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Solar photovoltaic power system for Bungin Island

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ABSTRACT

Bungin Island currently relies on diesel -based electricity power generation, resulting in limited supply reliability. This study evaluates the technical feasibility of an off-grid solar photovoltaic (PV) system integrated with lithium-ion battery energy storage (BESS) using photovoltaic system (PVsyst) simulation. Based on measured load demand of 2,830 kWh/day and NASA solar resource data, the optimized configuration consist of a 0.713 MWp PV array and an 11.54 MWh battery system. Simulation result indicates an annual PV production (E_Array) of 1,258.3 MWh/year. Of this, 1,032.9 MWh/year is delivered to the load, with excess energy of 120.84 MWh/year and a limited unmet load of 13.7 MWh/year (1.33%). The system achieves a solar fraction 98.67%, a performance ratio (PR) of 77.6% and a capacity factor of 17.34%. These results demonstrate that a properly sized PV-battery configuration can reliably replace diesel generation, providing a robust framework for high-renewable electrification in densely populated small islands.

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1. INTRODUCTION

Reliable electricity supply is a cornerstone for socio-economic development in geographically isolated regions. Many small islands, such as Bungin Island in Indonesia, still rely heavily on diesel-based power generation, which suffers from fuel price volatility, logistical vulnerabilities, and limited operating hours [1]–[4]. While Indonesia's equatorial location offers significant solar potential (4.5–5.5 kWh/m²), transitioning to off-grid solar photovoltaic (PV) systems integrated with battery energy storage (BESS) is essential to mitigate these challenges and reduce carbon footprints [5]–[9].

Recent advancements in simulation tools like photovoltaic system (Pvsyst) and HOMER have enabled precise performance assessments using metrics such as performance ratio (PR) and capacity factor [10]–[15]. However, most existing studies on islanded microgrids utilize generalized load profiles or simplified configurations that do not account for the unique operational characteristics of ultra-dense populations [16], [17]. Site-specific technical evaluations that integrate actual local demand and high-resolution climatic data remain scarce, particularly for Indonesian small islands with extreme population density.

This study addresses this research gap by evaluating a high-penetration off-grid PV-BESS system specifically optimized for Bungin Island. The scientific contribution and novelty of this work lie in the technical validation of an AC-coupled architecture (0.713 MWp) designed using actual, high-resolution measured hourly load data from an ultra-dense island community, rather than relying on generalized or synthetic daily average load profiles common in previous literature. In ultra-dense island contexts, land scarcity and highly concentrated residential evening peaks create unique operational challenges.

By incorporating site-specific microclimatic loss factors—including marine coastal soiling coefficients and high-temperature thermal degradation modeling—this paper establishes a precise sizing ratio blueprint (MWh storage capacity per MWp array) necessary to achieve near-total energy autonomy (solar fraction >98%) without diesel backup. Consequently, this study provides a highly replicable technical framework and a empirical benchmark for deploying large-scale PV systems in densely populated, isolated environments with similar extreme geographical constraints.

2. METHOD

2.1. Research framework and methodological justification

This study adopts a simulation-based research framework to evaluate the technical feasibility of an off-grid solar PV power system for Bungin Island. The methodology is structured into five main stages: load assessment, solar resource input, system sizing, system simulation, and performance evaluation. The overall research workflow is illustrated in Figure 1, which presents the sequential process used to design and assess the proposed system.

The selection of PVsyst as the primary simulation tool is justified by its high precision in modeling complex loss factors, such as the thermal behavior of modules in tropical climates and specific battery aging cycles, which are often oversimplified in other tools. Furthermore, the framework focuses on an AC-coupled architecture justification. This configuration was chosen over DC-coupled systems due to its superior flexibility in integrating large-scale PV arrays (0.713 MWp) with existing island distribution infrastructure and its efficiency in handling peak daytime loads directly through the PV inverters. By following this sequential process, the study ensures that the system sizing is grounded in site-specific climatic data and measured load profiles, providing a higher level of reliability than generalized models.

