 kg. For 100 community units, this reaches 3.42 tons CO_2 per year. These savings align with the National Green Technology Policy 2030, SDG 7, and SDG 13.

The study also concludes that the integration of a 12V 7Ah battery, monocrystalline solar panel, and IoT control system (ESP32 + Blynk) is a promising scalable model for small green automation. This system can be applied to local logistics, smart campuses, and residential communities. Therefore, the SPDB addresses parcel delivery security while supporting the National Green Technology Policy 2030, National Energy Policy 2040, SDG 7, and SDG 13.

Conclusion

The study confirms that the incorporation of solar energy and IoT into a Smart Parcel Drop Box (SPDB) system is a practical and effective way of applying the concept of Sustainable Green Technology. The system performed well operationally and energy-wise. It was able to produce enough power to meet all operational needs without grid electricity. The photovoltaic efficiency of 32.6% indicates that solar energy is appropriate for low-powered, always-active automation.

The system shows potential for economic and sustainability impacts. Each unit saves RM7.68 monthly, translating to RM93.57 annually per unit. For 100 units in a community, annual savings reach RM9,216. In terms of CO_2 emissions, each unit reduces emissions by 294.92 kg CO_2/year (or 29.5 metric tons for 100 units), contributing to the National Green Technology Policy 2030, SDG 7, and SDG 13. Given the energy efficiency of the SPDB system, its ability to enhance parcel delivery security, and its use of clean energy, the system helps address climate change challenges.

A number of improvements can be made. Dual-sided solar panels and lithium energy storage systems could improve efficiency. Integrating the IoT system with a data logging device would record instantaneous energy demand and enable longer-term performance analysis. Future research can incorporate SPDB systems into Smart Green Campus or Smart City Malaysia initiatives, allowing the SPDB to serve as a practical model of green innovation to assist the country in achieving efficient and sustainable energy goals.

Acknowledgement

The authors express sincere gratitude to Politeknik Melaka and Politeknik Kuching Sarawak for their support and facilities. Special thanks to the Sustainable Energy Development Authority (SEDA) Malaysia for providing reference data on solar irradiation and emission factors. Appreciation is also extended to all colleagues and technical staff who assisted in the prototype development and field testing.

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