Performance and Efficiency of Solar Energy-Based Public Street Lighting in Reducing Urban Emissions

Zuraidah Tharo[1,a)], Eddy Sutejo[2, b)],Gavana Mustaqim SK[3, c)]
[1, 2, 3] *Faculty of Science and Technology, Universitas Pembangunan Panca Budi,*
Jl. Gatot Subroto Km 45, Medan, North Sumatra, Indonesia
a)zuraidahtharo@dosen.pancabudi.ac.id
b)*e_sutejo69@gmail.com*
c)gavana.mustaqim01@gmail.com

Abstract - Solar energy-based public street lighting has become an innovative solution in reducing urban emissions while improving energy efficiency. This study aims to evaluate the performance and efficiency of solar energy-basedpublic street lighting in an urban context. Through data analysis and case studies in several major cities, this research measures the contribution of this technology to reducing carbon emissions and operational costs. The results show that solar energy-based public street lightingsignificantly reduces emissions and increases energy and cost efficiency. Additionally, this study identifies factors affecting the performance of this system, including climate conditions, solar panel technology, and maintenance management. These findings are expected to encourage broader adoption of solar energy-based public street lightingtechnology as a strategic step towards sustainable urban development.
Keywords: Innovation, Solar Energy-Based Public Street Lighting, Emissions

INTRODUCTION

Environmental issues, particularly greenhouse gas emissions, are a major concern in sustainable urban development. Cities, as centers of human activity, significantly contribute to increasing carbon dioxide (CO2) emissions, mostly from fossil energy consumption. One sector contributing to significant energy consumption is public street lighting. Efficient and environmentally friendly public street lightingis urgently needed to reduce negative environmental impacts.

Solar energy, as a renewable energy source, offers a potential solution to this issue. The application of solar energy-based public street lightingnot only reduces dependence on fossil fuels but also decreases CO2 emissions generated from fuel combustion. This technology utilizes abundant and emission-free solar energy, which can be converted into electricity for street lighting.

This research focuses on evaluating the performance and efficiency of solar energy-based public street lighting in an urban context. The analysis aims to understand the effectiveness of this technology in reducing emissions and increasing energy and operational cost efficiency. The study includes data collection from several major cities that have implemented solar energy-based public street lightingand identifies factors affecting the system's performance, including climate conditions, the technology used, and maintenance management.

The objective of this research is to provide a comprehensive overview of the benefits and challenges of implementing solar energy-based public street lightingin urban areas. The results are expected to encourage wider adoption of this technology as part of sustainable and environmentally friendly urban development strategies.

Solar energy is one of the most potential and clean renewable energy sources available on this planet. It is generated from solar radiation, which can be converted into other forms of energy, such as heat and electricity, through various technologies. Some basic concepts crucial to understanding solar energy include the photovoltaic process, solar collector technology, and the benefits and challenges associated with using solar energy.

1. **Photovoltaic Process**

The photovoltaic process is a method in which energy from sunlight is directly converted into electricity using semiconductor materials. This process occurs within a solar cell, which consists of layers of semiconductor material, usually silicon. When sunlight hits the solar cell, photons from the sunlight are absorbed by the semiconductor material. This causes electrons in the material to gain energy and move freely, creating an electric current. This flow of electrons can then be used to generate electricity for various applications.

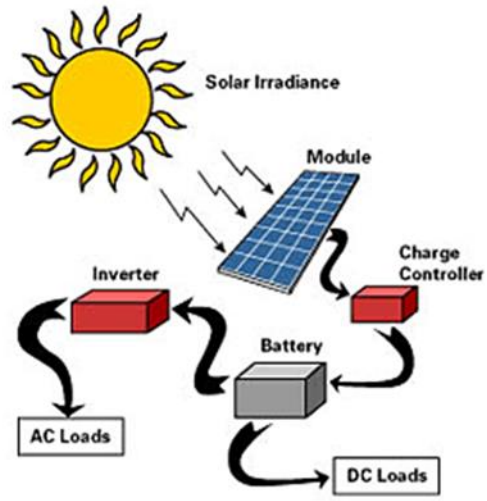

Figure 1. Photovoltaic Process

2. **Solar Collector Technology**

Solar collector technology refers to devices used to capture and convert solar energy into thermal energy. There are two main types of solar collectors: thermal solar collectors and photovoltaic solar collectors. Thermal solar collectors are used to heat water or air for domestic or industrial purposes, while photovoltaic solar collectors are used to generate electricity. This technology typically involves the use of solar panels installed on rooftops or open areas that receive direct sunlight.


