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Implementing a Building-Integrated Off-Grid Solar Power System for Micro-Scale Vending Shop

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ABSTRACT

This research undertook the mission of addressing the energy requirements of a micro-scale vending shop located in West Jakarta. The core objective was to design, implement, and evaluate an off-grid solar power system integrated into the shop's structure, with a particular focus on lighting during night operations. Over a span of seven days in November 2021, the system's performance and efficiency were systematically assessed. The solar irradiation measurements indicated a favorable solar resource, slightly surpassing predictions. However, the daily efficiency of the solar panel system, hovering between 8.2% to 8.9%, highlighted the influence of temporal and shading factors. Despite the economic challenge posed by the Levelized Cost of Energy (LCOE) at 2,781 IDR/kWh, this solar PV system demonstrated its potential by significantly reducing greenhouse gas emissions, estimated at approximately 459 Kg CO2/year. This research contributes essential insights into the dynamics of building-integrated solar systems, providing a path toward cleaner, sustainable energy solutions, albeit with economic considerations.

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1. INTRODUCTION

Solar energy has incredible potential to power our daily lives. Researchers suggest that the amount of sunlight that strikes the Earth's surface in an hour and a half is enough to handle the entire world's energy consumption for a full year [1], [2]. As the global community grapples with the imperative to reduce reliance on conventional energy sources and mitigate the environmental impact of greenhouse gas emissions, this study represents a timely exploration of renewable energy's potential.

The implementation of Building-Integrated Solar Power System on small roof surface proved to challenging. Previously, BIPV system was implemented to power a small bus shelter [3], [4]. The research shows that the bus stop shelter can generate sufficient daily energy for load even in a worst-case scenario. The implementation on other limited roof area such as solar PV systems on marine vessels also has been reported [5]. The system provides some benefits, majorly on producing green, clean, and eco-friendly energy that does not emit GHGs. Also, for those who care about the environment, solar panels are the greatest choice.

Another significant challenge faced by this solar power system on restricted surface area is its limited power production capacity, which subsequently results in higher energy costs. This challenge necessitates careful consideration of component selection, as the efficiency of the system can be compromised due to losses incurred in major components, including solar panels, inverters, batteries, and charge controllers [6]. Therefore, the process of component selection must be executed with precision to optimize the system's overall efficiency and cost-effectiveness [7].

The research objective is to create an innovative and sustainable energy solution for a micro-scale vending shop in West Jakarta, with the goal of reducing reliance on conventional energy sources and fostering a cleaner and more cost-effective energy future. This entails designing and constructing a building-integrated off-grid solar power system to fulfill the shop's lighting needs, especially during nighttime operations. The research also involves evaluating the system's real-world performance, including aspects such as energy production, storage, consumption, and overall efficiency. Furthermore, the study aims to determine the economic and environmental feasibility of this solar power system, providing a holistic approach to address the energy needs of the vending shop while contributing to a more sustainable and economically viable energy landscape.

2. EXPERIMENTAL METHODS

A solar panel system was set up at a vending shop with latitude -6.2 and longitude 106.8, which places it in the Kebon Jeruk district of West Jakarta. To maximize the efficiency and effectiveness of the solar PV system, solar panels oriented northward and tilted at an angle of 82 degrees. This orientation and tilt are chosen to ensure that the panels receive sunlight optimally for energy generation [8]. The location has been assessed to have a solar potential of 3.98 kWh/m^2/day. This data has been obtained from RET Screen Expert database sources [9]. The sun shines from 7 AM until 5 PM, approximately 10 hours of daylight. The peak intensity of solar irradiation was observed between 10 AM and 2 PM. During these hours, the sun's rays are most direct and powerful, which is when the solar panels will generate the most electricity.

2.1. Energy consumption assessment

The energy consumption assessment in this section outlines a structured approach to comprehending the energy needs of a vending shop, particularly with regard to its lighting requirements. This process is pivotal for the successful design of an energy system, such as a solar PV system, that can meet the shop's power needs efficiently. This analysis delves into the quantity of energy the shop typically consumes during a standard day, as well as the specific patterns of energy usage.

