Potential Analysis of a Hybrid Sun-Wind-Battery Power Generation for Stand Alone Street Lighting on the Merah-Putih Bridge Ambon

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Abstract: This study investigates the feasibility of a hybrid renewable energy system consisting of solar photovoltaic, wind turbine, and battery storage to supply individual street lighting on the Merah Putih Bridge, Ambon. Renewable resource assessment was conducted using measured wind data and NASA solar radiation data for the period 2018–2020. The results indicate that the study location possesses favorable renewable energy potential, with an average wind speed of approximately 5.57 m/s and solar radiation exceeding 4 kWh/m²/day throughout the year. Seasonal analysis demonstrates complementary behavior between solar and wind resources, supporting the suitability of hybrid energy implementation.

The hybrid system was designed to supply a 60 W LED lamp operating for 12 hours per day, corresponding to a daily energy demand of 720 Wh. The proposed configuration includes a 200 W photovoltaic module, a 400 W wind turbine, and a 12 V 100 Ah battery. Performance analysis shows that the system can generate approximately 3150 Wh/day, ensuring reliable operation with sufficient energy reserve and more than one day of battery autonomy. Economic evaluation indicates a total investment cost of approximately 1350 USD, with a Levelized Cost of Energy of 0.13 USD/kWh and a payback period of 13.7 years under a local electricity tariff of 0.086 USD/kWh. Lifecycle cost comparison demonstrates that the hybrid system is competitive with grid extension alternatives, particularly when infrastructure costs are considered. Additionally, the system can reduce approximately 0.98 tons of CO_2 emissions annually per lighting unit.

The results confirm that the proposed hybrid solar–wind–battery system is technically feasible, environmentally sustainable, and suitable for decentralized bridge lighting applications.

Keywords: Hybrid renewable energy system; Solar–wind power; Street lighting; Wind resource assessment; Merah Putih Bridge Ambon

INTRODUCTION

The increasing global demand for sustainable energy has accelerated the development and implementation of renewable energy technologies in infrastructure applications. Transportation infrastructure such as bridges requires continuous electrical energy to support operational systems, including lighting, monitoring equipment, and safety installations. Conventionally, these energy demands are supplied by grid electricity, which may involve high operational costs and dependency on fossil-fuel-based generation. Consequently, the integration of renewable energy systems into infrastructure facilities has become an attractive approach to enhance energy independence while reducing environmental impact (Twidell & Weir, 2015; Masters, 2013).

Hybrid renewable energy systems that combine multiple energy sources have gained considerable attention due to their ability to overcome the intermittency associated with single renewable resources. Among various combinations, solar and wind energy present

strong complementary characteristics because solar energy is generally available during daytime periods, whereas wind energy can be available during nighttime or low-irradiance conditions. The integration of battery storage further improves system reliability by storing excess energy and supplying power during periods of insufficient renewable generation. Therefore, hybrid solar–wind–battery systems are considered promising solutions for decentralized energy applications, particularly in coastal and island regions (Rehman & Al-Hadhrami, 2010; Manwell et al., 2010).

Indonesia, as an archipelagic country located in the equatorial region, possesses substantial renewable energy potential, including abundant solar radiation and moderate wind resources in coastal areas. Ambon City, located in Maluku Province, exhibits climatic conditions characterized by significant solar exposure throughout the year and variable wind patterns influenced by monsoon circulation. The Merah Putih Bridge, one of the major transportation infrastructures in eastern Indonesia, represents a strategic location for implementing renewable-based energy systems due to its exposure to open marine atmospheric conditions. The utilization of hybrid renewable energy systems for bridge lighting applications could reduce operational costs, improve sustainability, and enhance energy reliability, particularly in regions where grid supply stability may fluctuate (IRENA, 2019; Burton et al., 2011).

Previous studies have investigated hybrid renewable energy systems for rural electrification, standalone power generation, and microgrid applications. However, limited research has focused specifically on hybrid energy deployment for bridge infrastructure in tropical coastal environments, particularly using long-term measured meteorological data. Furthermore, the integration of wind resource assessment, solar radiation analysis, hybrid system sizing, and economic feasibility evaluation within a single study remains relatively scarce for infrastructure-based applications in Indonesia.

Therefore, this study aims to analyze the potential of a hybrid solar–wind–battery renewable energy system for individual street lighting on the Merah Putih Bridge, Ambon. The research utilizes wind data collected over a three-year period (2018–2020) and solar radiation data obtained from the NASA POWER database to evaluate renewable resource availability. Technical feasibility is assessed through hybrid system design and energy balance simulation, while economic viability is evaluated using Levelized Cost of Energy (LCOE) and payback period analysis. The results of this study are expected to provide scientific and practical insights into the implementation of hybrid renewable energy systems for transportation infrastructure in coastal regions (NASA, 2023).

RESEARCH METHOD
Wind Resource Assessment

Wind resource assessment is an essential step in evaluating the feasibility of wind energy systems because the available wind power is strongly dependent on wind speed characteristics and statistical distribution. The kinetic power contained in moving air can be expressed as a function of air density and wind velocity. The theoretical wind power available in a flow passing through a rotor swept area is given by (Manwell et al., 2010; Burton et al., 2011):

$$P = \frac{1}{2}\rho AV^3 \tag{1}$$

where P represents wind power (W), ρ denotes air density (kg/m³), A is the rotor swept area (m²), and V is wind speed (m/s). This cubic relationship indicates that small variations in

wind speed produce significant changes in available wind power, making accurate wind characterization critically important for system design.