Figure 2. Solar Panels

3. Benefits of Solar Energy

Solar energy offers a number of benefits, including:

a. **Environmentally Friendly:** Solar energy does not produce greenhouse gas emissions or other pollutants, thus helping to reduce negative environmental impacts.
b. **Renewable Energy Source:** The sun is an energy source that will not run out for billions of years, making it a very reliable energy source.
c. **Energy Cost Reduction:** Although the initial cost of installing solar panels can be high, the use of solar energy can reduce long-term electricity costs.
d. **Reliability and Energy Independence:** Solar energy can be used in remote locations without access to the power grid, providing energy independence for users.

4. Challenges of Solar Energy

Despite its many benefits, there are some challenges in using solar energy:

a. **Initial Cost:** The initial investment for installing solar energy systems is still relatively high, although this cost continues to decrease with technological advancements.
b. **Intermittency:** The availability of solar energy depends on the weather and time of day, with reduced electricity production on cloudy days or at night.
c. **Efficiency:** The efficiency of converting solar energy to electricity remains an active area of research, with the aim of increasing the amount of energy that can be generated.

5. Technological Developments and Applications

Advances in solar energy technology continue to evolve, with innovations in semiconductor materials, solar panel design, and energy storage systems. In addition to being used for small-scale electricity generation such as for households, solar energy is also applied on a large scale through solar power plants and smart grids that integrate various renewable energy sources.

A deep understanding of solar energy theory and technology is a crucial foundation for optimizing its use in various applications, including solar energy-based public street lighting, which is the focus of this research.

Calculations in Solar Energy

To design and optimize a solar energy system, various calculations need to be performed. Some key calculations include:

1. Calculation of Solar Energy Potential

Solar energy potential at a location can be calculated using solar radiation. Solar radiation is expressed in kWh/m²/day. Solar energy potential is calculated by the equation:

$$\text{Potential Energy (kWh)}=\text{Solar Panel Area (m2)}\times\text{Solar Radiation (kWh/m}^2\text{/day)}\times\text{Panel Efficiency} \quad (1)$$

2. Calculation of Solar Panel Capacity

Solar panel capacity is the total amount of power that a solar panel can produce. This capacity is usually expressed in watt-peak (Wp). The formula:

$$\text{Solar Panel Capacity (Wp)}=\text{Solar Panel Area (m}^2\text{)}\times\text{Panel Efficiency}\times 1000 \quad (2)$$

3. Calculation of Energy Output

The daily energy output of a solar panel system can be calculated by multiplying the panel capacity by the average number of hours of sunlight per day.

$$\text{Energy Output (kWh)}=\text{Panel Capacity (kWp)}\times\text{Sunlight Hours (hours/day)} \quad (3)$$

4. Calculation of the Number of Solar Panels Required

To meet certain energy needs, the number of solar panels required can be calculated by:

$$\text{Number of panels}=\frac{daily\ energy\ requirements(kWh)}{energy\ output\ of\ each\ panel\ (kWh)} \quad (4)$$

5. Calculation of System Efficiency

Solar energy system efficiency includes several factors such as solar panel efficiency, inverter efficiency, and system losses. The equation for total system efficiency is:

$$\text{System Efficiency}=\text{Panel Efficiency}\times\text{Inverter Efficiency}\times\text{System Loss Factor} \quad (5)$$

6. Calculation of Return on Investment (ROI)

The ROI for a solar energy system can be calculated to determine economic feasibility. The equation:

$$\text{ROI (\%)}=\frac{annual\ savings}{Investment\ costs}\text{x}100 \quad (6)$$

7. Calculation of Avoided Emissions

To calculate the CO_2 emissions avoided by using solar energy, the emissions factor from the conventional energy sources that are replaced is used. The equation:

$$CO_2\text{ Emissions Avoided (kg)}=\text{Energy Output (kWh)}\times\text{Emission Factor (kg /kWh)} \quad (7)$$

II. RESEARCHMETHOD

The research methodology used in evaluating the performance and efficiency of solar energy-based public street lighting in reducing urban emissions includes several stages, namely literature study, data collection, data analysis, and result interpretation. The details of the research methodology used are as follows:

1. Literature Study The initial stage of the research involves a literature study to understand the basic concepts, technology, and recent developments related to solar energy-based public street lighting. The literature study includes:

- Scientific articles, journals, and publications related to solar energy and public street lighting.
- Books and technical reports on the design and implementation of solar energy systems.
- Case studies from various cities that have implemented this technology.