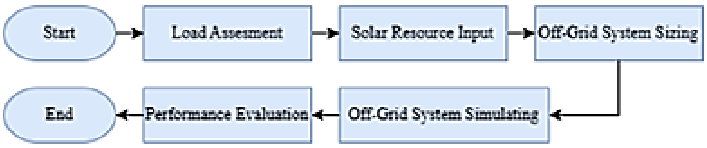

Figure 1. Research methodology flowchart for the proposed off-grid solar PV system

2.2. Load assessment

The electrical load on Bungin Island is dominated by residential activities, characterized by low daytime consumption and a peak demand of 127 kW during evening hours. As shown in Figure 2 and Table 1, the total daily energy demand is 2,830 kWh, which forms the baseline for the PV and BESS sizing to ensure uninterrupted off-grid operation.

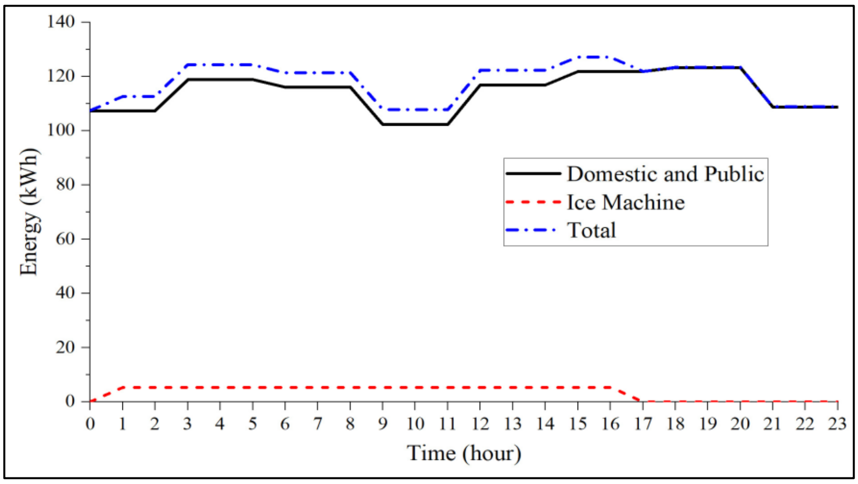

Figure 2. Daily electrical load profile of Bungin Island

Table 1. Summary of electrical load demand parameters

Parameter	Bungin Island
Daily energy demand (kWh)	2,830
Daily energy demand per household (kWh/household)	2.67
Monthly energy demand (kWh)	85,000
Annual energy demand (kWh)	1,020,245
Peak load (kW)	127

2.3. Solar resource input

Solar resource data, including global horizontal irradiation and ambient temperature, were obtained from the NASA database via PVsyst. Figure 3 indicates a stable solar potential throughout the year, with average daily irradiation between 4.5 and 5.5 kWh/m². This data is used to estimate yield and account for thermal efficiency losses in the modules.

Site **Pulau Bungin (Indonesia)**

Data source Meteonorm 8.2 (2016-2021), Sat=100%

	Global horizontal irradiation	Horizontal diffuse irradiation	Temperature	Wind Velocity	Linke turbidity	Relative humidity
	kWh/m²/day	kWh/m²/day	°C	m/s	[-]	%
January	5.17	2.60	27.0	0.91	3.898	84.4
February	4.92	3.06	26.9	1.10	3.884	85.2
March	5.36	2.64	27.2	0.79	3.593	82.5
April	5.66	2.13	27.1	0.69	3.583	81.7
May	5.23	1.98	27.5	1.10	3.598	75.7
June	4.96	1.86	26.3	1.49	3.644	75.1
July	5.27	1.81	26.3	1.60	3.617	70.4
August	5.51	2.38	26.6	1.69	3.746	67.1
September	5.71	2.34	27.2	1.61	3.969	69.1
October	5.90	2.77	28.4	1.50	4.361	70.4
November	5.73	2.67	28.1	1.10	4.350	77.9
December	5.56	2.60	27.5	0.79	4.033	82.0
Year	**5.42**	**2.40**	**27.2**	**1.2**	**3.856**	**76.8**

Global horizontal irradiation year-to-year variability 3.5%

Figure 3. Monthly solar irradiation and ambient temperature for Bungin Island

2.4. System sizing

2.4.1. PV array and battery storage

The system incorporates 1,296 monocrystalline modules (550 Wp each), totaling 0.713 MWp. The array is configured into 108 strings (27 modules/string) to match inverter voltage limits (Table 2 and Figure 4). To ensure autonomy during nighttime and low-irradiation periods, a 11.54 MWh $LiFePO_4$ BESS (Huawei LUNA2000) is integrated. The storage consists of 1,200 units with an 80% maximum depth of discharge and 96% round-trip efficiency (Table 3 and Figure 5).