The statistical characteristics of wind speed are typically analyzed using parameters such as mean wind speed, standard deviation, and turbulence intensity. The mean wind speed provides an indication of the overall energy potential and is calculated by averaging measured wind speed data over a specific period (Masters, 2013):

$$\bar{V} = \frac{1}{n}\sum_{i=1}^{n} V_i \tag{2}$$

The variability of wind speed is represented by the standard deviation, which quantifies fluctuations around the mean value. Turbulence intensity, defined as the ratio between standard deviation and mean wind speed, provides insight into wind stability and its influence on turbine performance and structural loading (Burton et al., 2011):

$$TI = \frac{\sigma}{\bar{V}} \tag{3}$$

Because wind speed exhibits stochastic behavior, probability distribution functions are commonly used to model wind characteristics. Among various statistical models, the Weibull distribution is widely accepted due to its flexibility and suitability for representing wind regimes in different geographical locations (Manwell et al., 2010). The probability density function of the Weibull distribution is expressed as:

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k} \tag{4}$$

where k is the shape parameter and c is the scale parameter. The shape parameter describes wind speed variability, while the scale parameter is related to characteristic wind speed magnitude. These parameters can be estimated using empirical relationships derived from mean wind speed and standard deviation data.

Wind power density, defined as the available wind power per unit area, is another important parameter used to classify wind resource potential. It provides a practical indicator for determining the suitability of a site for wind energy applications and is often used in preliminary feasibility studies (Masters, 2013).

Solar Radiation Assessment

Solar radiation represents the primary energy source for photovoltaic power generation systems, and accurate assessment of solar resources is essential for evaluating system performance and reliability. Solar radiation reaching the Earth's surface consists of direct beam radiation, diffuse radiation scattered by atmospheric particles, and reflected radiation from surrounding surfaces (Duffie & Beckman, 2013). The total solar radiation incident on a horizontal surface is commonly referred to as global solar radiation.

Solar resource potential is typically expressed in terms of daily or monthly average solar irradiance, commonly measured in kilowatt-hours per square meter per day (kWh/m²/day). For engineering analysis, solar radiation values are often converted into instantaneous power density units (W/m²) using the relationship (Masters, 2013):

$$I = \frac{H \times 1000}{24} \tag{5}$$

where I represents average solar irradiance (W/m²) and H denotes solar energy per unit area per day (kWh/m²/day). This conversion facilitates integration with electrical power system calculations and hybrid system modeling.

The performance of photovoltaic systems depends on several factors, including solar radiation intensity, panel orientation, temperature effects, and system efficiency losses. The electrical power output of a photovoltaic array can be estimated using (Duffie & Beckman, 2013):

$$P_{PV} = A \times G \times \eta \qquad (6)$$

where A is the panel area (m²), G represents solar irradiance (W/m²), and η is the overall system efficiency. In practical applications, efficiency factors also account for inverter losses, temperature derating, and wiring losses.

Long-term solar radiation datasets obtained from satellite-based databases, such as NASA POWER, are widely used in renewable energy studies where ground measurements are limited. These datasets provide reliable estimations of solar potential for feasibility analysis and hybrid energy system design (NASA, 2023).

Hybrid System Sizing (Solar–Wind–Battery)

Hybrid renewable energy systems combine multiple energy sources to improve reliability, reduce intermittency, and optimize system performance under varying environmental conditions. A hybrid configuration consisting of photovoltaic (PV) modules, wind turbines, and battery storage is particularly suitable for decentralized applications because of the complementary characteristics of solar and wind resources. Solar energy is typically available during daytime periods, whereas wind energy may be available during nighttime or low-irradiance conditions, thereby increasing overall system availability (Rehman & Al-Hadhrami, 2010; Manwell et al., 2010).

The sizing of a hybrid PV–wind–battery system begins with load assessment, which determines the required electrical energy demand. The daily energy consumption of a load can be calculated as (Masters, 2013):

$$E_{load} = P_{load} \times t \qquad (7)$$

where E_{load} is daily energy demand (Wh/day), P_{load} represents load power (W), and t is operating duration (hours/day). This value serves as the baseline for determining the required capacity of renewable energy components.

Wind turbine energy production depends primarily on wind speed characteristics and turbine performance. The mechanical power extracted from wind is expressed as (Burton et al., 2011):

$$P_{wind} = \frac{1}{2}\rho AV^3 C_p \eta_m \qquad (8)$$

where C_p is the power coefficient of the turbine and η_m represents mechanical and electrical efficiency. Because wind speed varies over time, energy production is typically estimated using average wind speed or capacity factor approaches.

