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Implementation and Feasibility Study of Solar-powered Streetlighting Systems in Rural Community Area

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Abstract. Green technology plays a pivotal role in establishing a sustainable and secure environment for citizens by introducing smart solar-powered streetlights. Numerous cities have embraced this eco-friendly approach by incorporating solar-powered street lighting systems (SP-SLS) into their infrastructure. Despite its popularity, rural communities, especially in Indonesia, have yet to fully experience the advantages of this green technology. Nonetheless, the effectiveness of SP-SLS installation in relation to geographic conditions and shadowing levels remains unidentified. Addressing this knowledge gap, our study proposes a comprehensive design and feasibility analysis of solar-powered street lighting systems tailored for rural Indonesian communities, with the primary aim of curtailing power consumption and minimizing environmental impact. Our proposed green technology entails the deployment of ten streetlamps, each equipped with an integrated solar generator and an adaptive night-time lighting system employing standard LEDs. Furthermore, our design accounts for varying shadow levels during installation to ensure optimal lighting outcomes. The results of this implementation showcase a remarkable decrease in electricity usage attributed to the adoption of green technology. Additionally, the application of this lighting system demonstrates a reduction in the emission of 4417 kg/year of greenhouse gases into the atmosphere.

1 Introduction

Smart villages represent the latest advancements in rural infrastructure, assuming a pivotal role in the overall development of these regions. By integrating cutting-edge green technologies, villages can effectively optimize resource allocation and enhance the residents' quality of life. Research underscores the potential of smart villages to manage resources efficiently and sustainably in rural communities, encompassing aspects like street lighting. In this regard, it is noted that plans are underway to install approximately 200 thousand of

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streetlamps, with a special focus on supporting the development of villages situated in the Indonesian border area [1].

As of November 2017, the proportion of rural households with access to electricity from state-owned electricity companies had reached 89% [2]. However, this percentage still lags behind the national achievement of 93%. The 2018 target for households to receive electricity service from Indonesian electricity companies was set at 93%. In the context of the Magelang area, with a total of 358,573 households, the count of households lacking access to electricity stands at 39,443. Moreover, there remain 22 hamlets deprived of the benefits of electricity. These hamlets continue to be in darkness, untouched by the era of light. Often situated in remote and challenging terrains like hilly areas with limited infrastructure, these unelectrified hamlets are facing difficulties, notably the absence of proper roads.

The provision of street lighting in rural regions holds significance for the safety, convenience, and economic advancement of the populace [3–4]. Nevertheless, numerous villages confront hurdles concerning street lighting, encompassing issues of uneven distribution and energy efficiency [5]. Considering this, embracing the concept of smart villages becomes imperative for optimizing energy consumption, including the deployment of modern lighting systems tailored to community needs. Given this context, the implementation of smart villages in Indonesia assumes heightened importance, especially for villages grappling with street lighting challenges. In the Indonesian border areas, inadequacies in rural public infrastructure, particularly street lighting, have been noted [6–7]. One illustrative instance is Seworan Village in Magelang, where a collective approach has been adopted to address the scarcity of street lighting installations. Nevertheless, issues persist, stemming from conventional technology utilization, suboptimal lighting, and reliance on non-standard electricity supplies.

In response to the aforementioned concerns, this study proposes a green technology for street lighting development by incorporating solar-powered street lighting systems (SP-SLS) in Seworan Village. The primary aim is to not only generate power for street lighting but also to effectively alleviate environmental impact. In addition, the implementation of this lighting system has proved to be environmentally beneficial, leading to a substantial reduction in the emission of 4417 kg/year of greenhouse gases. This outcome underscores the significance of adopting eco-friendly technologies in addressing environmental concerns and promoting sustainable practices.

