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Techno-Economic Evaluation of Hybrid Photovoltaic-Wind Energy Systems for Indonesian Government Buildings

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Abstract: The burgeoning population in Indonesia necessitates an escalation in energy provision. The reliance on diminishing fossil fuels, coupled with their adverse environmental repercussions, propels the exploration of renewable alternatives. This study investigates the techno-economic viability of implementing hybrid photovoltaic (PV) and wind turbine systems across government edifices within five urban locales: Semarang, Surabaya, Yogyakarta, Jakarta, and Denpasar. Employing the Hybrid Optimization Model for Electric Renewables (HOMER), simulations and optimizations of the hybrid systems were conducted, aiming to fulfil an electrical demand of 2636.1 kWh. The analysis is predicated on a 25-year operational lifespan. Results indicate that Denpasar presents the optimum potential for the hybrid system, with an annual electricity generation of 1,360,195 kWh surpassing the consumption demand of 1,214,136 kWh. The Net Present Cost (NPC) is calculated at IDR 27,529,340,000.00 and the Cost of Energy (COE) at IDR 997.17, yielding an attractive investment prospect with a Break Even Point (BEP) at 8.2 years. The estimated initial outlay for the Denpasar government building's PV system stands at IDR 4,149,376,743.96. The findings underscore the financial and technical feasibility of harnessing solar and wind synergies for sustainable energy solutions in Indonesian government infrastructure. These outcomes have pivotal implications for policy-making and strategic energy planning, demonstrating a replicable model for renewable integration in similar tropical regions.

Keywords: Renewable energy; Hybrid systems; Hybrid Optimization Model for Electric Renewables (HOMER); Techno-economic analysis; Solar-wind energy

1 Introduction

An escalating population trajectory is directly proportional to the burgeoning demand for energy [1]. It is observed that primary energy reserves, specifically oil and coal, are diminishing, heralding the potential onset of energy deficits [2]. The depletion of fossil fuel reserves, coupled with the exacerbation of the greenhouse effect, has catalyzed a quest for alternative, eco-friendlier energy sources [3]. Renewable energy is being widely researched and developed to overcome these various problems [4, 5]. Intensive development has positioned solar energy as a renewable frontrunner [6]. The intrinsic characteristics of solar energy, notably its chemical-free and non-radioactive nature, render it benign to the environment [7, 8]. The application of solar energy is diverse, spanning electricity production, water heating, air heating, and support for various industrial drying processes [9, 10]. Nevertheless, the uneven distribution of solar irradiance necessitates sophisticated technology for optimization [11]. It has been posited that hybrid power plants could offer an economical and efficient solution [12]. The present study models an optimal generating system to address renewable energy requirements.

Solar and wind energy are burgeoning in popularity, with economic potential that is becoming increasingly competitive with that of conventional power plants [13, 14]. These renewable sources are profuse in nature and their utilization does not contribute to CO_2 emissions, thereby affirming their environmental soundness. Indonesia, straddling the equator, reaps substantial solar irradiance annually [15]. As an archipelagic nation subjected to monsoonal winds, it experiences two distinct seasons, offering opportunities to harness wind energy [16]. The synergy of solar and wind energy promises a complementary power source, with solar being predominant during the dry season and wind during the rainy season and nocturnal hours [17, 18]. The use of hybrid solar and wind energy has proven more effective than relying solely on solar energy in various regions of Indonesia [19].

Techno-economic analysis has been established as a necessary component in designing generating systems. This analytical approach quantifies in monetary terms the feasibility of engineering projects [20]. Such analysis has corroborated the viability of projects like the rooftop PLTS System on the Denpasar mayor's office [21]. Furthermore, Arifin et al. [22] have conducted simulations on the potential of interconnected PV-Wind hybrid systems in urban Java. This analysis aimed to create effective, renewable energy with technical, economic and environmental security to solve Indonesian energy crisis [23, 24]. The current research utilizes the HOMER software to examine cost-effectiveness and economic feasibility for power generation systems [25].