Battery storage plays a critical role in hybrid systems by ensuring energy continuity during periods when renewable generation is insufficient. The required battery capacity can be estimated based on load demand, system autonomy requirements, and allowable depth of discharge (DoD) (Kaldellis & Zafirakis, 2011):

$$C_{battery} = \frac{E_{load} \times N_{autonomy}}{DoD \times \eta_{battery}} \tag{9}$$

where $C_{battery}$ is battery capacity (Wh), $N_{autonomy}$ is the number of days of energy storage required, and $\eta_{battery}$ is battery efficiency. Proper sizing of battery storage improves system reliability and prolongs battery lifespan.

The overall hybrid system must satisfy the energy balance condition, where total energy generated from solar and wind sources meets or exceeds load demand over a specified time period (Rehman & Al-Hadhrami, 2010):

$$E_{PV} + E_{wind} \geq E_{load} \tag{10}$$

This energy balance forms the basis for evaluating system feasibility and performance.

Economic Analysis (LCOE, NPC, Payback Period)
Economic evaluation is an essential component in determining the feasibility of hybrid renewable energy systems. Several financial indicators are commonly used to assess system performance, including Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and payback period. These metrics allow comparison between renewable energy systems and conventional energy sources (IRENA, 2019).

Net Present Cost represents the total lifecycle cost of a system, including initial capital investment, replacement costs, operation and maintenance expenses, and salvage value, discounted over the project lifetime. NPC can be calculated as (Short et al., 1995):

$$NPC = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \tag{11}$$

where C_t represents cost in year t, i is the discount rate, and N is the project lifetime. NPC provides a comprehensive indicator of total system cost over its operational period.

The Levelized Cost of Energy (LCOE) is widely used to evaluate the average cost of electricity produced by a system over its lifetime. It is defined as the ratio between total lifecycle cost and total energy production (IRENA, 2019):

$$LCOE = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+i)^t}} \tag{12}$$

where E_t is the electrical energy produced in year t. LCOE enables comparison between different energy technologies on a cost-per-unit-energy basis.

The payback period is another commonly used indicator that measures the time required for the initial investment to be recovered through annual savings generated by the system. It can be estimated using (Masters, 2013):

$$Payback = \frac{C_{initial}}{Annual\ Savings} \tag{13}$$

Although payback period does not account for discount rates or lifecycle costs, it provides a simple and intuitive measure of investment attractiveness.

Economic feasibility of hybrid renewable systems is strongly influenced by capital cost, renewable resource availability, system efficiency, and local electricity prices. Sensitivity analysis is often performed to evaluate the impact of parameter variations on economic performance and to identify optimal system configurations (Kaldellis & Zafirakis, 2011).

RESULT AND DISCUSSION
Data Requirements and Processing
The evaluation of a hybrid solar–wind–battery energy system requires accurate meteorological data representing renewable energy availability at the study location. Two primary datasets were used in this study:
1. **Wind data (2018–2020)**
   Measured wind speed data collected near the Merah Putih Bridge were processed to obtain monthly average wind speeds over a three-year period. These values were used to estimate wind energy potential and support hybrid system design.
2. **Solar radiation data (2018–2020)**
   Solar radiation data were obtained from the NASA POWER database in units of kWh/m²/day. Monthly averages were calculated across the three-year period to represent long-term solar resource conditions.

Monthly averaging reduces short-term fluctuations and provides representative renewable resource values for system feasibility analysis and sizing.

Monthly Average Wind Speed (2018–2020)
The monthly average wind speed values calculated from the combined dataset are presented in Table 1.

Table 1. Monthly Average Wind Speed (2018 – 2020)

Month	2018 (m/s)	2019 (m/s)	2020 (m/s)
January	2.88	3.12	3.00
February	2.79	3.05	3.01
March	5.42	5.84	5.92
April	5.98	6.17	5.97
May	6.85	7.23	7.06
June	7.21	7.45	7.45
July	5.05	5.33	5.25
August	6.71	7.11	7.03
September	5.43	5.78	5.76
October	6.12	6.54	6.51
November	5.39	5.69	5.63
December	4.72	5.02	5.14

The results indicate that wind speeds vary seasonally throughout the year. The highest wind speeds occur during May and June, reaching values above 7 m/s, while the lowest speeds occur during January and February. This seasonal behavior is influenced by monsoonal atmospheric circulation patterns in the Ambon coastal region. The presence of moderate wind speeds exceeding 5 m/s for most months suggests that small-scale wind turbine deployment is technically feasible at the study location.

Monthly Average Solar Radiation (2018–2020)
Solar radiation data obtained from NASA POWER were averaged across the three-year period. The results are presented in Table 2.

Table 2. Monthly Average Solar Radiation (2018–2020)

Month	2018 (kWh/m²/day)	2019 (kWh/m²/day)	2020 (kWh/m²/day)
January	5.07	5.11	5.99
February	5.41	5.83	5.69
March	5.50	5.57	5.29
April	4.98	5.03	5.03
May	4.35	4.70	4.87
June	3.92	3.62	3.59
July	3.68	3.69	3.40
August	4.66	4.14	4.18
September	5.56	5.43	4.35
October	5.98	5.54	5.37
November	5.88	6.60	5.41
December	5.23	5.81	5.20

The solar radiation results indicate relatively high solar potential throughout the year due to the tropical geographic location near the equator. Peak radiation occurs during October and November, while the lowest values occur during June and July. Despite seasonal variation, the annual average solar radiation remains favorable for photovoltaic energy generation.