This section then offers a specific example related to the shop's lighting requirements. To attain an illumination level of 250 lux, a calculation was conducted employing the method as detailed in reference [10]. This calculation is based on factors such as the room's area, which is 12 square meters, and the specification that 18-watt LED lamps are utilized in the shop. Each of these lamps can emit roughly 1300 lumens. Based on this calculation, it is established that five LED lamps are necessary to achieve the desired lighting level of 250 lux. The details of the power requirements for the shop's lighting are provided in Table 1.

Table 1. Energy usage

Appliance	Operational schedule	Quantity	Watts (AC)	Operation Hours/day	Watts Hours/day
LED Lights	Night use	5	18	12	1080

2.2. System Design and Configuration

The configuration of a standalone solar power generator was designed to meet the lighting needs of a micro-scale vending shop. The shop's operational hours require lighting during the night, totaling approximately 12 hours. To meet this demand, five LED lamps are specified. These components parameters are systematically calculated based on the shop's specific requirements. The method used for this calculation adheres to the approach outlined in reference [4], [11]. Furthermore, the specific characteristic of the component, as described in Table

3, was determined based on the calculation as detailed in the reference [12].

The designed system is guided by several key criteria. These criteria include low initial investment cost, a long operational lifetime, high efficiency, ease of construction, and cost-effective maintenance. These factors are essential for a sustainable and economically viable solution. To arrive at the best system configuration, the VDI 2221 method is applied. Details regarding this selection process can be found in reference [12]. This method facilitates the systematic and rational choice of the most suitable configuration based on multiple considerations, as shown in Table 2. These selections are pivotal in ensuring the system's efficiency and cost-effectiveness.

The detailed technical design of the solar PV system was systematically developed. This design encompasses the specification of the panels, battery storage, and other essential components. Specific components, such as PV panels, charging controllers, DC to AC inverters, and batteries, are chosen based on both technical requirements and cost considerations, as shown in Figure 1.

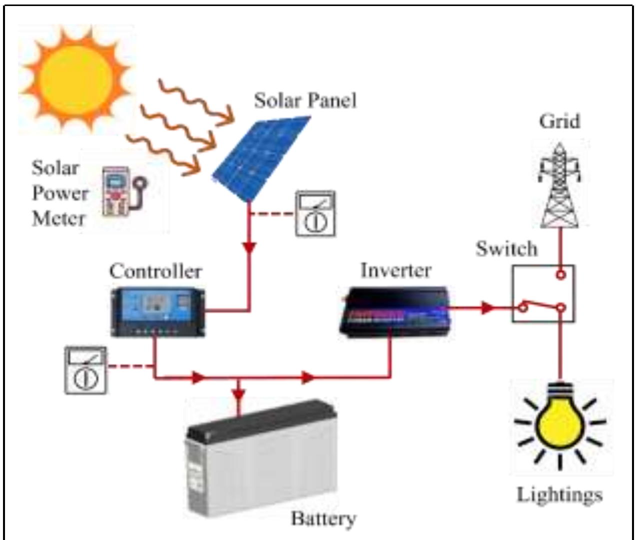


Figure 1. Schematic diagram of stand-alone solar power system.

__Table 2.__ Criteria of design process.

Component	Criteria	Alternative 1	Alternative 2	Alternative 3
Solar panel	1. Inexpensive 2. High durability 3. High efficiency	 Monocrystalline	 Polycrystalline	 Thin film
Solar Charge Controller (SCC)	1. Inexpensive 2. High durability 3. High efficiency	 Simple 1- or 2-stage controller	 PWM (Pulse Width Modulated)	 Maximum Power Point Tracking (MPPT)
Battery	1. Inexpensive 2. High durability 3. Higher lifetime	 Flooded	 AGM sealed	 Deep cycle
Inverter	1. Inexpensive 2. High efficiency	 Square wave	 Pure sine wave	 Modified sine wave
Frame structure	1. Inexpensive 2. High durability 3. Easy to build	 Wood frame	 Structural steel frame	 Cold-formed steel frame

