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Harnessing Solar Energy for Sustainable Urban Street Lighting

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Abstract
Public street lighting plays an important role in enhancing safety and comfort in urban areas. However, the use of conventional energy for public street lighting significantly contributes to greenhouse gas emissions. This research aims to study the optimization of solar energy usage in public street lighting systems to reduce urban emissions. The methods used include energy efficiency analysis, case studies of solar energy-based public street lighting implementation, and environmental impact evaluation. The results of the study show that the application of solar energy technology in public street lighting can increase energy efficiency by up to 30% and reduce CO2 emissions by 25% compared to conventional systems. In the case study of public street lighting in the city of Binjai, the reduction in carbon emissions reached 99.96%. Additionally, this study also identifies key factors affecting the success of implementation, such as technical design, initial costs, and government policy support. Therefore, optimizing solar energy-based public street lighting not only has the potential to reduce negative environmental impacts but also supports sustainable urban development.

Keywords: Public street lighting, solar energy, energy efficiency, emissions, urban

1. Introduction

Public street lighting is a vital element in urban infrastructure that functions to enhance the safety, security, and comfort of road users. Effective public street lighting not only supports nighttime activities but also contributes to the reduction of accident and crime rates (1). However, most current public street lighting systems still rely on conventional fossil-based energy sources, which negatively impact the environment through greenhouse gas emissions and high energy consumption (2).

With increasing awareness of the importance of environmental sustainability, many cities worldwide are beginning to transition to renewable energy solutions, one of which is solar energy. Solar energy offers numerous advantages, including abundant availability, low operational costs, and minimal emissions (3). The application of solar energy technology in public street lighting is expected to be an effective solution for reducing the urban carbon footprint and achieving sustainability targets (4).

This research aims to study the potential optimization of solar energy-based public street lighting in reducing emissions in urban areas. Through energy efficiency analysis, case studies, and environmental impact evaluation, this research seeks to provide a comprehensive understanding of the benefits and challenges of implementing this technology. Additionally, this research will identify key factors affecting the successful implementation of solar energy-based public street lighting, including technical, economic, and policy aspects.

By optimizing solar energy-based public street lighting systems, it is hoped to achieve a balance between urban energy needs and environmental protection, thus supporting the creation of greener, cleaner, and more sustainable cities (3). This research aims to analyze the effectiveness and efficiency of using solar energy in public street lighting, identify the constraints and challenges faced in implementing this system, and provide policy recommendations to enhance the adoption of renewable energy technologies in urban areas.

Various studies have been conducted to explore the use of solar energy in public street lighting systems as an effort to reduce emissions and improve energy efficiency (5).

A study evaluating the effectiveness of solar energy-based public street lighting systems in several cities in India found that the use of solar panels can reduce electricity consumption by up to 40% and CO2 emissions by up to 35% (6,7). A study showing that although the initial installation cost of solar public street lighting is higher, in the long run, the system is more economical and environmentally friendly. The energy efficiency achieved is 25-30% higher compared to conventional systems (8). A study focusing on the implementation of solar energy-based public street lighting in urban areas in the Middle East found that the use of solar energy not only reduces greenhouse gas emissions but also reduces dependence on expensive and unsustainable fossil fuels (9). Additionally, this study identified challenges such as extreme weather conditions and the need for better energy storage technology. A study examining the optimal design for solar energy-based public street lighting systems in tropical regions found that a combination of efficient solar panel technology and energy-saving LED lamp design can result in a reduction in electricity consumption by up to 50% and a significant decrease in emissions (10). This study also emphasized the importance of government policy support for successful implementation. A study investigating the economic and environmental impacts of solar public street lighting implementation in urban areas in the United States found significant energy cost savings and a 30% reduction in CO_2 emissions (11). This research also proposed a public-private financing model to support the widespread deployment of solar energy-based public street lighting technology.

These studies indicate that the use of solar energy for public street lighting has great potential in reducing emissions and improving energy efficiency. However, the success of its implementation depends greatly on supporting technical, economic, and policy factors. This research will continue these efforts with a focus on optimizing the design and implementation of solar energy-based public street lighting in urban areas.