2 Study Literature

Seworan Village comprises four hamlets, and its residents have a medium to low income. Despite the presence of numerous public roads connecting the hamlets, these roads lack an installed street lighting system (SLS). It is important to note that the distance between the hamlets is quite significant, encompassing passages through plantations and areas that are susceptible to criminal activities. Considering these factors along with the community's circumstances, we are seeking assistance for the installation of street lighting to mitigate the risk of crime. Collaboration amongst social institutions, particularly those affiliated with Muhammadiyah, is highly anticipated due to the inadequate road access to these 22 hamlets. The active participation of the community in a collaborative effort is equally essential. During the installation and maintenance processes, there will be instances where trees need to be trimmed or possibly removed. Furthermore, the demand for electricity supply to power the street lighting has posed financial burdens, requiring regular contributions from village residents and relying on the installation efforts of one of the residents. An appropriate solution that can be employed is the installation of a solar-powered street lighting system (SP-SLS).

Since 2021, several grants from Government Institutions and Non-Governmental Organizations regarding the procurement of street lighting installations have been provided to Seworan Village. However, the quantity and quality of the street lighting are still very minimal. This can be seen from the low-power lamps (<50 watts) used for street lighting, the light distribution still below 0.5 Cd/m^2 [8], and the electrical installations and illuminated areas only covering 10 percent of the road length. Moreover, the electrical installations are organized through mutual cooperation by collecting contributions from the village community, with a system that relies on one resident's electrical system. Additionally, from an energy consumption perspective, research in 2015 [9] revealed that street lighting on the island of Java consumed 3,448 GWh of electricity and contributed to greenhouse gas emissions of 2.99 million tons of CO_2 into the air, which is expected to continue increasing. The high energy consumption and emissions from street lighting are partly due to the use of inefficient technologies with a relatively short lifespan, and the majority of power plants owned by PLN (89.53%) that supply electricity to street lighting still rely on fossil fuel sources [10]. In light of these issues, the use of solar-powered street lighting, or SP-SLS can be a solution. SP-SLS harnesses the potential of renewable energy in the form of solar energy, which is converted into electrical energy through an environmentally friendly process that does not produce pollution [11]. The lamps used in SP-SLS are LED lamps, which are more energy-efficient and have a longer lifespan.

A number of studies have been conducted on solar-powered street lighting systems, highlighting their effectiveness and advantages. In a study [12], the authors evaluated the performance of a solar street lighting system in terms of energy efficiency and cost-effectiveness. The results demonstrated that the system successfully reduced energy consumption and operational costs compared to conventional grid-powered lighting systems. Furthermore, research by [13] focused on the design and optimization of solar-powered street lighting systems. The study proposed a comprehensive model that considered factors such as solar panel placement, battery capacity, and LED lighting efficiency to maximize system performance. The findings indicated that the optimized system design led to significant energy savings and improved lighting quality. Additionally, a study by [14] investigated the environmental benefits of solar-powered street lighting systems. The research assessed the reduction in greenhouse gas emissions achieved through the use of renewable solar energy instead of conventional grid electricity. The results showed a substantial decrease in carbon dioxide emissions, contributing to the mitigation of climate change. These literature studies provide valuable insights into the design, performance, and environmental impact of solar-powered street lighting systems, highlighting their potential as sustainable and efficient alternatives to conventional lighting solutions.

3 Methodology

By following the methodology, this study aims to address the identified needs, empower the community, and contribute to the overall well-being and development of the targeted area. The methodology used in this study consists of several steps listed below.

3.1 Observation and Planning

The planning phase begins with observing the problems that occur in the field, such as measuring the length of the road, the number of installation points, and the funding plan. Subsequently, communication is conducted with the Seworan Village government to follow up on these issues and find practical and targeted solutions. Based on the simulation data in Figure 1, the geographical location of Seworan Village has a stable solar radiation intensity throughout the year. The intensity slightly decreases from November to April due to the location entering the rainy season. However, the monthly solar radiation intensity remains stable in the range of 130 kWh/m^2 to 190 kWh/m^2, with monthly temperatures ranging from 26.5 ºC to 28.8 ºC. Using these data, the daily solar radiation intensity can be calculated by dividing the monthly intensity by 30 days so that the daily solar radiation intensity remains stable in the range of 4.33 kWh/m^2 to 6.33 kWh/m^2.