Table 3. Technical specifications

Component	Specification
Solar PV	Poly-Si 6×100 Wp
Solar charge controller	PWM, 12V, max. 60 A
Battery	AGM sealed lead acid battery, 12V, 1×200 Ah
Inverter	Pure sine wave, 12V, 1000W
Structural frame	Cold formed galvanized steel frame, rectangular hollow section with 0.75 mm thickness, metal roofing screw for joints.

2.3. Installation and Evaluation

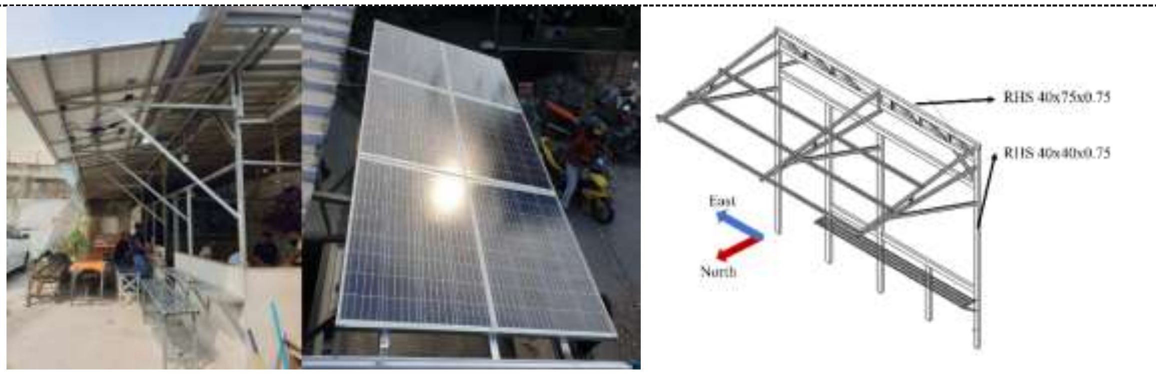
The critical phase of implementing the designed solar power system on the actual rooftop of the vending shop and subsequently evaluating its performance. Successful installation and real-world evaluation are pivotal to ensuring the system functions as intended. This phase is carefully executed to guarantee that all system components are correctly installed, as shown in Figure 2 and 3.

To meet the power demands, six solar panels are required. These panels are strategically placed on the north side of the shop's rooftop, acting as a canopy that provides shade and prevents direct sunlight from permeating the shop area. To seal the gap between the solar panels and the roof and avoid water leakage during rainfall, a layer of plastic fiber is employed. Any potential leakage points are thoroughly sealed with weatherproof rubber sealant. The structural frame supporting the solar panels is constructed from galvanized steel with a frame structure using rectangular hollow sections, each with a thickness of 0.75 mm, as shown in Figure 3(c). The frame components are securely joined together using metal screws. The design and construction of this structure were informed by a Finite Element Analysis, as detailed in Reference [13].

Following the installation, a critical aspect of the process is to monitor and collect real-world data concerning the system's performance. This includes tracking and recording various metrics related to energy production and system efficiency. To assess the real-time intensity of solar irradiation, an SM-206 Solar Power Meter is employed. This instrument provides measurements with an accuracy typically within ± 10W/m^2. It quantifies the amount of sunlight energy received by the solar panels hourly.

The power generated by the solar panels is quantified by measuring the output at the solar panel's endpoint. Additionally, measurements are taken at the output of the SCC, which is a key component in regulating and storing the generated energy.

Figure 2. Components cofiguration.



(a) (b) (c)

Figure 3. Solar panel installation; (a) bottom view, (b) top view, (c) structural frame.