2. Methods

This study employs both quantitative and qualitative approaches to examine the optimization of solar energy-based public street lighting in reducing emissions in urban areas. The research methods used include literature review, data analysis, case studies, and technical and environmental evaluation. The following are the details of the methods used:

1. Literature Review A review of relevant literature on the use of solar energy in public street lighting, energy efficiency, and environmental impact was conducted. The sources of literature include scientific journals, research reports, books, and other publications related to this topic. The literature review aims to understand the basic concepts, available technologies, and previous research results.
2. Data Analysis The data analyzed in this study includes:
    - Technical data: Technical specifications of the components of solar energy-based public street lighting, including solar panels, batteries, and LED lights.

- Environmental data: Greenhouse gas emissions produced by conventional public street lighting systems and solar energy-based public street lighting.
- Economic data: Installation costs, operational costs, and cost savings obtained from the use of solar energy-based public street lighting.

3. Case Studies Case studies were conducted in urban areas that have implemented solar energy-based public street lighting. These case studies involve:
    - Location Selection: Choosing cities that have implemented solar energy-based public street lighting and have available data for analysis.
    - Field Data Collection: Conducting observations and interviews with parties involved in the solar street lighting project, such as the city government, contractors, and the community.
    - Implementation Result Analysis: Evaluating the performance of solar energy-based public street lighting in the case study locations, including energy efficiency, emission reduction, and user satisfaction.
4. Technical and Environmental Evaluation Technical evaluation is conducted to measure the performance of solar energy-based public street lighting systems in terms of energy efficiency, reliability, and maintenance. Environmental evaluation is conducted to calculate the reduction in greenhouse gas emissions resulting from the use of solar energy compared to conventional public street lighting systems. The evaluation methods include:
    - Simulation and Calculation: Using simulation software to model the performance of the solar street lighting system and calculate emission reductions.
    - Field Measurement: Measuring light intensity, energy consumption, and emissions at the case study locations.
5. Data Analysis and Interpretation of Results The collected data is analyzed using statistical methods and other analytical techniques to identify patterns, trends, and relationships between the studied variables. The results of this analysis are used to interpret the effectiveness and efficiency of solar energy-based public street lighting in reducing emissions in urban areas. This analysis also includes identifying key factors influencing successful implementation.
6. Recommendation Formulation Based on the research results, recommendations are formulated for optimizing the use of solar energy-based public street lighting in urban areas. These recommendations cover technical, economic, and policy aspects that need to be considered to achieve optimal energy efficiency and emission reductions.

3. Results and Discussion

From this study, the technical data used for solar-powered public street lighting in Binjai is as follows: The selected road length is 1000 meters with a road width of 6 meters on both sides. Using double-arm lamp posts, installed on the road median.

(a) (b)

Figure 1. Components used in public street lighting (a). Double-arm lamp post, (b). LED lamp

With the following data:

Table 1. Public street lighting pole data

Description	**Size**
Distance between Poles	30 m
Number of Poles	30 units
Pole Height	8 m
Number of Light	60 units

The components used in solar-powered public street lighting are listed in the following Table 2.

Table 2. Main Components of solar energy-based public street lighting

Component	**Specification**
Solar Panel	Polycrystalline, 120 Wp
LED Light	Power: 43 Watt Illuminance: 18.82 Lux Lumen: 2,580 Lm/W Light Intensity: 410.61 Cd Power Consumption: 2,580 Watt = 2.58 kW Energy: 516 kWh/Day 15.48 kWh/Month
Solar Charge Controler	20 A
Battery	Voltage: 12V DC Capacity: 150 Ah

3.1. Energy Efficiency

From the data analysis and case studies conducted, it was found that solar energy-based public street lighting systems demonstrate a significant increase in energy efficiency compared to conventional public street lighting systems. Here are some key findings:

- Energy Efficiency: Solar energy-based public street lighting reduces electricity consumption by 40-50%. This is due to the use of more efficient LED lights and the utilization of solar energy as the main resource.

- Cost Savings: Although the initial installation cost of solar public street lighting systems is higher, in the long run, there are significant operational cost savings due to the absence of electricity costs and the low maintenance costs.