Table 2. PV module specifications and array configuration

Parameter	Value
Module type	Monocrystalline silicon
Nominal power per module (Wp)	550
Total of modules	1,296
Total installed capacity (MWp)	0.713
Modules per string	27
Number of strings	108
Number of MPPT inputs	12

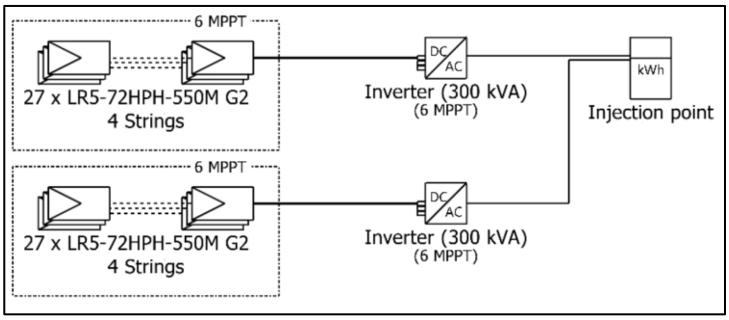

Figure 4. PV array configuration and string arrangement

Table 3. BESS system specifications

Parameter	Specification
Battery technology	Lithium-ion ($LiFePO_4$)
Battery model	LUNA2000-10-S0
Total number of battery units	1,200 units
Total installed storage capacity	11.54 MWh
Maximum depth of discharge	80%
Battery round-trip efficiency	96%

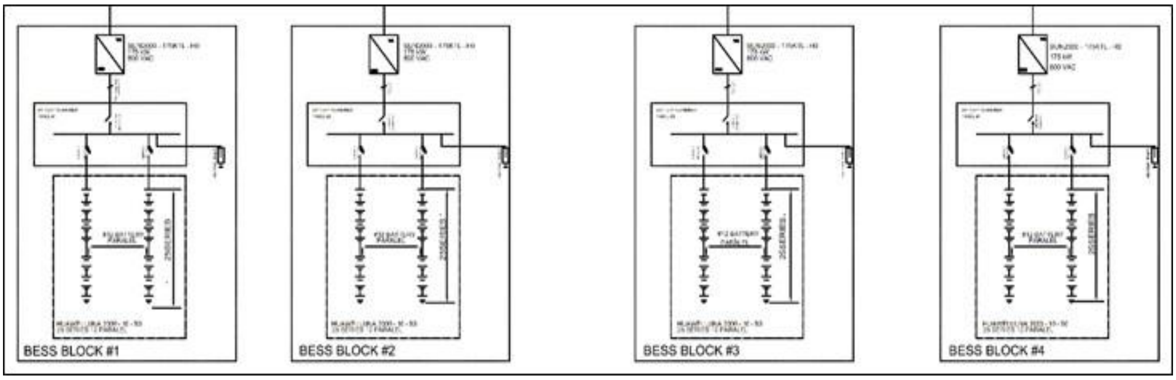

Figure 5. BESS system configuration

2.4.2. Power conversion system

The power conversion system (PCS) employs an AC-coupled architecture consisting of PV string invertes and battery bidirectional inverters PCS. The total PV inverter capacity is 600 kWac, designed with a DC/AC ration of 1.18 (0.713 MWp/0.6 MWac) to optimize energy harvest during low-irradiation periods. The ensure system stability and high-rate charging capability, the battery inverter capacity is set at 700 kWac. This capacity significantly exceeds the peak load of 127 kW, providing a robust power buffer for transient surges and maintaining stable bidirectional energy flow between the BESS and the AC busbar. The inverter operate at a nominal voltage of 800 Vac to minimize Ohmic losses acress the collection system before the voltage is stepped down to the island’s distribution level. Detailed technical specifications of the inverters ar summarized in Table 4, and the overall electrical interconnection is illustrated in the sing-line diagram in Figure 6.