3. RESULTS AND DISCUSSIONS

An off-grid solar power generator integrated into the building structure was installed to provide lighting for a micro-scale vending shop, operating during night. The system comprises six solar panels, ingeniously serving as a canopy. The generated solar energy is efficiently stored in a 200Ah lead acid battery, ensuring power availability when needed. In this section, the results of the system's performance evaluation were reported.

3.1. Performance and Efficiency evaluation

This section provides a detailed assessment of the performance and efficiency of the solar power system over a period of seven days, from November 15, 2021, to November 21, 2021. Figure 4 illustrates the energy output from the solar panel and the energy transferred to the battery via the Solar Charge Controller (SCC). This data is then compared to the solar irradiation measurements. The findings reveal that the average solar irradiation at the shop's location was approximately 5.726 kWh/m^2/day. Notably, this measured data slightly exceeded the predicted values provided by the Global Solar Atlas for December, which fell within the range of 4.89 to 5.03 kWh/m^2/day. During the data collection period, the weather was characterized by sunny conditions with light cloud cover, and no heavy rain was reported during the day.

The solar panels employed in the system were reported by the manufacturer to have an efficiency of 10%. These panels were subjected to laboratory testing, exposed to 1000 W/m^2 of light, and were reported to be capable of producing a maximum of 100W. Figure 7 presents the results of the daily efficiency of the solar panel's output, which ranged between 8.2% to 8.9%. Notably, the highest efficiency was observed between 12 AM and 1 PM, with an efficiency exceeding 10%.

Figure 5 and Figure 6 display the solar power profile during the seven-day period, with November 15, 2021, registering the highest energy harvested and November 17, 2021, marking the lowest energy yield. The results indicate that the most effective energy harvesting occurred from 10 AM to 2 PM, a span of four hours. However, due to the surrounding tall buildings that cast shadows on the solar panel surface, energy conversion was impeded during other hours of the day. These shadows limited the amount of sunlight available for conversion into electricity.

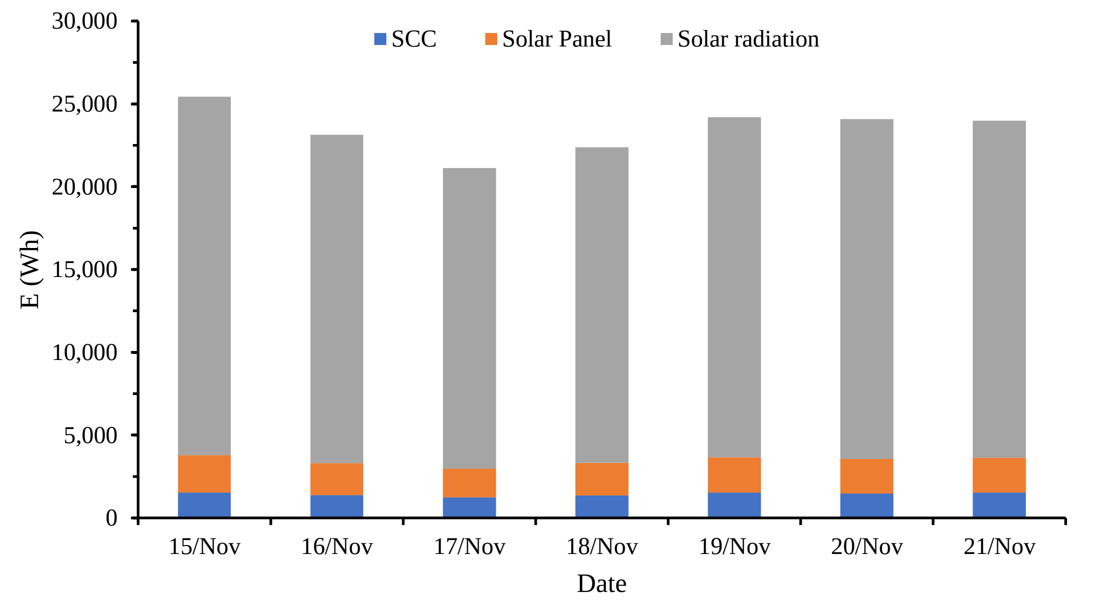


Figure 4. Daily **e**nergy production.