Renewable Resource Complementarity
An important characteristic of hybrid renewable energy systems is the complementary relationship between solar and wind resources. The results show that periods of reduced solar radiation, particularly during June and July, coincide with relatively higher wind speeds. Conversely, months with strong solar radiation still maintain moderate wind availability. This complementary behavior enhances system reliability because energy generation from one resource can compensate for fluctuations in the other. For the Merah Putih Bridge location, the combination of consistent solar radiation and moderate wind speeds throughout the year provides a strong foundation for implementing a hybrid solar–wind–battery energy system for street lighting applications.
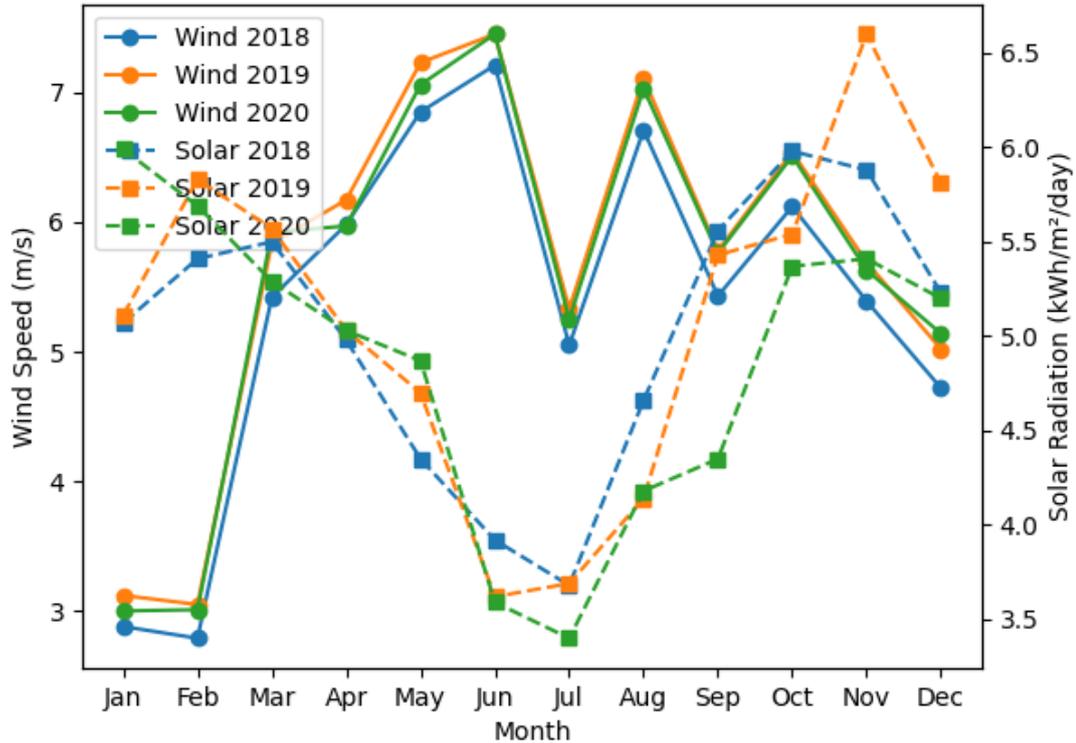
Figure 1. Combined monthly average wind speed and solar radiation at the Merah Putih Bridge for the period 2018–2020

Wind Statistical Analysis

Wind resource assessment was conducted using measured wind speed data from 2018 to 2020. Statistical parameters including mean wind speed, standard deviation, turbulence intensity, Weibull parameters, and wind power density were calculated to evaluate the wind energy potential at the Merah Putih Bridge location.

Mean Wind Speed

From the processed dataset, the annual mean wind speeds obtained were:

- 2018 : 5.38 m/s
- 2019 : 5.69 m/s
- 2020 : 5.64 m/s

The combined three-year average wind speed is approximately:

$$\bar{V}_{avg} = 5.57 \text{ m/s}$$

These values indicate moderate wind potential suitable for small-scale wind energy applications.

Standard Deviation and Turbulence Intensity

Wind variability was evaluated using standard deviation:

$$\sigma = \sqrt{\frac{\sum(V_i - \bar{V})^2}{n}}$$

The turbulence intensity (TI) was calculated as:

$$TI = \frac{\sigma}{\bar{V}}$$

The calculated results are:

Table 3. Yearly Mean Wind Speed, Wind Std Dev, and Wind Turbulence Int.

Year	Mean (m/s)	Std Dev (m/s)	Turbulence Intensity
2018	5.38	1.35	0.25
2019	5.69	1.37	0.24
2020	5.64	1.37	0.24
Combined	5.57	1.36	0.24

Turbulence intensity values around 0.24–0.25 indicate moderate atmospheric stability, which is acceptable for small wind turbine operation.