Table 4. Inverter specifications

Parameter	Specification
Rated AC power	300 kW
Nominal AC voltage	800 Vac
Efficiency (maximum/assumed)	99% / 96%

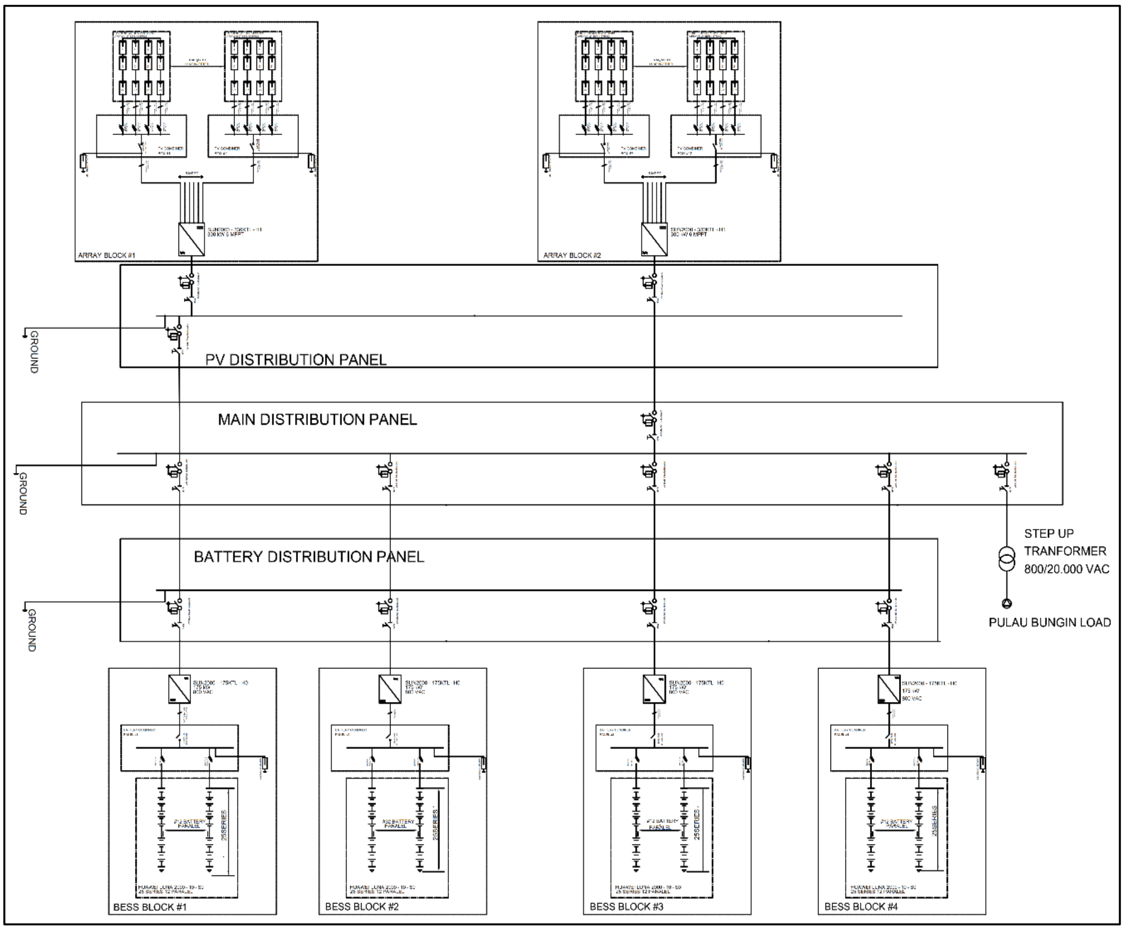

Figure 6. Single-line diagram of the off-grid PV system

2.4.3. System simulation

The complete system configuration is implemented in PVsyst to evaluate annual performance. The simulation is conducted over a one-year period using a 1-hour time step to capture seasonal variations in solar energy availability. The simulation inputs and settings based on the PVsyst project definition shown in Figure 7 are as follows:

a) PV module and orientation: longi solar LR5-72HPH-550M G2 (550 Wp) with 27 modules in series per string. PV modules are installed on a fixed tilted plane with a tilt angle of 15° and an azimuth of 0° (facing North).
b) Inverter and configuration: Huawei Technologies SUN2000-330KTL-H1 (300 kWac) with a maximum input voltage of 1,500 V and an output voltage of 800 Vac. The system consists of two sub-arrays, with a total of 1,296 modules and 48 strings (24 strings per sub-array), achieving a P_{nom} ratio (DC/AC ratio) of 1.188.
c) Simulation loss parameter assumptions: to ensure high-fidelity replication, specific environmental and technical loss factors observed were integrated into the execution parameters:
   - Optical and environmental losses: the incidence angle modifier (IAM) factor on global irradiation is configured at -1.5%. Soiling loss is set at -3.0% to account for the dust and saline environment of the coastal island. Year-to-year global horizontal irradiation variability is modeled at 3.5% based on Meteonorm 8.2 data.
   - Array internal losses: PV conversion efficiency at STC is defined at 21.32%. Internal module quality loss is set at -0.7%, and string/module mismatch loss is modeled at -2.1%. Ohmic wiring losses (DC) are constrained to -1.0%.
   - Power conversion and storage losses: inverter efficiency loss during dynamic operation is set at -1.4%. The battery system integrated a -4.0% charge/discharge round-trip efficiency loss, a -0.1% storage energy balance discrepancy, and a -2.3% battery global loss component.

The simulation layout and orientation settings demonstrate the feasibility of the proposed system from both technical and spatial perspectives. Performance evaluation is conducted using widely adopted indicators such as PR and capacity factor, which are standard metrics in PV system assessment [18], [19].

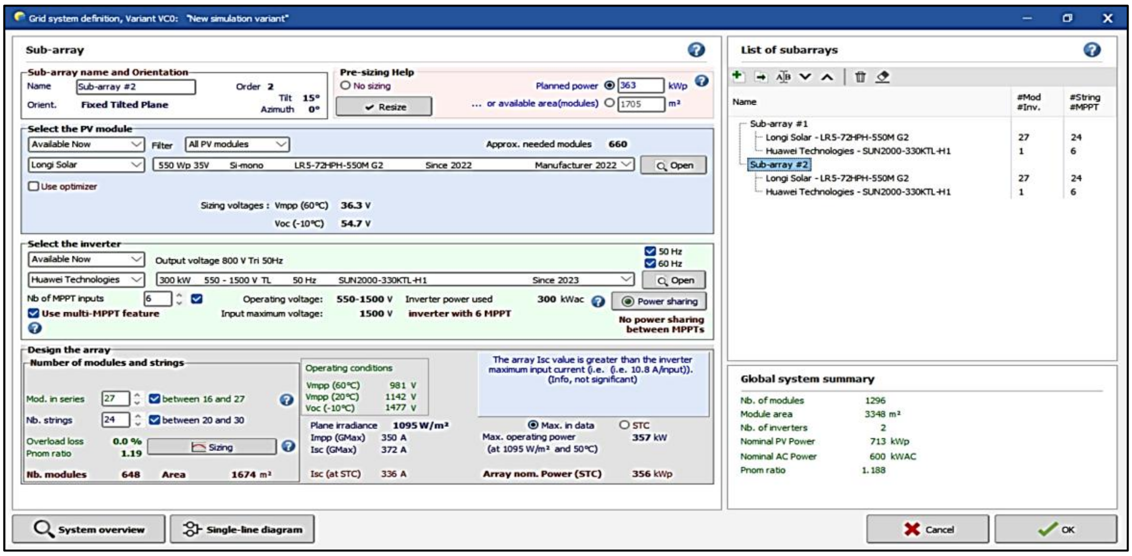

Figure 7. System layout and configuration implemented in PVsyst

2.4.4. Performance evaluation

The technical viability of the off-grid system is evaluated using standardized performance indicators according to ISO/IEC 61724-1. The key metrics are defined as follows:

a) Performance ratio (PR):

The PR indicates the overall effect of losses (temperature, inverter, wiring) on the system's rated output. It is calculated as:

$$PR = \frac{E_{out}}{P_{nom} \times (\frac{G_{i.glob}}{G_{i.ref}})}$$

where E_{out} is the actual energy delivered to the load and battery (kWh), P_{nom} is the installed peak power (kWp), $G_{i.glob}$ is the global incident solar radiation (kWh/m^2), and $G_{i.ref}$ is the standard solar irradiance ($1kW/m^2$).