The objective of this research is to simulate PV-Wind hybrid energy as a sustainable, efficient, and eco-friendly source of electrical energy for government buildings in Semarang, Surabaya, Yogyakarta, Jakarta, and Denpasar cities. The adoption of an on-grid system configuration, connecting with the PLN (Perusahaan Listrik Negara) electricity network, is considered. This study analyses the techno-economic aspects of PV-Wind hybrid power generation for Indonesian government buildings, with simulation outcomes offering comparative insights and evaluation of factors affecting cost-effectiveness in system design.

2 Research Methods

2.1 Research Flow

The methodology of this study was systematically approached, initiating with a comprehensive literature review, followed by rigorous data collection, leading to detailed simulations and subsequent analyses. Simulations of the PV-Turbine Hybrid PLTS (solar power plants) were executed using the HOMER software to ascertain the optimal configuration of the hybrid systems, as shown in Figure 1.

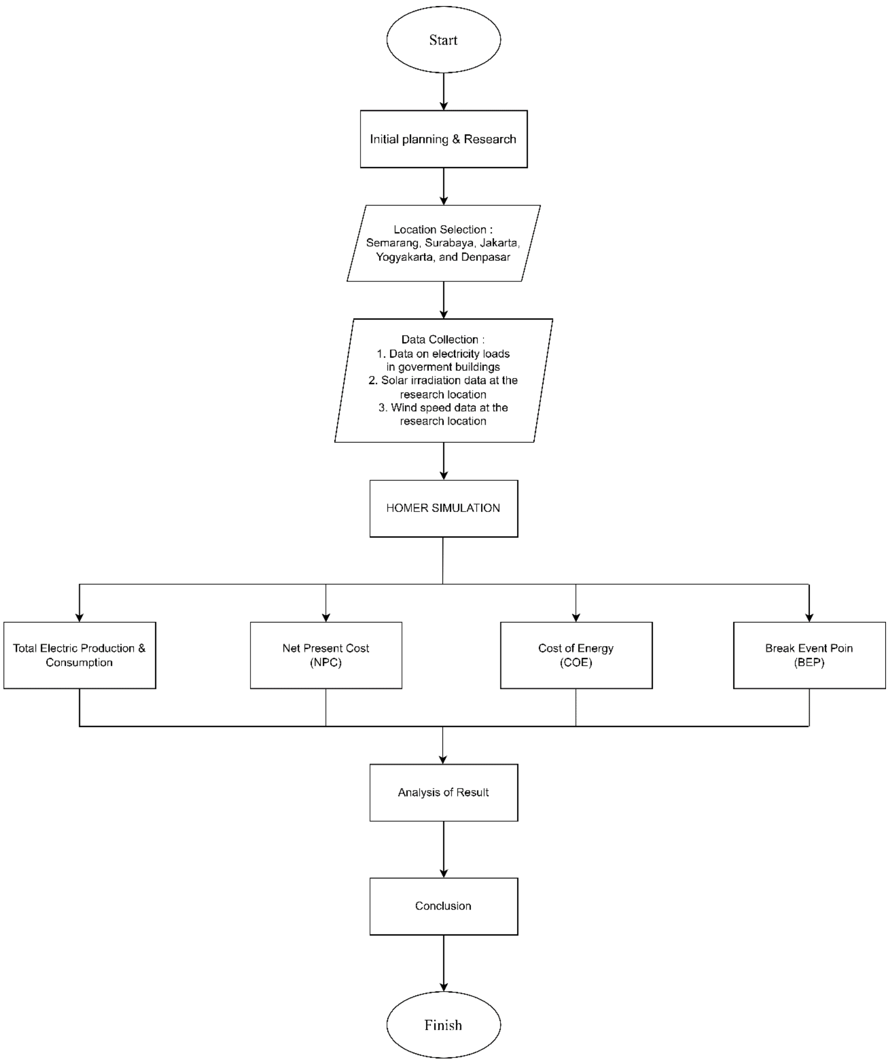


Figure 1. Flow of hybrid PLTS for government buildings

2.2 Description of the Hybrid PV-Turbine System Design Model

The design of the Hybrid PV-Wind Turbine System was modeled utilizing the HOMER software, developed by the National Renewable Energy Laboratory (NREL) [26]. This tool facilitates the optimization of microgrid configurations, allowing for the computation of total energy output and variations in system costs, as well as the economic and financial feasibility of different designs. HOMER is instrumental in the assessment of power generation systems, determining their suitability for grid-connected (On-Grid) or off-grid (Off-Grid) applications.