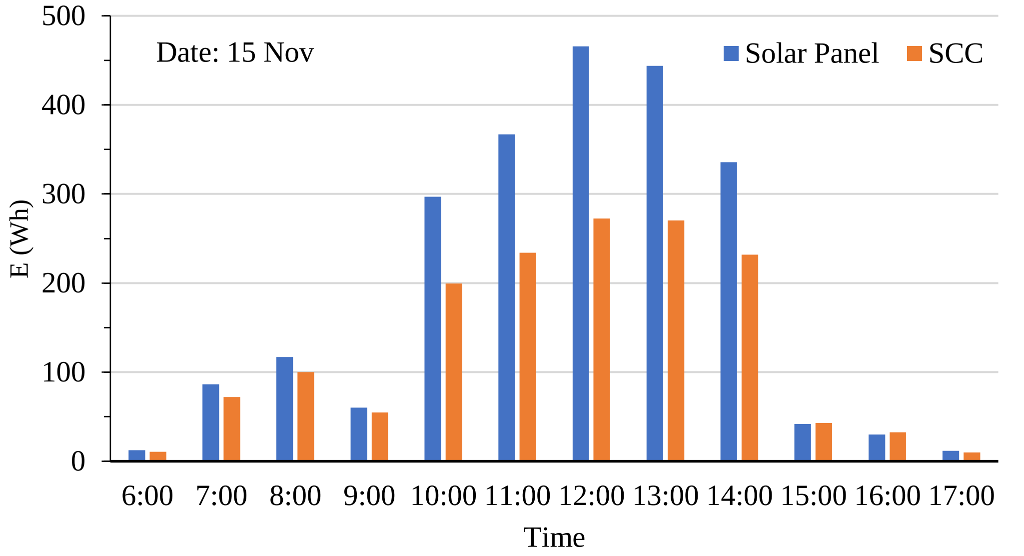


Figure 5. Energy production profile at 15 November 2021.

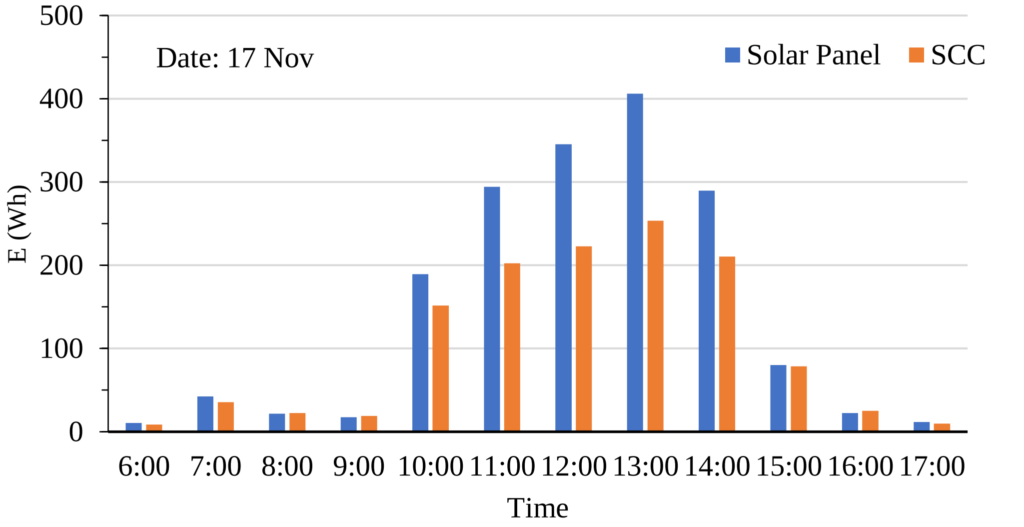


Figure 6. Energy production profile at 17 November 2021.