b) Capacity factor (CF):

This represents the ratio of the actual annual energy output to the maximum theoretical output if the system operated at full rated capacity 24/7:

$$CF = \frac{E_{annual}}{P_{nom} \times 8760} \times 100\%$$

c) Solar fraction (SF):

SF measures the percentage of the total load demand met by solar energy, which is critical for the energy autonomy of Bungin Island:

$$SF = \left(1 - \frac{E_{unmet}}{E_{demand}}\right) \times 100\%$$

d) Unmet load fraction (ULF):

To assess system reliability, the ULF quantifies the energy deficit relative to the annual demand:

$$ULF = \frac{E_{unmet}}{E_{demand}} \times 100\%$$

A target threshold of ULF < 2%$is established to ensure the system's robustness as a primary power source.

Annual energy production results are summarized in Table 5, while the PR distribution and the detailed breakdown of system losses are illustrated in Figures 8 and 9, respectively. PVsyst has been extensively used for PV system modeling and performance evaluation under site-specific climatic conditions [20]-[24].

Table 5. Annual energy production and performance indicators

Parameter (PVsyst output)	Description	Value	Unit
E_{array}	Total annual energy produced by the PV array	1,258.3	MWh/year
E_{Load}	Useful energy supplied to the electrical load	1,032.9	MWh/year
E_{Excess}	Excess energy not utilized by the load	120.84	MWh/year
E_{Excess}/E_{Array}	Excess energy fraction	11.7	%
E_{FrGrid}	Unmet load (energy deficit)	13.7	MWh/year
Solar fraction	Share of load supplied by solar PV	98.67	%
Performance ratio (PR)	Overall system performance indicator	77.6	%
Capacity factor (CF)	Ratio of actual to maximum possible energy output	17.34	%