In this methodology, HOMER was employed to identify the most efficient system configuration, prioritizing the results based on the NPC from the lowest to the highest [27]. Such a prioritization ensures the selection of the most cost-effective system to fulfill the electricity requirements of government buildings. Within the scope of this research, the specifications for the solar panel comprised the Schneider Conext CL25000 E with a generic PV model. The wind turbine selected was the Bergey Excel 6-R series, and the inverter was the KEHUA France KF-BCS 630K-B series. Figure 2 presents the On-Grid system design as conceptualized using the HOMER software.

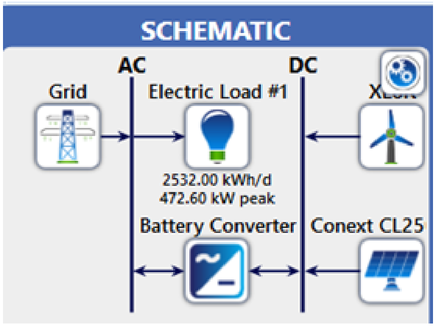


Figure 2. Modeling scheme for a Hybrid PV-Turbine PLTS System for government buildings

Within the configuration under study, the solar panel array is connected to a wind turbine, serving as a direct current (DC) input. An inverter is then employed to transform the DC voltage from the PV cells and the turbine into alternating current (AC) voltage, which is subsequently delivered to the electrical load. Should the voltage generated by the renewable sources prove insufficient for the demands of government buildings, the national electricity utility, PLN, is posited to supplement the shortfall, as shown in Figure 3.

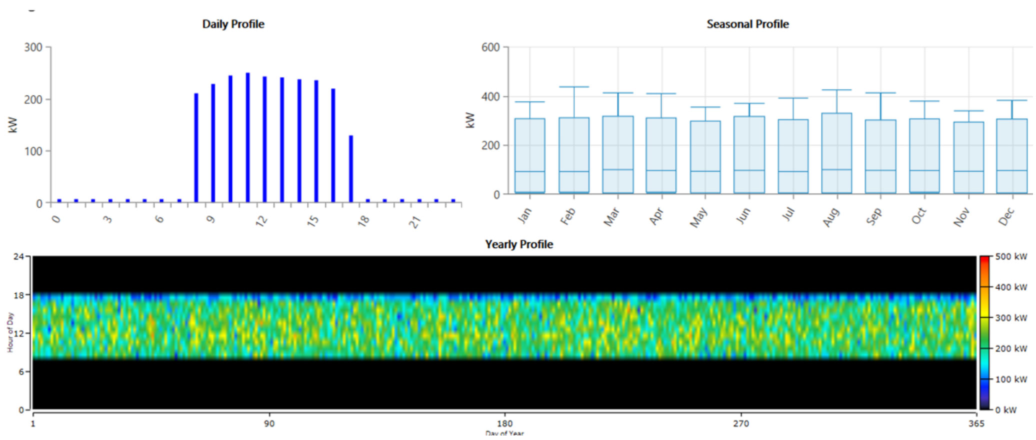


Figure 3. Electric load profile of PLTS Hybrid PV-Turbine for government building

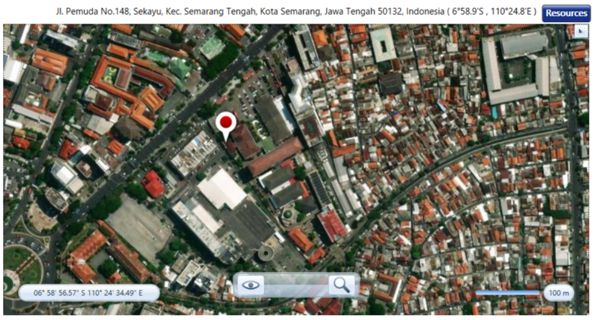
Table 1. Hybrid PV-Turbine PLTS System components for government buildings