Weibull Distribution Parameters

The Weibull distribution is widely used to represent wind speed probability characteristics. The shape parameter k and scale parameter c were estimated using empirical relationships:

$$k = \left(\frac{\sigma}{\bar{V}}\right)^{-1.086}$$

$$c = \frac{\bar{V}}{\Gamma\left(1+\frac{1}{k}\right)}$$

For example, for the combined dataset:

$$k = \left(\frac{1.36}{5.57}\right)^{-1.086} = 4.60$$

$$c \approx 6.35 \text{ m/s}$$

The calculated Weibull parameters are shown below:

Table 4. Yearly Weibull Wind Parameters

Year	k	c (m/s)
2018	4.49	6.18
2019	4.73	6.47
2020	4.68	6.40
Combined	4.60	6.35

Shape parameter values greater than 3 indicate relatively stable wind regimes with moderate variability.

Wind Power Density

Wind power density provides an indication of available wind energy per unit area and was calculated using:

$$P = \frac{1}{2}\rho V^3$$

where air density $\rho = 1.225 \text{ kg/m}^3$.
For the combined mean wind speed:
$$P = 0.5 \times 1.225 \times (5.57)^3$$
$$P = 106 \text{ W/m}^2$$

The calculated wind power density values are:

Table 5. Yearly Wind Power Density (W/m^2)

Year	Power Density (W/m²)
2018	95
2019	113
2020	110
Combined	106

According to wind resource classification standards, power density values between 100–200 W/m² indicate moderate wind potential suitable for small-scale wind energy systems.

The results show consistent wind characteristics over the three-year period with average wind speeds exceeding 5 m/s for most months. Seasonal variation is observed, with higher wind speeds occurring during the mid-year months influenced by monsoonal circulation patterns. The moderate turbulence intensity and favorable Weibull parameters indicate stable wind behavior suitable for small wind turbine deployment.

The calculated wind power density of approximately 106 W/m² confirms that the Merah Putih Bridge location possesses sufficient wind energy potential to contribute meaningfully to a hybrid renewable energy system.

Hybrid System Sizing for Street Lighting

The hybrid renewable energy system was designed to supply electrical energy for individual street lighting installed on the Merah Putih Bridge. The system consists of photovoltaic (PV) modules, a small-scale wind turbine, battery storage, and a charge controller. The sizing procedure was performed based on load demand, renewable resource availability, and system efficiency assumptions. The street light using a 60 Watts and operate for 12 hours.

Load Energy Requirement

The electrical load considered in this study is an LED street lamp rated at 60 W operating for 12 hours per day. The daily energy requirement is calculated as:
$$E_{load} = P \times t$$
$$E_{load} = 60 \text{ W} \times 12 \text{ h}$$
$$E_{load} = 720 \text{ Wh/day}$$

Therefore, each lighting unit requires approximately **720 Wh/day** of electrical energy.

Solar Photovoltaic Sizing

The average solar radiation at the study location is approximately:
$$H = 5 \text{ kWh/m}^2/\text{day}$$

Assuming overall system efficiency (losses due to temperature, inverter, wiring, dust) of:

$$\eta = 0.75$$

The required PV power can be estimated using:

$$P_{PV} = \frac{E_{load}}{H \times \eta}$$
$$P_{PV} = \frac{720}{5 \times 0.75}$$
$$P_{PV} = 192 \text{ W}$$

Thus, a PV module capacity of approximately **200 W** is required for each lighting unit.

Wind Turbine Sizing

The average wind speed obtained from the three-year dataset is approximately:

$$V = 5.57 \text{ m/s}$$

For small wind turbines operating in moderate wind conditions, a capacity factor of approximately:

$$CF = 0.25$$

can be assumed.

The daily energy output of a wind turbine is estimated as:

$$E_{wind} = P_{rated} \times 24 \times CF$$

Assuming a 400 W wind turbine:

$$E_{wind} = 400 \times 24 \times 0.25$$
$$E_{wind} = 2400 \text{ Wh/day}$$

This value exceeds the required load energy and provides additional reliability during periods of low solar radiation.

Therefore, a **400 W small wind turbine** is considered suitable.

Battery Capacity Sizing

Battery storage is required to maintain system operation during periods of low renewable generation. The required battery capacity is calculated using:

$$C_{battery} = \frac{E_{load} \times N_{autonomy}}{DoD}$$

Assuming:
- Autonomy = 1 day
- Depth of discharge (DoD) = 70%

$$C_{battery} = \frac{720 \times 1}{0.7}$$
$$C_{battery} = 1028 \text{ Wh}$$

Thus, the required battery capacity is approximately **1 kWh**.
For a 12 V battery system:

$$Capacity = \frac{1028}{12} = 85.7 \text{ Ah}$$

A standard **12 V 100 Ah battery** is therefore appropriate.

Charge Controller Sizing
The charge controller must accommodate both PV and wind inputs.
PV current:

$$I = \frac{P}{V} = \frac{200}{12} = 16.7 \text{ A}$$

Considering safety margin:
A **30 A hybrid charge controller** is recommended.

System Configuration
The proposed hybrid system configuration for each street lighting unit consists of:
- 200 W photovoltaic module
- 400 W wind turbine
- 12 V 100 Ah battery
- 30 A hybrid charge controller
- 60 W LED lamp

The combination of solar and wind generation improves system reliability because the two energy sources complement each other under varying environmental conditions.