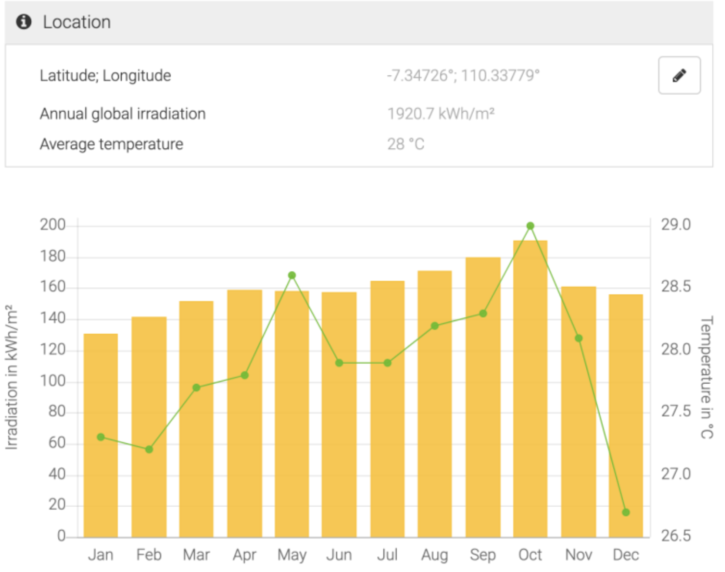


Fig. 1. Projection of potential electricity that can be harvested from solar energy per square meter

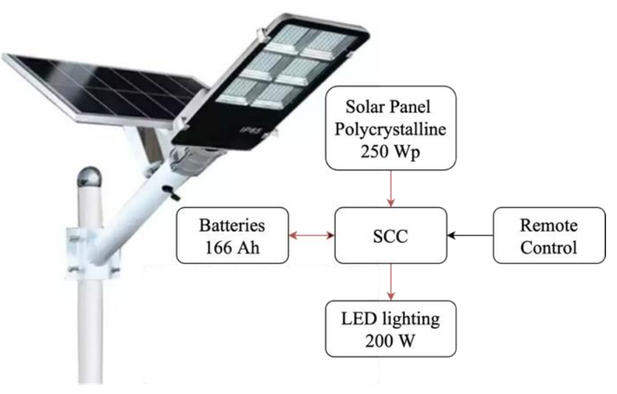


Fig. 2. A system diagram of the proposed solar-powered street lighting system utilizes a solar panel, battery, LED lighting, and an intelligent controller to manage power from the input to the outputs.

3.2 Implementation

Coordination with the Seworan Village Government has been conducted to comprehend their specific requirements. Based on the initial communication, the study has concluded that several sets of solar-powered street lighting installations should be deployed. As a result, the chosen approach incorporates independent electrical power, considering aspects such as installation, power demands, and maintenance. The proposed system is depicted in Figure 2. The process of charging and supplying power to the LED lights will be managed by a Solar

Charge Controller (SSC). During daylight hours, the SCC oversees the conversion of solar energy into electrical power, effectively charging the connected battery packs [15]. This energy accumulation ensures a sustainable power reservoir for the streetlights during night-time operation. Furthermore, the SCC can also be controlled using a remote control to setting power output, thus conserving battery power. To calculate the required capacity of the solar panel and battery for lighting with a power consumption of 200 watts for 10 hours, the daily energy consumption and the desired autonomy or backup time need to be considered.

3.2.1 Daily Energy Consumption

The daily energy consumption can be calculated by multiplying the power consumption of the lamp by the operating hours.

Daily energy consumption = *Power consumption per lamp × Operating hours* ... (1)
= *200 watts × 10 hours*
= *2000 watt-hours or 2 kilowatt-hours (kWh)*

The daily energy consumption value data (2kWh) is still below the daily energy potential/m^2 according to Figure 1 data. The daily energy potential data in the area is in the range of 4.33 kWh to 6.33 kWh so the proposed SP-SLS design is feasible to be realized.