Parameter	Schneider Conext CL25000 E with Generic PV	Bergey Excel 6-R	KEHUA France KF-BCS 630K-B
Capital Costs	Rp. 320,000.00	Rp. 38,500,000.00	Rp. 5,100,000.00
Replacement Cost	-	Rp. 38,500,000.00	Rp. 10,200,000.00
O&M Costs	Rp. 320,000.00	Rp. 3,850,000.00	Rp. 500,000.00
Lifetime	25 years	20 years	10 years

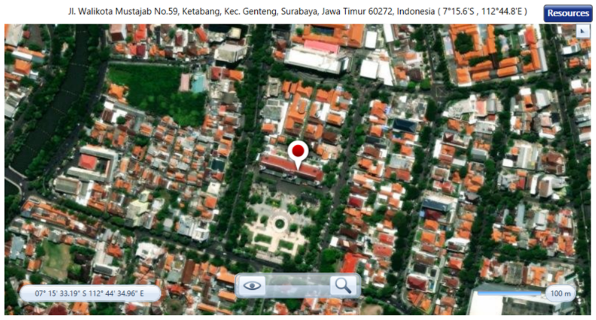
Prior to the commencement of simulations with the HOMER Pro software, requisite data are inputted into the system. These encompass load profiles, renewable energy source data (inclusive of solar irradiance, ambient temperature, and wind velocity), along with technical and economic parameters. Table 1 delineates the list of components integrated into the aforementioned system. It is to be noted that these components are readily procurable within Indonesia, with particular availability on the island of Java.

2.3 Description of the Hybrid PV-Turbine System Design Location

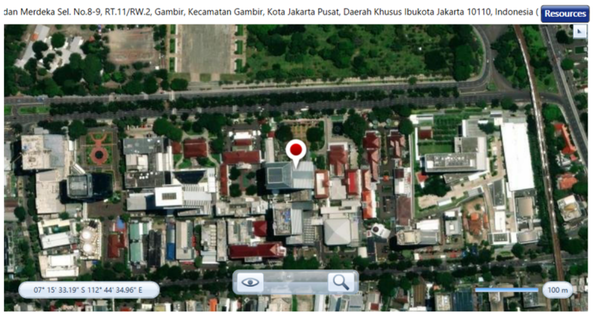
Simulations for the design of the Hybrid PLTS destined for governmental structures are to be conducted within several notable urban centers across Indonesia, including Semarang, Surabaya, Jakarta, Yogyakarta, and Denpasar. The objective of these simulations is to ascertain the economic viability and potential of the aforementioned systems within five major Indonesian cities. The locations selected for the proposed development are depicted in Figure 4.



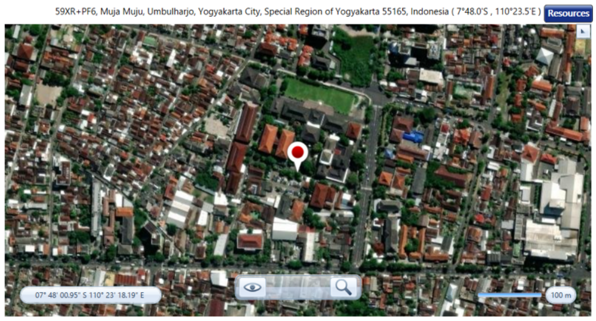
(a) Location of Hybrid PLTS System design for government building Semarang City



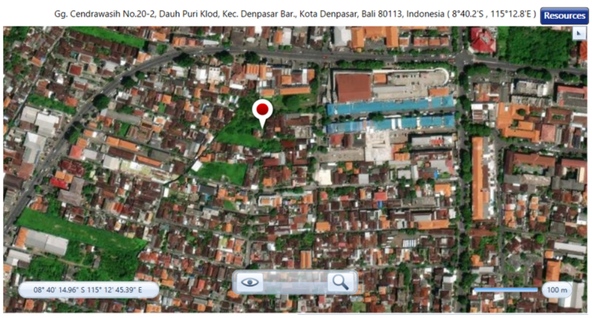
(b) Location of Hybrid PLTS System design for government buildings in Surabaya City



(c) Location of Hybrid PLTS System design for government buildings in Jakarta City



(d) Location of Hybrid PLTS System design for government buildings, Yogyakarta City



(e) Location of Hybrid PLTS System design for government buildings, Denpasar City

Figure 4. Location of Hybrid PV-Turbine PLTS design for government building

2.4 Potential Use of Solar Energy

Solar power plants (PLTS) harness solar radiation, with the efficacy of conversion to electrical energy being contingent upon the PV cells' capacity to absorb this radiation. It has been observed that an augmentation in the intensity of solar radiation impinging upon the photovoltaic cell corresponds to an increased electrical output [28].