2. Data Collection Data collection is carried out through several methods to obtain comprehensive information:

- **Primary Data:** Direct observations in the field, performance measurements of solar energy-based PJU systems, and interviews with related parties such as project managers and road users.
- **Secondary Data:** Collecting data from official sources such as local governments, energy companies, and research institutions. This data includes energy usage statistics, emission data, and technical information about the PJU systems used.

3. Case Studies Selecting several major cities as case studies for in-depth analysis of the application of solar energy-based PJU. These cities are chosen based on criteria such as implementation scale, diverse climatic conditions, and available data. The case studies include:

- Evaluation of the existing condition of PJU before and after the application of solar energy.
- Analysis of the performance and energy efficiency of solar energy-based PJU systems.

- Measurement of achieved emission reductions.

4. Data Analysis Data analysis is conducted with several approaches:

- **Quantitative Analysis:** Using statistical methods to process numerical data collected. This analysis includes calculating energy efficiency, emission reductions, and operational cost savings.
- **Qualitative Analysis:** Interpreting non-numerical data such as interviews and field observations to understand the factors influencing system performance.
- **Modeling and Simulation:** Using simulation software to model the performance of solar energy-based PJU systems under various conditions and test different scenarios.

5. Result Interpretation The data analysis results are interpreted to answer research questions and achieve research objectives. This interpretation includes:

- Assessing the extent to which solar energy-based PJU can reduce urban emissions.
- Identifying factors that influence the performance and efficiency of the system.
- Formulating recommendations to improve the implementation and efficiency of solar energy-based PJU.

6. Validation and Verification Validation of the research results is done by comparing the findings with similar literature and case studies. Data verification is carried out to ensure the accuracy and consistency of the collected data.

7. Reporting and Publication The research results are compiled into a comprehensive report and published in scientific journals and conferences to share the findings with the academic community and practitioners in the field of renewable energy.

With this systematic and comprehensive research methodology, it is expected that a clear picture can be obtained regarding the performance and efficiency of solar energy-based public street lighting and its contribution to reducing urban emissions.

III. RESULTS AND DISCUSSION CONTAIN

1. Research Results

A. Performance of Solar Energy-Based Public Street Lighting

Field observations and measurements indicate that solar energy-based Public Street Lightinggenerally perform well under various urban climate conditions. Some key findings include:

- **Energy Production:** The average daily energy production per solar panel reaches 4-5 kWh in areas with high solar radiation and about 3-4 kWh in areas with moderate solar radiation.
- **Operating Time:** Thesolar energy-based Public Street Lighting system is able to operate optimally for 10-12 hours each night, with sufficient energy reserves for cloudy days.
- **Solar Panel Performance:** The efficiency of solar panels ranges from 15-18%, depending on the technology used and environmental conditions.

B. Energy Efficiency

The energy efficiency of solar energy-based Public Street Lightingcompared to conventional shows significant results:

- **Energy Savings:** Solar energy-basedPublic Street Lighting systems save about 70-80% of electrical energy compared to conventionalPublic Street Lighting using the electrical grid.
- **Cost Efficiency:** Although the initial installation cost is higher, the operational and maintenance costs of solar energy-based Public Street Lightingare lower, resulting in long-term cost savings of up to 50%.

C. Emission Reduction

Emission data analysis shows significant carbon emission reductions:

- **Avoided Emissions:** The average CO_2 emission reduction is 0.5 kg per kWh of energy generated by the solar energy-based Public Street Lightingsystem.
- **Total Emission Reduction:** For one city with 1,000 solar energy-basedPublic Street Lighting, the emission reduction reaches approximately 500 tons of CO_2every year.

2. Discussion

A. Factors Influencing Performance

Several factors influence the performance of solar energy-based Public Street Lighting in urban areas, including:

- **Climate Conditions**: High solar radiation increases energy production, while cloudy or rainy conditions reduce system efficiency.