3.2.2 Solar Panel Capacity

To meet the daily energy consumption, the efficiency and the available sunlight in the location need to be considered. An average of 8 peak sun hours per day for the location. In this case, the required solar panel capacity can be calculated as follows:

Required solar panel capacity = *Daily energy consumption (kWh) / Peak sun hours* ... (2)
= *2 kWh / 8 hours*
= *0.25 kilowatts peak (kWp)*
= *250 watts peak*

Therefore, a solar panel is needed with a capacity of approximately 0.25 kWp to meet the daily energy consumption of 2 kWh, considering an average of 8 peak sun hours per day.

3.2.3 Battery Capacity

To determine the battery capacity, we need to consider the desired autonomy or backup time. Assuming you want the system to provide power for 1 night without solar energy, the required battery capacity can be calculated as follows:

Required battery capacity = *Daily energy consumption (kWh) × Autonomy (in days)* ... (3)
= *2 kWh × 1 day*
= *2 kilowatt-hours (kWh)*
= *166 Ah*
= *12 V x 55 Ah*

Batteries are needed with a capacity of approximately 2 kWh to provide 1 night of autonomy, considering a daily energy consumption of 2 kWh. These calculations yield an estimate that three packs of 55 Ah, 12-volt batteries are required. These calculations provide an estimation that three pack of batteries with capacity of 55 Ah and 12 volt are need. Actual system design may vary depending on factors such as geographical location, solar irradiance, battery efficiency, and system losses.

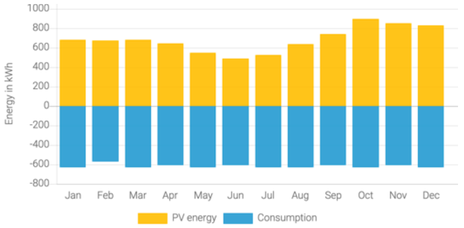
3.3 Implementation and Sustainability

Previously, community-based efforts had led to the installation of several SLS units; however, these devices only illuminated half of the village road's length. The conventional streetlights that were installed also lacked attention to occupational health and safety measures. Furthermore, the power supply for these streetlights was directly drawn from the state electricity company's installation, posing significant risks, and failing to meet established standards. The proposed SP-SLS offers the potential to simplify the installation process for such devices. This development program holds substantial prospects for further advancements, including the integration of IoT-based monitoring components accessible to authorized personnel.

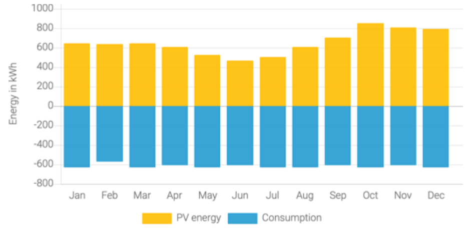
The program has designated the dates of May 19 to 21, 2023, for its execution in the targeted area. Initially, a trial of an SP-SLS unit was conducted to ensure its optimal functionality. The results of the test affirm that the SP-SLS device is dependable in providing nighttime illumination and has a lasting capacity of 10 hours. Subsequently, the development of 10 SP-SLS units ensued. These 10 solar-powered street lighting systems (SP-SLS) units were then installed in Seworan Village, Grabag, Magelang, located in Central Java. The deployment of each unit aimed to evaluate the longevity and compatibility of SP-SLS in illuminating the village road vicinity.

4 Experimental Results

Solar power generation is a renewable energy technology that harnesses the energy from the sun to generate electricity. It relies on the photovoltaic effect, where solar panels made of semiconducting materials convert sunlight into direct current (DC) electricity. This DC electricity is then converted into alternating current (AC) electricity through an inverter, which can be used to power homes, businesses, and even entire communities. Solar power offers numerous benefits, including reduced reliance on fossil fuels, lower greenhouse gas emissions, and long-term cost savings. However, the efficiency of solar power generation can be affected by various factors, one of which is the level of shadow or shading.