Data pertaining to solar radiation intensity across various urban locations, namely Semarang, Surabaya, Jakarta, Yogyakarta, and Denpasar, has been collated and is presented in Table 2. These measurements were procured from the archives of the National Aeronautics and Space Administration (NASA).

Table 2. Solar radiation intensity data

Month	1	2	3	4	5
January	2.55	2.53	1.87	2.69	3.35
February	2.62	2.71	1.63	2.7	3.83
March	3.29	3.01	2.37	3.13	4.32
April	3.59	3.46	2.64	3.52	5.33
May	4.19	4.28	2.79	3.85	5.16
June	4.33	4.75	2.75	3.95	5.01
July	4.76	5.5	3.04	3.99	4.63
August	5.06	6.09	3.31	4.01	4.96
September	5.06	6.13	3.26	3.74	5.18
October	4.04	4.92	2.57	3.01	5.02
November	3.16	3.23	2.08	2.52	4.24
December	2.42	2.21	1.80	2.40	3.10
Average	3.76	4.07	2.51	3.29	4.45
Minimal	2.42	2.21	1.63	2.4	3.1

Description: 1. Semarang, 2. Surabaya, 3. Jakarta, 4. Yogyakarta, 5. Denpasar. Radiation intensity data is in $\mathrm{Wh/m^2}$ units

Denpasar City, exhibiting an average solar radiation intensity of 4.45 $\mathrm{kWh/m^2}$, presents considerable prospects for the deployment of the Hybrid PLTS System. It is postulated that the efficiency of the energy output from such systems is positively correlated with higher intensities of incident solar radiation.

2.5 Potential Use of Wind Energy

Wind velocity data, sourced from the NASA, facilitate the analysis of wind energy's potential integration into Hybrid PLTS, specifically within Semarang, Surabaya, Jakarta, Yogyakarta, and Denpasar. The wind velocity metrics for these municipalities are delineated in Table 3.

Table 3. Wind speed data

Month	1	2	3	4	5
January	5.13	4.41	4.33	3.86	3.78
February	5.09	4.54	4.24	3.95	3.75
March	3.62	3.40	3.73	3.35	3.27
April	3.12	3.25	3.19	3.49	3.77
May	3.65	3.92	3.01	4.12	4.66
June	3.99	4.44	3.16	4.52	5.12
July	4.15	4.86	3.19	5.04	5.47
August	4.08	5.02	3.14	5.29	5.42
September	3.72	4.70	2.89	5.09	4.91
October	3.15	3.76	2.73	4.52	4.34
November	2.80	2.89	2.95	3.90	3.72
December	3.83	3.42	3.99	3.74	3.60
Average	3.86	4.05	3.38	4.24	4.32
Minimal	2.80	2.89	2.73	3.35	3.27

Description: 1. Semarang, 2. Surabaya, 3. Jakarta, 4. Yogyakarta, 5. Denpasar. Wind speed intensity data in units of m/s

Elevated wind speed values correlate with enhanced efficiency in energy output from the generation system. The data presented indicates that Denpasar City exhibits the highest mean wind speed, registering at an average of 4.32 m/s, thereby underscoring its substantial potential for the deployment of the Hybrid PLTS System.

2.6 Main System Components

2.6.1 Total expense

To list the total expense, Table 4 summarizes the data daily total load.