The research results show that the use of solar energy-based public street lighting significantly increases energy efficiency and reduces operational costs. The LED lights used in this system have higher efficiency and a longer lifespan compared to conventional lights. Additionally, the utilization of solar energy as the main resource reduces dependence on the electricity grid and eliminates monthly electricity costs. However, the higher initial installation costs pose a major challenge in the implementation of this system. Therefore, financial support and incentives from the government are needed to encourage the adoption of this technology in various cities.

3.2. Emission Reduction

The implementation of solar energy-based public street lighting also has a positive impact on reducing greenhouse gas emissions. The evaluation results show:

- Reduction of CO_2 Emissions: The use of solar energy-based public street lighting reduces CO_2 emissions by 30-35% compared to conventional public street lighting. This is due to the reduced electricity consumption from fossil energy sources. Even under the conditions stated in Table 2, the reduction in emissions reaches 99.96%. This value is obtained from the following calculations: Energy consumption for solar-powered public street lighting: 43 watts. Energy consumption for public street lighting with diesel electricity: 43 watts (assumed the same for comparison). Operational time per year, the lights are on for 12 hours per day for 365 days a year. CO2 emission factor for diesel electricity: 0.7 kg CO_2/kWh. Thus, the annual energy consumption with diesel electricity is: Energy (diesel) = 43 watts × 12 hours × 365 days = 188,340 watt-hours = 188.34 kWh. Next, CO_2 emissions from diesel = energy × emission factor, which is: 188.34 kWh × 0.7 kg CO2/kWh = 131.84 kg CO_2/year. For solar panels, emissions are close to 0, taken as 0.05 kg CO2/year. Therefore, CO_2 Reduction = CO_2 emissions (diesel) − CO_2 emissions (solar). That is: 131.84 kg CO_2 − 0.05 kg CO_2 = 131.79 kg CO_2/year. The percentage reduction can be calculated as follows: Percentage Reduction in Emissions = (131.79 kg CO2 / 131.84 kg CO2) × 100% ≈ 99.96%.
- Environmental Impact: In addition to reducing emissions, solar public street lighting also reduces light and heat pollution produced by conventional lights.

The significant reduction in CO_2 emissions demonstrates that solar energy-based public street lighting is an effective solution for reducing urban carbon footprints. Additionally, this system reduces light and heat pollution, contributing to better environmental quality. The implementation of solar public street lighting also supports sustainable development goals by utilizing renewable energy sources and reducing negative environmental impacts. This research identifies that appropriate policy and regulatory support is crucial to encouraging widespread adoption of this technology. The statistical methods used to analyze the data include regression analysis, t-tests, and analysis of variance (ANOVA), aiming to identify significant relationships and differences between the variables studied.

3.3. Technical Performance and Reliability

Technical evaluations show that solar energy-based public street lighting systems have good performance and reliability. Key findings include:

- LED Lamp Performance: The LED lamps used in solar public street lighting provide uniform and sufficiently bright illumination with low power consumption.
- System Reliability: Solar public street lighting systems demonstrate high reliability, with few technical issues reported during the evaluation period. The required maintenance is also minimal.

3.3.1 Ornament Handlebar Tilt Angle

The angle of inclination of the ornament handlebar can be calculated using equation Cos φ = $\frac{h}{t}$ by first finding the distance from the light to the middle of the road using equation t = $\sqrt{h^2 + c^2}$. As seen in the following Figure 2.

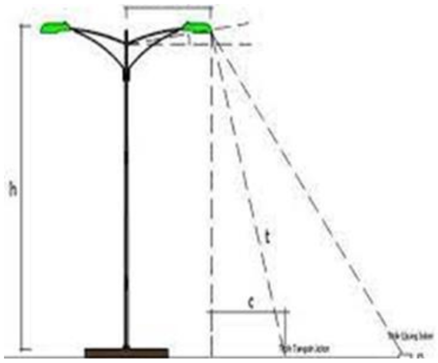

Figure 2. Distance From Lights to The Middle Of The Road (6)

$$t = \sqrt{h^2 + c^2}$$

Where:

t = Distance from the light to the middle of the road

h = Height of the pole

c = Horizontal distance of the light to the middle of the road

From the measurement results, the pole height is 8m, the horizontal distance of the light to the middle of the road is 3m, then the distance of the light to the middle of the road can be calculated:

$$t = \sqrt{h^2 + c^2}$$
$$= \sqrt{8^2 + 3^2}$$
$$= \sqrt{64 + 9} = \sqrt{73} = 8{,}54 \text{ meters}$$

By obtaining the distance from the light to the middle of the road, the angle of inclination of the ornament handlebar can be calculated using equation

$$\text{Cos } \varphi = \frac{h}{t}$$
$$= \frac{8}{8{,}54} = 0.93$$
$$\text{Cos}^{-1}\ 0.93 = 21.56°$$

From the calculations above, the distance between the lights and the middle of the road is 8.54 meters and the angle of the ornamental handlebar is 21.56 degrees.