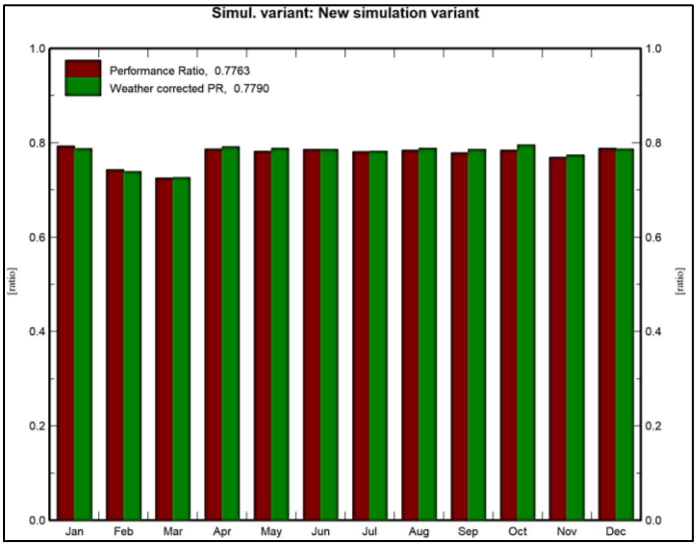

Figure 8. PR of the proposed system

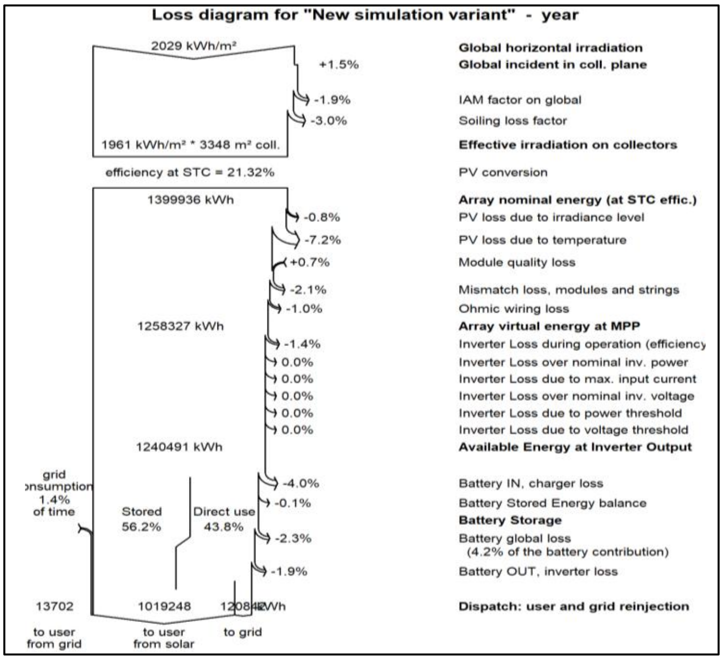

Figure 9. Breakdown of system losses

3. RESULTS AND DISCUSSION

3.1. Annual of energy production and system performance

The annual energy production results obtained from the PVsyst simulation are summarized in Table 5. The total annual energy generated by the PV array (E_{Array}) reaches 1,258.3 MWh/year. Of this energy, 1,032.9 MWh/year is effectively delivered to the electrical load (E_{Load}), indicating a high utilization rate of the available solar resource. A monthly production analysis was conducted to assess the system's stability across different seasons. The results show that the highest production occurs in August due to optimal solar altitude in the southern hemisphere, while the lowest occurs in January during the monsoon peak. Statistical evaluation of the monthly data yields a coefficient of variation (CV) of 8.4%, which confirms that the solar resource on Bungin Island is relatively stable and reliable as a primary energy source.

Furthermore, the solar fraction of 98.67% demonstrates that the proposed off-grid configuration can almost entirely replace diesel-based generation. The remaining unmet load (E_{FrGrid}) of 13.7 MWh/year (1.33%) is critically evaluated as a result of consecutive low-irradiance days during the rainy season. While minor, this unmet load highlight the technical limits of a 100% renewable system without secondary backup. Conversely, the surplus energy (E_{Excess}) of 120.84 MWh/year (11.7% of production) represents a significant opportunity for demand-side integration, which will be further discussed in section 3.6.

3.2. Critical analysis of PR and thermal losses

The simulated annual PR of 77.6% falls within the typical optimal range reported for high-penetration off-grid PV systems integrated with BESS. However, a critical evaluation of the loss distribution (Figure 9) reveals that temperature-related effects represent a major vector of performance degradation, inducing a 7.2% drop in module efficiency. Because Bungin Island is situated in an equatorial coastal zone, ambient temperatures consistently hover around 27.0 °C to 28.4 °C. Under peak solar irradiance, the cell operating temperature escalates far above the standard test condition (STC) of 25 °C. This thermal stress directly degrades generation capacity. This finding demonstrates that in tropical island microgrids, utilizing an optimized DC/AC ratio (1.188 in this study) is a critical design necessity to compensate for ambient thermal losses and maximize power availability during lower irradiance window

3.3. Analysis of environmental losses and system autonomy

The coastal environment introduces specific geographical challenges, primarily reflected in the 3.0% soiling loss and 1.5% IAM factor. Salt-spray accumulation and high relative humidity (averaging 76.8%) require stringent maintenance scheduling to prevent deeper soiling degradation. Despite these combined atmospheric and hardware losses, the system achieves a Solar Fraction of 98.67%.

The annual excess energy (E_{Excess}) of 120.84 MWh/year (11.7% of production) occurs predominantly during peak solar hours (11:00 AM to 2:00 PM) when the 11.54 MWh BESS reaches its maximum state-of-charge. In standard off-grid systems, this represents an operational inefficiency due to energy curtailment. However, for the Bungin Island community, this surplus presents a significant opportunity for demand-side management (DSM). This 120.84 MWh/year could be structurally redirected to power community ice-making machines for local fishermen or small-scale water desalination units, thereby optimizing the socio-economic return of the infrastructure investment. Conversely, the minor unmet load of 1.33% (13.7 MWh/year) underscores the physical limitations of standalone solar systems during multi-day low-irradiance monsoon periods, indicating that absolute diesel elimination requires either cost-prohibitive battery over-sizing or a small standby generator for emergency top-ups.