Table 4. Daily total load data

Afternoon (07:00-17:00)		Evening (17:00-07:00)	
O'clock	**Load (kW)**	**O'clock**	**Load (kW)**
7	7.5	18	7
8	210	19	6.8
9	228	20	6.75
10	245	21	6.75
11	250	22	6.5
12	243	23	6.5
13	240	0	6.4
14	238	1	6.4
15	235	2	6.5
16	220	3	6.6
17	129.5	4	6.75
		5	6.9
		6	6.9
Total (kW)	2109		87.75
Increase the load by 20%, so the total power (kW)	2530.8		105.3
Total load per day (kW)		2636.1	

2.6.2 Photovoltaic solar panels

Photovoltaic solar panels are a device that can produce electrical energy from solar radiation [29]. The power produced by the solar panel module can be calculated using the following Eq. (1) [30].

$$PPV = F_{pv} \cdot Y_{pv} \frac{G_T}{G_{T,STC}} \tag{1}$$

where,

PPV: Power produced by the PV module (kW)

Fpv: PV derating factor

Ypv: Power output PV at standard conditions (kW)

GT: Instantaneous radiation on the surface of the PV module ($\mathrm{kW/m^2}$)

GT, STC: Instantaneous radiation under standard conditions (1 $\mathrm{kW/m^2}$)

The type of solar panel used in this Hybrid PLTS System is the Schneider Conext CL25000 E solar panel with generic PV. This solar panel has the specifications shown in Table 5 and can be seen in Figure 5.

Table 5. Solar panel specifications

Technical Specifications	Mark
Maximum power (Pmax)	25000 Wp
Maximum voltage (Vmp)	1000 V
Maximum current (Imp)	37 A
Open circuit voltage (Voc)	480 V
Short circuit current (Isc)	36 A
Module efficiency	98%
Derating factors	85%

2.6.3 Wind turbine

A wind turbine is a device that captures kinetic energy in the form of wind energy and converts mechanical energy (turbine movement) into electrical energy through a generator [28]. The following equation is used to calculate the potential power produced by a wind turbine (P_{mt}) every day [31].

$$P_{mt} = \frac{1}{2}\rho \times v^3 \times A \times cp \tag{2}$$

Figure 5. Schneider conext CL25000 E with generic PV

where,

P_{mt}: The potential power produced by a wind turbine
ρ: Density of air $(\mathrm{kg/m^3})$
v: Wind speed (m/s)
A: Blade area (m^2)
cp: Turbine efficiency

The type of wind turbine used in this Hybrid PLTS System is Bergey Excel 6-R. This wind turbine has the specifications shown in Table 6 and can be seen in Figure 6.

Table 6. Bergey excel 6-R specifications

Technical Specifications	Mark
Output power	5.5 kW
Maximum voltage (Vmp)	230 V
Furling wind speed	14-20 m/s
Cut-in wind speed	2.5 m/s
Number of blades	3
Rotor speed (RPM)	0-400 RPM

Figure 6. Bergey excel 6-R

2.6.4 Inverters

The inverter functions to change the current from DC electric voltage (direct current) produced by the PV array into AC electric voltage (alternating current) with a frequency of 50Hz/60Hz [32]. Hybrid PLTS for Government Buildings uses a KEHUA France KF-BCS 630K-B inverter. The specifications of this inverter are shown in Table 7 and depicted in Figure 7.

Table 7. KEHUA France KF-BCS 630K-B specifications

Type of Technical Specification	Mark
Output power	700 kW
Maximum power	1400 kW
Output frequency	50-60 Hz
Input dc voltage	48 V
Efficiency	94%

Figure 7. KEHUA France KF-BCS 630K-B

2.7 Economy

2.7.1 NPC

The optimality of the system configuration is ascertained by the magnitude of the NPC, which reflects the aggregate cost of the system over its lifespan. The HOMER software sequences the optimization outcomes by ascending NPC values, thereby privileging the most cost-effective configurations [33]. The total NPC encompasses the entirety of the project expenditures, encapsulating component costs, replacement, maintenance, operational fuel, and the cost of capital. The NPC is calculable by employing the following Eq. (3) [22].

$$NPC = \frac{C_{ann,tot}}{CRF.i.R_{\text{proj}}} \tag{3}$$

where,

Cann, tot: Total annual fee (Rp/year)
CRF: Capital recovery factor
i: interest rate
Rproj: life of use (years)

2.7.2 COE

In conjunction with the determination of NPC, the analysis further extends to the computation of the COE, representative of the average cost per kilowatt-hour for the electricity generated by the system. The COE is derived by the division of the total annualized system cost ($C_{\text{ann,tot}}$) by the annual electrical energy output accommodated by the system (E_{served}). This relationship is succinctly captured in the mathematical expression for COE, presented as Eq. (4) [34].

$$COE = \frac{C_{\text{ann , tot}}}{L_{\text{prim },AC} + L_{\text{prim },DC}} \tag{4}$$

where,

Lprim,AC: AC loads per year (kWh/year)
Lprim,DC: DC loads per year (kWh/year)

3 Results and Discussion

3.1 HOMER Simulation Results

Utilizing the HOMER software, the simulation conducts an optimization process to ascertain the most efficacious configuration of the proposed system. The optimal system configuration, as determined by HOMER, favors an on-grid setup. The annual energy output produced by the system across five cities is delineated in Table 8.