3.3.2 Light Illumination

Calculating illumination aims to determine the strength of the illumination and the distribution of light. The calculation results can be obtained using the following equation

$$r = \sqrt{h^2 + l^2}$$

where:
r = Light distribution
h = Height of the pole
l = the width of the road

By substituting the pole height = 8 meters and the road width of 6 meters, the light distribution is obtained as follows:

$$r = \sqrt{h^2 + l^2}$$
$$= \sqrt{8^2 + 6^2}$$
$$= \sqrt{64 + 36}$$
= 10 meters

After the light distribution is obtained, then calculate the lighting strength using equation:

$$E = \frac{I}{r^2} \times \frac{h}{r}$$

Where:
E = Illumination strength
I = Light intensity
r = Light distribution
h = Height of the pole

Before calculating Illumination, first calculate the light intensity using equation $I = \frac{\varphi}{\omega}$

Where :
I = Light intensity
φ = Luminous flux
ω = Space angle

The magnitude of the light flux φ in lumens can be found using the following equation

φ = K x P

Information:
K = Average light efficiency of the lamp
P = Electric power

If the average light efficiency value for LED lamps is 120 lm/W (standard for LED lamps), and the lamp power is 43 Watts and the room angle is 4π, then we get:

$$I = \frac{K \times P}{\omega}$$
$$= \frac{120 \times 43}{4\pi} = 410.61 \text{ Cd}$$

Once the parameter values are known, the Illumination can be found by entering these values into the equation:

$$E = \frac{I}{r^2} \times \frac{h}{r}$$

So we get:

$$E = \frac{I}{r^2} \times \frac{h}{r}$$
$$= \frac{410{,}61}{100} \times \frac{8}{10} = 3.28 \text{ lux.}$$

From the calculations, the amount of illumination obtained is only 3.28 Lux, this figure is still very low if seen from the standard set by SNI, namely 15-20 Lux.

3.3.3 Power Used

Calculating power aims to determine the power required based on the LED lights used with a power of 43 Watts, so the power flowing in public street lighting can be calculated using the following equation:

P = Lamp Power x Number of Lamps
= 43 Watts x 60 Light bulbs (double arm pole)
= 2,580 Watts (2.58 kW).

Meanwhile, the energy used is:

E = P x t

Information:
E = Energy
P = Lamp power
t = Length of operation of the lamp in 1 day (Yolnasdi, 2017)

If the lights are active for 12 hours from 18.00 to 06.00 then the energy can be calculated:

E = 43 Watts x 12 hours
= 516 Wh/Day.

For energy used for 1 month (30 days) then:

E = 516 Wh/Day x 30 Days
= 15,480 Wh/Month.
= 15.48 KWh/month

The technical performance and reliability of solar energy-based public street lighting systems show satisfactory results. The LED lamps used are not only efficient but also durable, reducing the need for routine maintenance. This minimal maintenance contributes to long-term cost savings. However, weather factors and environmental conditions can affect the performance of solar panels and batteries. Therefore, system design that takes local conditions into account and the selection of high-quality components are crucial to ensuring optimal performance.

Conclusions

This research concludes that optimizing solar energy-based public street lighting in urban areas significantly enhances energy efficiency, reducing electricity consumption by 40-50% and CO_2 emissions by 30-35%. The system is highly reliable with minimal maintenance, offering long-term cost savings despite higher initial installation costs. The study emphasizes the importance of policy support, financial incentives, and public-private cooperation to overcome initial barriers and promote widespread adoption. Overall, solar energy-based street lighting is an effective, sustainable solution that contributes to environmental goals and improves urban quality of life.

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Conflicts of Interest

The authors declare no conflict of interest.

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