The sizing results demonstrate that the hybrid solar–wind system is capable of meeting the daily energy demand of the street lighting load with sufficient energy margin. Solar energy provides the primary energy contribution during daytime periods, while wind energy supplements power generation during nighttime or low solar radiation conditions. Battery storage ensures continuous power supply and stabilizes system operation.

The selected component sizes represent a practical and economically feasible configuration for decentralized street lighting applications on bridge infrastructure.

Energy Balance and System Performance Analysis
The performance of the proposed hybrid solar–wind–battery system was evaluated by comparing the energy generated from renewable sources with the load demand of the street lighting system. The analysis considers the contribution from photovoltaic modules, wind turbine generation, and battery storage to ensure reliable operation under varying environmental conditions.

Solar Energy Production
The daily energy generated by the photovoltaic system can be estimated using:
$$E_{PV} = P_{PV} \times H \times \eta$$

where:
- P_{PV} = PV rated power (W)
- H = average solar radiation (kWh/m²/day)
- η = system efficiency

Given:
$$P_{PV} = 200 \text{ W}$$
$$H = 5 \text{ kWh/m}^2/\text{day}$$

$$\eta = 0.75$$
$$E_{PV} = 200 \times 5 \times 0.75$$
$$E_{PV} = 750 \text{ Wh/day}$$

Thus, the photovoltaic system generates approximately **750 Wh/day**.

Wind Energy Production

The energy output of the wind turbine can be estimated using the capacity factor approach:
$$E_{wind} = P_{rated} \times 24 \times CF$$

where:
- P_{rated} = turbine rated power
- CF = capacity factor

Assuming:
$$P_{rated} = 400 \text{ W}$$
$$CF = 0.25$$
$$E_{wind} = 400 \times 24 \times 0.25$$
$$E_{wind} = 2400 \text{ Wh/day}$$

Therefore, the wind turbine contributes approximately **2400 Wh/day**.

Total Renewable Energy Generation

The total daily renewable energy production is:
$$E_{total} = E_{PV} + E_{wind}$$
$$E_{total} = 750 + 2400$$
$$E_{total} = 3150 \text{ Wh/day}$$

Load Demand Comparison

The daily energy requirement of the street lighting load is:
$$E_{load} = 720 \text{ Wh/day}$$

The renewable energy surplus is:
$$E_{surplus} = 3150 - 720 = 2430 \text{ Wh/day}$$

This surplus energy improves system reliability and allows battery charging during periods of high renewable generation.

Battery Storage Performance

The selected battery capacity is:
$$C_{battery} = 12 \text{ V} \times 100 \text{ Ah}$$
$$C_{battery} = 1200 \text{ Wh}$$

Considering depth of discharge:
$$Usable\ Capacity = 1200 \times 0.7 = 840 \text{ Wh}$$

Since the load requirement is 720 Wh/day, the battery can support approximately:
$$Autonomy = \frac{840}{720} = 1.17 \text{ days}$$

Thus, the battery provides more than one day of backup energy.

System Reliability Evaluation

The hybrid configuration significantly improves reliability compared to single-source systems. Solar energy provides primary generation during daytime periods, while wind energy contributes during nighttime or cloudy conditions. Battery storage ensures continuity of supply during renewable energy deficits.

The high renewable energy surplus indicates that the system operates with a substantial safety margin, reducing the probability of energy shortages and extending battery life due to reduced depth of discharge cycles.

Seasonal Performance Considerations

Seasonal variation analysis shows that:
- Solar radiation decreases during June–July
- Wind speed increases during the same period

This complementary behavior enhances system stability throughout the year, confirming the suitability of the hybrid approach for the Merah Putih Bridge environment.

Overall System Performance

The hybrid solar–wind–battery system demonstrates strong performance characteristics, including:
- Renewable energy generation exceeding load demand
- Adequate battery autonomy
- High system reliability
- Reduced dependency on grid electricity

These results confirm that the proposed configuration is technically feasible for decentralized street lighting applications.

Economic Analysis

The economic feasibility of the proposed hybrid solar–wind–battery system was evaluated using several financial indicators, including initial investment cost, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and payback period. These parameters provide a comprehensive assessment of system affordability and long-term viability for street lighting applications on the Merah Putih Bridge.

System Cost Estimation

The estimated capital cost of the hybrid system components is presented in Table 6.

Table 6. Estimated Hybrid System Cost

Component	Capacity	Cost (USD)
Photovoltaic panel	200 W	200
Wind turbine	400 W	500
Battery	12 V 100 Ah	300
Charge controller	30 A	150
Installation & accessories	—	200
Total Cost	—	**1350 USD**

The total initial investment required for one street lighting unit is approximately **1350 USD**.