Table 8. Total electric power production per year

City	Production	Amount of Production Power (kWh/year)	Total Production (kWh/year)
Semarang	PV	102,528	952,947
	Wind Turbines	45,771	
	Grid	804,647	
Yogyakarta	PV	101,978	1,255,760
	Wind Turbines	599,786	
	Grid	553,996	
Surabaya	PV	101,468	976,729
	Wind Turbines	94,641	
	Grid	780,620	
Jakarta	PV	104,456	998,089
	Wind Turbines	181,173	
	Grid	712,460	
Denpasar	PV	102,096	1,360,195
	Wind Turbines	770,987	
	Grid	487,112	

Table 9. Electrical power consumption per year

City	Consumption	Amount of Consumption (kWh/year)	Total Consumption (kWh/year)
Semarang	AC primary load	924,180	943,170
	Grid sales	18,990	
Yogyakarta	AC primary load	924,180	1,143,912
	Grid sales	219,732	
Surabaya	AC primary load	924,180	958,797
	Grid sales	34,617	
Jakarta	AC primary load	924,180	991,486
	Grid sales	67,306	
Denpasar	AC primary load	924,180	1,214,136
	Grid sales	289,956	

The HOMER simulation additionally yielded results for the annual electricity load consumption for each city, as detailed in Table 9.

Drawing from the data presented in Tables 8 and 9, it emerges that Denpasar City exhibits the most substantial potential, boasting the highest total electric power production at 1,360,195 kWh/year. Conversely, Semarang City demonstrates the least total power consumption, recorded at 943,170 kWh/year.

3.2 NPC

The NPC serves as a financial metric to ascertain the cumulative expenditure associated with the establishment and operational maintenance of a power generation facility. The NPC encompasses a multitude of financial aspects within each system configuration, such as initial capital outlay, costs of component replacement, operations and maintenance (O&M), fuel expenditures, and end-of-life salvage value [31]. The NPC figures play a pivotal role in evaluating the financial viability of each proposed system configuration; configurations with lower NPC values are indicative of greater economic potential. The simulation-derived NPC values for the various configurations under consideration are delineated in Table 10.

Table 10. NPC value

City	NPC (IDR)
Semarang	28,459,450,000.00
Yogyakarta	27,918,600,000.00
Surabaya	28,392,380,000.00
Jakarta	27,770,060,000.00
Denpasar	27,529,340,000.00

Based on the data in Table 10, it can be concluded that the city with the highest potential is Denpasar City, with an NPC value of IDR 27,529,340,000.00.

3.3 COE

The COE represents the average monetary expense incurred for each kilowatt-hour of electricity generated by the system [35]. This metric is integral to gauging the economic efficiency of the system configurations devised. Optimal configurations are characterized by lower COE values, which denote a higher economic advantage. The simulation results yield the COE values for the respective configurations, which are systematically cataloged in Table 11.

Table 11. COE value

City	COE (IDR)
Semarang	1,327.01
Yogyakarta	1,073.35
Surabaya	1,302.31
Jakarta	1,231.77
Denpasar	997.17

Based on the data in Table 11, it can be concluded that the city with the most potential is Denpasar City, with a COE value of IDR 997.17.

3.4 BEP

The BEP delineates the juncture at which revenue equals the costs, signifying a neutral financial position wherein neither profit nor loss is realized over a specified duration. It is a critical measure for evaluating the financial viability of energy systems. A lower BEP suggests a swifter recovery of investment, indicating a system with enhanced economic potential. The BEP values derived from the HOMER-based simulation across the various cities are delineated in Table 12, illustrating the comparative economic outcomes for each locale.