(a)



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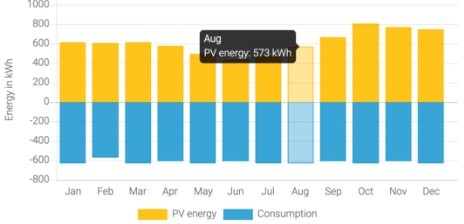

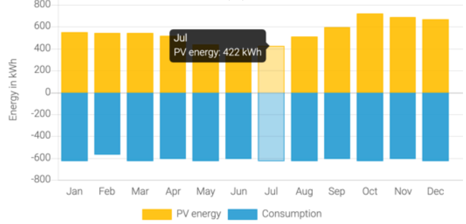

(c) (d)

Fig. 3. The simulation results of generating electricity from solar energy using ten SP-SLSs. The output power will vary each month depending on variations in the shadow level of (a) 0%, (b) 5%, (c) 10%, and (d) 20% in the SP-SLS installation area.

Shading plays a critical role in the efficiency of solar power systems, as it can significantly diminish the energy output of solar panels by obstructing or reducing the amount of sunlight that reaches the photovoltaic cells. Even minor shading on a small portion of a solar panel can have a substantial impact on its overall performance. Shadows can be caused by neighbouring buildings, trees, or other objects that cast their shadows on the solar panels. Careful consideration of the positioning and placement of solar panels is essential to minimize shading and maximize sun exposure throughout the day. Advanced technologies like bypass diodes can be employed to mitigate the effects of partial shading, enabling solar panels to continue generating electricity efficiently, even when specific sections are shaded. It is imperative to conduct thorough site analysis, implement appropriate design measures, and perform regular maintenance to ensure optimal solar power generation and minimize the impact of shading on the overall performance of the system.

In the context of the implementation of SP-SLS in remote area, the interplay of shade level, angle, and geographical factors has been investigated. The village benefits from abundant sunlight due to its equatorial location. However, the shadow level and angle play a crucial role in determining the effectiveness of solar power generation. Simulation results in Figure 3 demonstrate that installing 10 SP-SLSs in open areas yields efficient electricity generation from solar energy. Higher shadow levels, such as 5%, result in a slight decrease in power output, while at 10% shadow level, the decrease becomes more significant, rendering the energy generated insufficient to meet the required illumination time of less than 10 hours. In darker conditions, such as 20% shadow level, the average energy generated dramatically drops to less than 600 kWh per month. By carefully analysing these factors, adjustments can be made to the placement and orientation of the solar panels to ensure maximum sun exposure and increase overall energy output [13, 16]. However, field conditions in Seworan Village show that the installation of solar panels has been carried out randomly in various locations, resulting in an average shadow level ranging from 0% to 20%. The duration of lighting also varies depending on the installation location, aligning with the previously conducted simulations [17]. In addition, simulations show that annually, 4,417 kg of carbon dioxide can be removed from the atmosphere by using this green technology. These results indicate that the location of the village has a large potential for solar energy so that it is feasible to be utilized as a source of energy for street lighting.

5 Conclusions

The implementation of solar-powered street lighting systems brings forth a plethora of advantages. It presents an environmentally conscious solution by tapping into renewable solar energy, thereby lessening the dependence on fossil fuels. The economic analysis of such systems highlights the potential for substantial long-term savings, as it eliminates the necessity for grid-based electricity. This not only curtails operational costs but also diminishes maintenance expenditures inherent in conventional street lighting setups. Solar-powered street lighting demonstrates particular efficacy in remote locales like Seworan Village, where access to consistent electricity infrastructure may be uncertain. By harnessing solar power, such areas can enjoy a dependable and sustainable lighting source, augmenting safety and enhancing the residents' quality of life. According to simulations, the installation of ten SP-SLSs in the village led to a reduction of 4,417 kg/year in CO^2 emissions. Traditional street lighting systems, reliant on fossil fuels, substantially contribute to greenhouse gas emissions. By transitioning to solar energy, the reliance on such non-renewable resources is diminished, the proposed design is feasible to be implemented. This transition not only curbs carbon emissions but also aids in mitigating the effects of climate change, thereby promoting a healthier environment. To encapsulate, the incorporation of solar-powered street lighting systems offers an economically viable, dependable, and eco-conscious resolution for remote areas like Seworan Village. By harnessing solar power, these systems ensure efficient illumination, lessen dependence on the grid, and contribute to the reduction of CO^2 emissions. In this way, they not only promote a sustainable and environmentally responsible future but also present a path toward enhancing the overall well-being of such communities.

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