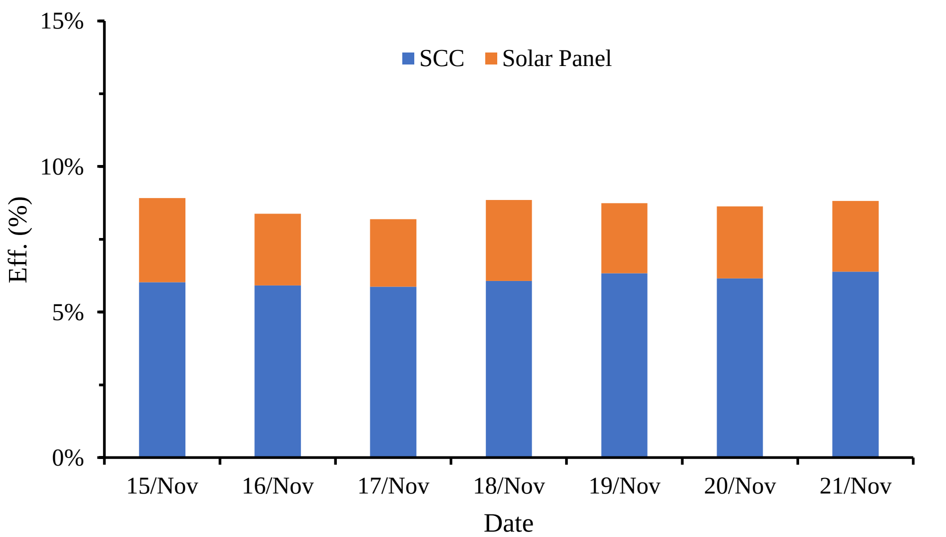


Figure 7. Efficiency of the solar PV system

3.2. Economic and Environmental Effect Analysis

The current solar system installation has been previously subject to an economic analysis, as documented in reference [14]. The analysis revealed a Levelized Cost of Energy (LCOE) for the system amounting to 2,781 IDR/kWh or 0.185 USD/kWh. It's important to note that this cost is nearly double the rate charged by the local electricity provider company (PLN) from the Jamali grid (Jawa-Bali), which bills residential customers at a rate of 1,444.7 IDR/kWh or 0.096 USD/kWh. However, the solar PV energy cost is much cheaper compared to using diesel-powered generators [15], [16]. While the economic practicality of the Solar PV system implementation may appear challenging, it has demonstrated a significant reduction in greenhouse gas emissions [17]. The implementation of the solar PV system is estimated to potentially reduce greenhouse gas emissions by approximately 459 Kg CO_2/year, as shown in Table 4.

Table 4. Estimation of carbon emission produced per kWh.

Energy Source	CO_2e Kg CO_2/kWh Reff. [18], [19]	CO_2e Kg CO_2/kWh/year
Solar PV	0.07	38.00
PLN - Jamali Grid	0.89	497.31

4. CONCLUSIONS

The research was undertaken to meet the energy requirements of a micro-scale vending shop in West Jakarta through the design and implementation of a building-integrated off-grid solar power system. Data was meticulously gathered over a seven-day period, revealing the system's efficiency ranged from 8.2% to 8.9% daily, with a peak exceeding 10% as rated by the manufacturer between 12 AM and 1 PM. Notably, the solar power profiles disclosed the most efficient energy harvest occurred within a four-hour window from 10 AM to 2 PM. However, tall surrounding buildings introduced shadows on the solar panel's surface, limiting energy conversion at other times, underscoring the impact of shading on system efficiency. While the LCOE for the solar system amounted to 2,781 IDR/kWh or 0.185 USD/kWh, nearly double the local electricity provider's rate, this economic challenge was offset by the system's potential to markedly reduce greenhouse gas emissions by an estimated 459 Kg CO^2/year. Consequently, while economic feasibility may pose challenges, this solar system proves to be an environmentally responsible choice, offering an alternative energy source and a tangible reduction in greenhouse gas emissions for a cleaner and more sustainable energy future.

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