Table 12. BEP value

City	Year of BEP Occurrence
Semarang	3.1
Yogyakarta	8.2
Surabaya	4.2
Jakarta	9.8
Denpasar	8.2

Based on the data in Table 12, it can be concluded that the city with the most potential BEP value is Semarang City, with a BEP value of 3.1 years.

3.5 Proposed System

The outcomes of the HOMER software simulations have identified Denpasar as the city offering the most auspicious prospects for the PLTS configuration in government edifices. The optimization facilitated by the HOMER software enabled the ascertainment of the most favourable system configuration, which was determined by assessing various metrics including the total electrical energy generated, total electrical energy utilized, NPC, COE, and BEP. The monthly electrical output from the optimized system configuration is depicted in Figure 8, whilst the cash flow projections for the proposed model, as simulated for Denpasar City, are exhibited in Table 13.

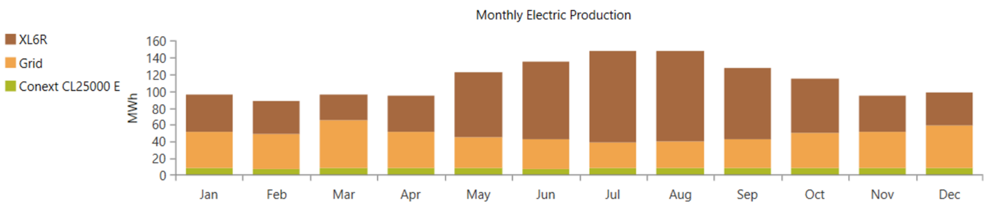


Figure 8. Monthly electricity production using the proposed model

Table 13. Cash flow on the proposed system

Components	Capital	Replacement	O&M	Salvage	Total
Bergey Excel 6-R	IDR 2,964,500,000.00	IDR 2,556,512,248.36	IDR 6,740,821,567.91	IDR - 1,847,707,607.68	IDR 10,414,126,208.60
KEHUA France KF-BCS 630K-B	IDR 1,139,966,366.24	IDR 4,083,398,945.89	IDR 2,541,284,238.72	IDR -947,354,597.13	IDR 6,817,294,953.73
PLN	-	-	IDR 10,150,892,323.82	-	IDR 10,150,892,323.82
Schneider Conext CL25000 E with generic PV	IDR 44,910,377.72	-	IDR 102,119,360.01	-	IDR 147,029,737.74
Systems	IDR 4,149,376,743.96	IDR 6,639,911,194.25	IDR 19,535,117,490.48	IDR - 2,795,062,204.80	IDR 27,529,343,223.88

4 Conclusion

In this investigation, an evaluative comparison was conducted of on-grid hybrid PV-Wind Turbine PLTS tailored for governmental structures across five major Indonesian urban centers: Semarang, Yogyakarta, Surabaya, Jakarta, and Denpasar. Utilising the HOMER software, system configurations were simulated and optimized. The results indicate a superior efficiency and cost-effectiveness for the hybrid (PV/Wind) system over a standard PV system, given identical electrical loads.

It was revealed through modelling that the hybrid system, when connected to the grid, obviates the need for supplementary battery storage under standard operational parameters. Moreover, surplus renewable energy is seamlessly integrated into the grid. Pertinent metrics considered in the assessment of system design potential encompassed total electrical output, consumption figures, NPC, COE, and BEP.

The simulations executed via the HOMER software identified Denpasar as the city with the highest potential for the implementation of hybrid PV/Wind Turbine systems in government buildings. The findings demonstrate Denpasar's capability to generate 1,360,195 kWh/year, with total electricity consumption recorded at 1,214,136 kWh/year. The NPC was determined at approximately IDR 27,529,340,000.00, and the COE was ascertained at IDR 997.17, suggesting a viable investment with the BEP projected at 8.2 years. The estimated initial construction cost for the PLTS at government edifices in Denpasar stands at IDR 4,149,376,743.96.

It is envisaged that the outcomes of this study will contribute to the advancement of renewable energy utilization, notably in harnessing solar and wind energy. The innovation presented by this hybrid PLTS design is anticipated to facilitate a reduction in future investment costs for componentry. Consequently, such hybrid power generation systems are poised for escalated development in the ensuing years.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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