https://doi.org/10.33322/jtpeep.v1i1/100

Research Article

Integration of Renewable Energy and Battery Storage Systems for Electrification of Gili Raja Island with a Techno-Economic Approach

Azmil Muftaqor Imami[1*]; Helmy Priya Hutama[1]; Muhammad Zharif Himawan[1] ; Rian Prima Hardiyanto[1]; Bambang Priyono[1]

[1] Universitas Indonesia

Corresponding author:** ***Azmil Muftaqor Imami, azmil.muftaqor@ui.ac.id

CITATION

Author Name. (2024). Article title. *Journal of Technology and Policy in Energy and Electric Power*. 1:1. https://doi.org/10.33322/jtpeep.v1i1

ARTICLE INFO

Received November 25, 2024
Accepted December 22, 2024
Available online December 30, 2024

Abstract: *Gili Raja Island is part of the small island clusters in Sumenep Regency. According to data from the Central Statistics Agency (BPS), 409 out of 2,133 households on this island still lack access to electricity. This study aims to determine the capacity requirements for power plant, to achieve Net Zero Emission (NZE). Using the HOMER Pro software, this study estimates the required generation capacity to meet the demand of Gili Raja Island, amounting to 1,917 MWh per year. The study results indicate that the lowest Levelized Cost of Electricity (LCOE) is achieved with a scenario combining wind turbines, diesel generator, and solar PV with NMC batteries, yielding a value of 0.189 $/kWh. To achieve NZE, based on HOMER optimization, the lowest LCOE for a fully clean energy portfolio is achieved with a combination of solar PV and lithium-ion batteries, with an LCOE of 0.246 $/kWh. This cost is 28% higher than the cheapest portfolio that includes diesel generator, but it can prevent 106,095 kgCO2 emissions annually from power plant operations. Choosing the right funding option is a crucial part of this study, with results showing that internal funding from PT PLN (Persero) offers the best scheme.*

Keywords: *Funding, Generation Portofolio, Techno-economic*

1. Introduction

Indonesia is the largest archipelagic country in the world with over 17,000 islands. The population living on these separated islands faces unique challenges, one of which is meeting the electricity needs of its people. According to PLN statistics in 2022, the electrification ratio in Indonesia is 97.63% [1]. To achieve a 100% electrification ratio, various energy sources are needed to reach this target. In addition to the goal of achieving full electrification, Indonesia also aims to reach net-zero emissions by 2060, one of which is by decarbonizing the electricity sector, particularly in the planning and development of power plants. One of the efforts made is through planning and building power plants that use renewable energy sources, with an energy mix target of 23% by 2025.

Gili Raja Island is located in East Java Province. The island faces several issues that need to be addressed, such as damaged road infrastructure, a clean water crisis, inadequate port infrastructure, and the presence of residents who still lack electricity services. To meet the island's electricity needs, one alternative is to build solar PV and wind turbines. This study will calculate the electricity needs of the population, determine the required capacity for solar PV and wind turbines, simulate using the HOMER Pro software, compare the costs of these two types of power plants, and determine the appropriate funding scheme to finance the development of these power plants.

1.1. Gili Raja Island

Gili Raja Island is an island in the cluster of small islands located in Giligenting District, Sumenep Regency, East Java Province. This island consists of four villages: Banbaru, Banmaeng, Jate, and Lombang , with an area of approximately 11.39 hectares [2].

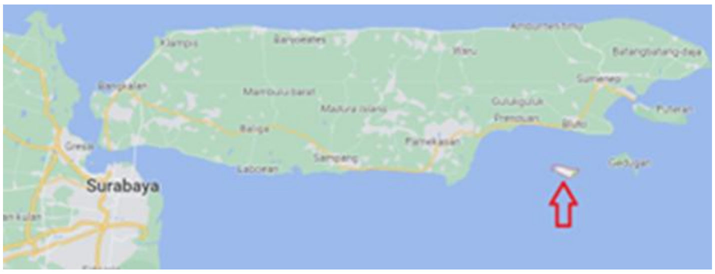


Figure 1. Location of Gili Raja Island

Figure 2. Map of Gili Raja Island

Based on data from the National Statistics Office (BPS-Statistics) of Sumenep Regency in 2023, Gili Raja Island has a population of 12,867 people, with the majority working as farmers and fishermen. The statistics also indicate that there are still 409 households out of 2,133 households that do not have access to electricity.

1.2. Solar PV

Solar PV operates by converting solar energy into electrical energy [3]. Solar PV uses photovoltaic modules, which consist of photovoltaic cells made of wide, flat semiconductor diodes. A diode is an electrical component that allows current to flow in one direction, made from semiconductor material and doped with two different elements, boron and phosphorus. When the two regions (P-N Junction) of these different elements meet, an electric field is formed. These photovoltaic cells, when exposed to sunlight, will generate current and voltage. Generally, the components of a Solar Power Plant include PV panels, inverters, and controllers. For PV systems that are not connected to the electrical grid, an additional component, such as a battery, is needed to ensure that the electricity demand can still be met at night. According to data from Solargis (2017), the solar energy potential in Indonesia is quite good, at 4.8 kWh/m², making Solar Power Plant a viable alternative for electricity supply, particularly in areas that do not yet have electricity access.