3.4. Discussion of technical feasibility

The simulation results demonstrate that the proposed off-grid solar PV system is technically feasible for supplying continuous electricity to Bungin Island. The combination of adequate PV capacity and BESS enables high renewable energy penetration while maintaining system reliability. The annual energy production and performance indicators confirm that the system can effectively replace diesel-based generation as the primary electricity source.

Furthermore, the use of site-specific load characteristics and long-term solar resource data enhances the reliability of the system design and performance evaluation. These results provide a practical technical reference for the deployment of off-grid PV systems in small island environments with similar geographical and climatic conditions. These results confirm the technical feasibility of off-grid PV systems for small island electrification, as reported in previous studies [25].

3.5. Comparative analysis and discussion

To validate the findings, the performance of the Bungin Island system is compared with other tropical off-grid studies, as shown in Table 6. The PR of 77.6% achieved in this study is highly competitive for an off-grid configuration. The high solar fraction (98.67%) is significantly higher than earlier studies [14], [16], which is a direct result of the optimized 11.54 MWh battery sizing. This highlights that for ultra-dense islands, over-sizing the storage capacity is more critical than increasing the PV array alone to ensure total diesel replacement.

Table 6. Comparison of system performance with previous studies.

Parameter	This study (Bungin Island)	Azman and Sulistiawan [14]	See *et al.* [8]	Josia [16]
Location type	Ultra-dense Island	Remote Island	Remote Island	Remote Island
PV capacity (MWp)	0.713	0.050	0.120	0.035
Battery capacity (MWh)	11.54	0.20	0.45	0.15
Performance ratio (%)	77.6	75.2	78.1	74.0
Solar fraction (%)	98.67	92.0	95.5	90.0
Unmet load (%)	1.33	8.0	4.5	10.0

3.6. Evaluation of energy balance

The simulation identifies an excess energy of 120.84 MWh/year. Critically, this surplus occurs during peak solar hours when the batteries are fully charged. While this represents a technical “loss,” it offers an opportunity for demand-side management, such as powering water desalination units or ice production for local fishermen, which would improve the overall project economy. Conversely, the unmet load of 13.7 MWh/year (1.33%) predominantly occurs during the monsoon season (December-January) when solar irradiance drops for several consecutive days. While small, this deficit confirms that a 100% renewable system without any backup (such as a small standby diesel generator or even larger BESS) remains a challenge during extreme meteorological anomalies.

3.7. Reliability and sensitivity analysis

To validate the system’s robustness, a sensitivity analysis was performed regarding solar irradiance fluctuations. A 10% reduction in annual global irradiation (representing extreme cloud cover years) would increase the unmet load from 1.33% to 3.5%. However, the integrated 11.54 MWh battery capacity provides approximately 3.2 days of autonomy for critical loads, ensuring that even during consecutive low-sunlight days, basic electricity supply remains stable without requiring diesel backup.

4. CONCLUSION

This study confirms the technical feasibility of transitioning Bungin Island’s power system from diesel dependency to a fully autonomous off-grid solar PV-Battery configuration. The optimized 0.713 MWp PV array and 11.54 MWh lithium-ion battery system demonstrate a high level of reliability, delivering an annual energy output of 1,258.3 MWh with a near-total solar fraction of 98.67%. The achieved PR of 77.6% and capacity factor of 17.34% validate the system’s efficiency within the constraints of a tropical, high-ambient-temperature environment.

The specific contribution of this research lies in providing a technical benchmark for high-penetration renewable microgrids in ultra-dense small island environments. Unlike previous studies that utilize generalized models, this work uses site-specific hourly load profiles to demonstrate that achieving over 98% energy autonomy is technically achievable through optimized storage sizing and an AC-coupled architecture. The critical evaluation of losses identifies thermal degradation and battery cycling as the primary performance drivers, yet the system successfully limits the unmet load to just 1.33%.

These findings serve as a robust technical reference for policy-makers and engineers in deploying large-scale solar systems for geographically isolated and densely populated regions. Future research should integrate economic feasibility studies and explore demand-side management to utilize the identified 120.84 MWh of annual excess energy for communal productive uses, such as water desalination or cold storage.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data supporting the conclusions of this study can be provided by the corresponding author upon reasonable request. However, any data that might reveal participants' identities or sensitive information are not publicly accessible due to privacy considerations.

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