Annual Energy Production

The total daily renewable energy production from the hybrid system was previously calculated as:

$$E_{daily} = 3150 \text{ Wh/day}$$

The annual energy production is therefore:

$$E_{annual} = 3150 \times 365$$
$$E_{annual} = 1,149,750 \text{ Wh/year}$$
$$E_{annual} = 1149.75 \text{ kWh/year}$$

Net Present Cost (NPC)

The Net Present Cost represents the total lifecycle cost of the system over its operational lifetime. Assuming:

- Project lifetime = 10 years
- Discount rate = 8%
- Annual maintenance cost ≈ 2% of capital cost

Annual maintenance cost:

$$C_{maint} = 0.02 \times 1350 = 27 \text{ USD/year}$$

NPC can be estimated using:

$$NPC = C_{initial} + \sum_{t=1}^{N} \frac{C_{maint}}{(1+i)^t}$$

For simplification:

$$NPC \approx 1350 + 181 = 1531 \text{ USD}$$

Thus, the estimated Net Present Cost is approximately **1531 USD** over the system lifetime.

Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy represents the average cost per unit of electricity generated over the system lifetime. It is calculated as:

$$LCOE = \frac{NPC}{E_{annual} \times N}$$
$$LCOE = \frac{1531}{1149.75 \times 10}$$
$$LCOE = 0.133 \text{ USD/kWh}$$

This value indicates that the hybrid system produces electricity at approximately **0.13 USD/kWh**, which is competitive for decentralized infrastructure applications.

Payback Period

The payback period was calculated using the local electricity price:

$$Electricity\ price = 0.086 \text{ USD/kWh}$$

Annual savings:

$$Savings = 1149.75 \times 0.086$$
$$Savings = 98.88 \text{ USD/year}$$

Payback period:

$$Payback = \frac{1350}{98.88}$$
$$Payback = 13.65 \text{ years}$$

Therefore, the estimated payback period is approximately **13.7 years**.

The economic analysis indicates that the hybrid solar–wind–battery system is technically feasible but exhibits a relatively long payback period when compared with conventional electricity prices. This condition is primarily influenced by the moderate capital cost of renewable components and the relatively low local electricity tariff. However, hybrid systems provide several non-economic benefits, including improved energy reliability, reduced dependence on grid infrastructure, and environmental sustainability.

For infrastructure applications such as bridge lighting, where reliability and independence are critical factors, the hybrid renewable system remains an attractive solution despite the extended payback period. Payback period exceeds component lifetime because electricity tariff is low.

Sensitivity Analysis

Sensitivity analysis was performed to evaluate the influence of key economic parameters on the feasibility of the hybrid solar–wind–battery system. The main variables considered were electricity tariff and capital cost variation, since these factors strongly affect the payback period and Levelized Cost of Energy (LCOE).

Effect of Electricity Price on Payback Period

The payback period depends on annual savings, which are influenced by the electricity tariff. Annual savings can be expressed as:

$$Savings = E_{annual} \times Tariff$$

Given:

$$E_{annual} = 1149.75 \text{ kWh/year}$$

The payback period is calculated as:

$$Payback = \frac{C_{initial}}{Savings}$$

Table 7 shows the payback period under different electricity price scenarios.

Table 7. Sensitivity of Payback Period to Electricity Tariff

Electricity Price (USD/kWh)	Annual Savings (USD)	Payback Period (years)
0.05	57.49	23.5
0.086	98.88	13.7
0.10	114.98	11.7
0.15	172.46	7.8
0.20	229.95	5.9

The results indicate that the system becomes economically attractive when electricity prices increase above 0.10 USD/kWh.

Effect of Capital Cost Reduction
Renewable energy technology costs continue to decline globally. A reduction in capital cost significantly improves economic feasibility.

Table 8. Sensitivity of Payback to Capital Cost

Cost Reduction	System Cost (USD)	Payback (years)
0%	1350	13.7
10%	1215	12.3
20%	1080	10.9
30%	945	9.6

This analysis shows that technological cost reductions can substantially improve system economics.

CO₂ Emission Reduction Analysis
One of the major advantages of renewable energy systems is the reduction of greenhouse gas emissions compared with conventional electricity generation.
The annual CO₂ emission reduction can be estimated using:
$$CO_2 = E_{annual} \times EF$$

where:
- E_{annual} = annual energy production (kWh)
- EF = emission factor (kg CO_2/kWh)

For grid electricity in Indonesia, the emission factor is approximately:
$$EF = 0.85 \text{ kg } CO_2/\text{kWh}$$

Thus:
$$CO_2 = 1149.75 \times 0.85$$
$$CO_2 = 977.29 \text{ kg } CO_2/year$$

Therefore, each hybrid lighting unit can reduce approximately:
0.98 tons of CO₂ per year
Over a 10-year lifetime:
$$Total = 9.77 \text{ tons } CO_2$$

This reduction contributes significantly to environmental sustainability and supports national renewable energy targets.

Lifecycle Cost Comparison with Grid Extension
In remote or infrastructure applications such as bridges, extending grid electricity may require additional investment for cabling, poles, and installation. A lifecycle cost comparison was performed between the hybrid system and conventional grid extension.