Light Intensity Obtained During the Study:$I = \frac{\varphi}{\omega}$

Where:

I = Light intensity in candela (cd)

ϕ = Light flux in lumens (lm)

ω = Solid angle (steradian)

Because the magnitude of the light flux φ in lumens is not yet known, using the light flux equation it can be calculated as follows:

$$\varphi = Lm/W \times P$$

Where :
Lm/W = Average light efficiency of the lamp = 120 Lm/w
P = Electric power = 43 W
then we get:φ = Lm/W x P
= 120 x 43
= 5160 lumen

Next, the light intensity price can be found by substituting the lumen value above with the spatial angle ω = 4π.

The light intensity is:$I = \frac{\text{Lm/W x P}}{\omega}$

$$= \frac{120 \text{ x } 43}{4\pi} = 410{,}61 \text{ Cd}$$

From the results of this calculation, it can be concluded that the product of lumens and lamp power is directly proportional to the light intensity, that is, the greater the lumens and lamp power, the greater the intensity produced, and vice versa, the smaller the lumens and lamp power, the smaller the intensity.

Next, calculating illumination aims to determine the distribution of light. The distribution of light can be found by using the Pythagorean equation, or calculating the diagonal r, namely:

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

Where: h = height of pole = 8 meters
l = Road width = 6 meters
r = Light distribution
so:: $r = \sqrt{8^2 + 6^2}$

$$= \sqrt{64 + 36}$$

= 10 meters

So with a light distribution radius of 10 meters, Illumination can be calculated as follows:

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

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

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

$$= \frac{410{,}61}{100} \text{ x } \frac{8}{10} = 3{,}28 \text{ / } 32{,}84 \text{ lux.}$$

Then calculating the luminance/lumen aims to determine the light flux φ in lumens emitted by a light source,

P = Lamp power x Number of light bulbs
P = 43 Watts x 60 Light bulbs
= 2,580 Lm/W

Lumen is a unit for measuring light intensity at a light source.

- **Solar Panel Technology:** The use of the latest high-efficiency solar panel technology can significantly improve system performance.
- **Maintenance Management:** Regular maintenance and cleaning of solar panels from dust and dirt are important to maintain efficiency.

B. Challenges and Solutions

Although the research results show good performance, there are several challenges in the implementation of solar energy-based public street lighting:

- **Initial Investment Cost:** The high initial cost can be a barrier to widespread adoption. Solutions include government subsidies and supportive financing schemes.
- **Energy Intermittency:** Dependence on weather results in energy production fluctuations. The use of energy storage batteries can help address this issue.

C. Policy Implications

These findings have important implications for urban energy and environmental policies:

- **Policy Support:** The government needs to provide incentives and regulations that support the implementation of solar energy-basedpublic street lighting, including subsidies and lower taxes for green technology.
- **Public Education:** Raising public awareness about the benefits of renewable energy and the importance of reducing carbon emissions through education programs and campaigns.

D. Recommendations

Based on the research results, several recommendations to improve the performance and efficiency of solar energy-based public street lightingare:

- **System Design Optimization:** Using high-efficiency solar panel technology and reliable storage batteries.

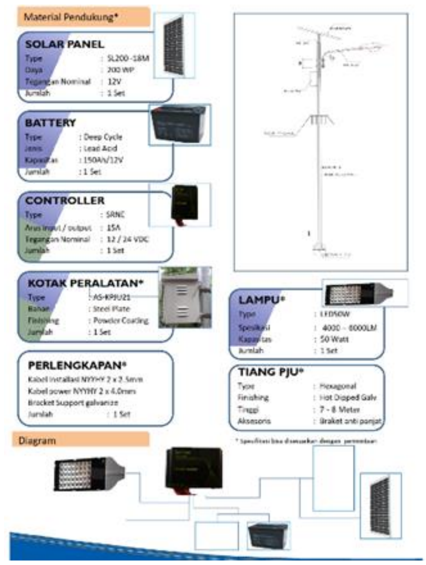

Figure 3. Solar Energy Based Public Lighting Design

- **Regular Maintenance:** Establishing a regular maintenance schedule to ensure optimal system performance.
- **Policy Development:** Encouraging the development of policies that support the use of renewable energy in the public sector.

IV. CONCLUSION

This research shows that solar energy-based public street lighting has high performance and efficiency in reducing urban emissions. Despite the challenges, the long-term economic and environmental benefits are very significant. The widespread implementation of this technology can be a strategic step in the development of sustainable and environmentally friendly cities.

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