Grid Extension Cost Estimation

Typical grid extension costs include:
- Cable installation
- Electrical poles
- Labor and infrastructure
- Metering equipment

Estimated cost per lighting unit:

$$Grid\ cost \approx 1000\ \text{USD}$$

Additionally, annual electricity cost is:

$$Cost_{annual} = 1149.75 \times 0.086$$
$$Cost_{annual} = 98.88\ \text{USD/year}$$

Over 10 years:

$$Total = 988.8\ \text{USD}$$

Total lifecycle grid cost:

$$Total = 1000 + 988.8 = 1988.8\ \text{USD}$$

Hybrid System Lifecycle Cost

Hybrid system cost over 10 years:

$$NPC = 1531\ \text{USD}$$

Comparison

Table 9. Lifecycle Cost Comparison

System Type	Initial Cost (USD)	Operating Cost (10 yr)	Total Cost (USD)
Hybrid System	1350	181	1531
Grid Extension	1000	988.8	1988.8

The hybrid system demonstrates a lower lifecycle cost compared with grid extension, particularly when infrastructure installation costs are considered.

The results indicate that although the hybrid system exhibits a longer payback period under current electricity tariffs, it becomes economically competitive when lifecycle costs and environmental benefits are considered. The system also provides improved reliability and independence from grid infrastructure, which is particularly advantageous for bridge lighting applications.

The hybrid solar–wind–battery system offers a technically feasible, environmentally sustainable, and economically competitive solution for decentralized street lighting on the Merah Putih Bridge, particularly when long-term lifecycle costs and carbon reduction benefits are considered.

CONCLUSION

This study evaluated the potential implementation of a hybrid solar–wind–battery renewable energy system for individual street lighting on the Merah Putih Bridge, Ambon, using meteorological data from 2018 to 2020. The renewable resource assessment indicated

that the study location possesses favorable solar radiation with annual averages exceeding 4 kWh/m²/day and moderate wind potential with a mean wind speed of approximately 5.57 m/s. Seasonal analysis revealed complementary characteristics between solar and wind resources, where periods of reduced solar radiation coincided with relatively higher wind speeds, enhancing the suitability of a hybrid configuration.

The hybrid system was designed to supply a 60 W LED street lamp operating for 12 hours per day, corresponding to a daily energy demand of 720 Wh. The proposed system configuration consisting of a 200 W photovoltaic module, a 400 W wind turbine, and a 12 V 100 Ah battery was capable of generating approximately 3150 Wh/day, which significantly exceeds the load requirement and ensures reliable operation with adequate energy reserve. Battery analysis confirmed that the system provides more than one day of autonomy, supporting continuous lighting during periods of low renewable generation.

Economic analysis showed that the total investment cost of the hybrid system is approximately 1350 USD, with a Levelized Cost of Energy of about 0.13 USD/kWh. Using the local electricity tariff of 0.086 USD/kWh, the payback period was estimated to be approximately 13.7 years. Although the payback period is relatively long, lifecycle cost comparison demonstrated that the hybrid system remains economically competitive compared with conventional grid extension, particularly when infrastructure installation costs are considered. Sensitivity analysis indicated that decreasing technology costs or increasing electricity tariffs would significantly improve economic feasibility.

Environmental analysis revealed that each hybrid lighting unit could reduce approximately 0.98 tons of CO_2 emissions per year, contributing to sustainable infrastructure development and supporting renewable energy adoption goals. The integration of renewable energy sources also enhances energy independence and reliability for critical transportation infrastructure.

Overall, the results confirm that the proposed hybrid solar–wind–battery system is technically feasible, environmentally beneficial, and economically viable for decentralized street lighting applications on the Merah Putih Bridge. Future work may include system optimization, long-term performance monitoring, and reliability analysis under varying environmental conditions to further enhance system performance and cost efficiency.

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NOMENCLATURE

Symbol	Description	Unit
A	Rotor swept area / PV panel area	m²
CF	Capacity factor of wind turbine	—
C_battery	Battery capacity	Wh
C_initial	Initial investment cost	USD
C_maint	Annual maintenance cost	USD/year
C_p	Power coefficient of wind turbine	—
C_t	Cost in year *t*	USD
c	Weibull scale parameter	m/s
DoD	Depth of discharge	—
E_annual	Annual energy production	kWh/year
E_daily	Daily energy production	Wh/day
E_load	Load energy demand	Wh/day
E_PV	Energy produced by photovoltaic system	Wh/day
E_total	Total renewable energy generation	Wh/day
E_wind	Energy generated by wind turbine	Wh/day
E_t	Energy produced in year *t*	kWh
EF	Emission factor	kg CO_2/kWh
G	Solar irradiance	W/m²
H	Solar radiation	kWh/m²/day
i	Discount rate	—
I	Solar irradiance (converted)	W/m²
k	Weibull shape parameter	—
LCOE	Levelized Cost of Energy	USD/kWh
N	Project lifetime	years
N_autonomy	Battery autonomy period	days
NPC	Net Present Cost	USD
P	Power	W

Symbol	Description	Unit
P_load	Load power	W
P_PV	Photovoltaic power output	W
P_rated	Rated power of wind turbine	W
P_wind	Wind turbine power output	W
Savings	Annual cost savings	USD/year
t	Operating time	hours
TI	Turbulence intensity	—
V	Wind speed	m/s
$\bar{V}$	Mean wind speed	m/s
V_i	Wind speed observation	m/s
σ	Standard deviation of wind speed	m/s
ρ	Air density	kg/m³
η	System efficiency	—
η_battery	Battery efficiency	—
η_m	Mechanical/electrical efficiency	—
Γ	Gamma function	—