1.3. Wind Turbines

Wind Turbines operate by converting wind energy into electrical energy. The wind energy, in the form of kinetic energy, passes through blades, which are converted into mechanical energy, then drives a generator, eventually producing electrical energy. A wind turbine consists of several main components, including wind turbines, pitch control to regulate the turbine blade angle, nacelle as a protective cover for components, and a generator to convert mechanical energy into electricity, among others [5]. Wind energy potential in Indonesia is relatively large, especially in the southern part of Java Island, NTT and NTB provinces, and much of Sulawesi Island [6]. According to the 2022 Indonesian Energy Outlook released by the National Energy Council, Indonesia's wind energy potential is 154.9 Gigawatts (GW).

1.4. Diesel Generator

Diesel generators operate using a diesel engine as the main driver or prime mover. The diesel engine works by generating mechanical energy, which is then used to drive the rotor components of a generator, producing electricity. Diesel generators are commonly used to meet electricity needs in small amounts, covering areas that are not widespread, such as rural areas or in industrial sectors that require their own electricity supply. The fuel used in diesel engines is diesel or petroleum-based hydrocarbons derived from crude oil processing [8]. Since April 2022, the Gili Raja Regency Government has been operating a diesel generator built in collaboration with PT PLN (Persero). However, the use of this diesel generator is still limited, with short operating durations.

1.5. Battery Energy Storage (BES)

Battery Energy Storage (BES) is commonly used as an energy storage medium for various applications, such as electric vehicles or static devices like telecommunication equipment, data centers, and renewable energy power plants. BES is used to address fluctuating energy supply issues caused by weather conditions, power outages, and other challenges, ensuring a continuous energy flow [9]. The performance of BES is influenced by charging and discharging cycles, load profiles, battery component configurations, and environmental conditions. The principle of BES operation is that batteries receive electricity from the power grid, directly from power plants, or from renewable energy sources such as solar panels, then store it and release electrical energy when needed. Some types of batteries used in BES systems include Lithium-ion, Lead-acid, Solid-state, and Nickel-cadmium [10].

1.6. HOMER Pro Software

HOMER Pro Software (Hybrid Optimization of Multiple Energy Resources Pro) is a software developed by UL Solutions used to optimize electrical power systems using renewable energy power plants such as PLTS and PLTB, with or without batteries [11].

Journal of Technology and Policy in Energy and Electric Power
Volume 1, Number 1, December 2024
https://doi.org/10.33322/jtpeep.v1i1/100

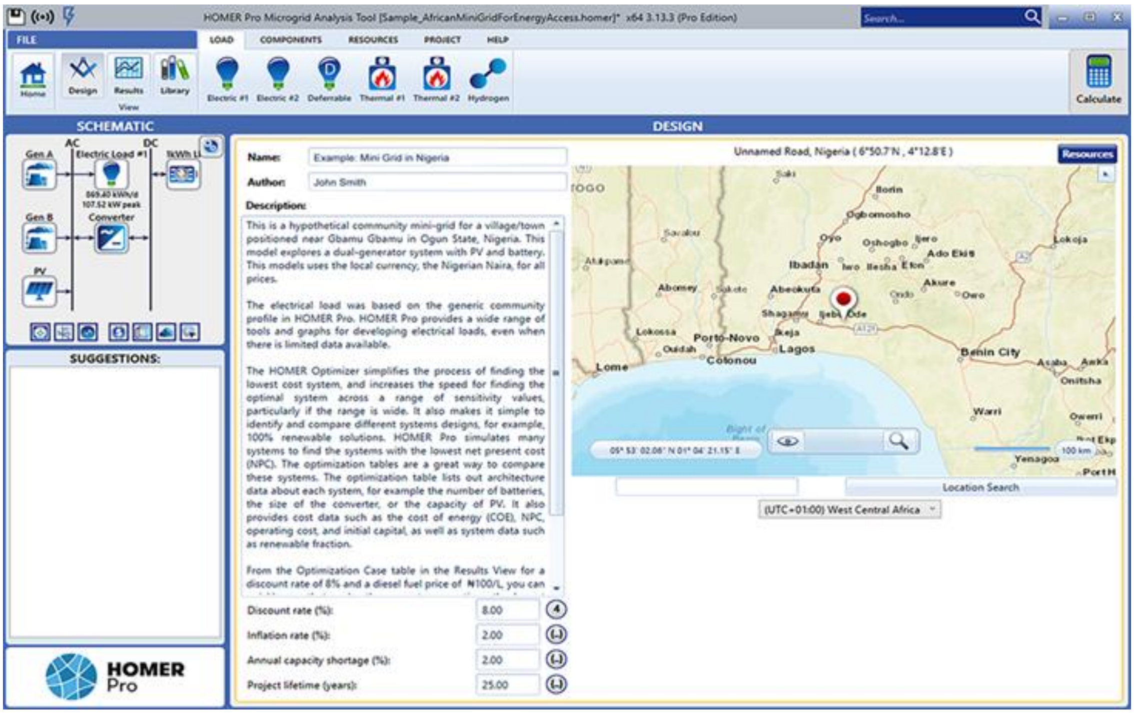


Figure 3. HOMER Pro Software Interface

HOMER Pro can simulate the operation of a hybrid system for one year or more, with time intervals ranging from one minute to one hour. In general, the HOMER Pro application includes several modules, such as the biomass, hydro, combined heat and power, hydrogen, and advanced storage modules. HOMER Pro has several functions, including simultaneously simulating technical and economic aspects, determining the best system combination with the lowest cost option, and comparing different scenarios to identify the best one. To simulate the capacity and cost requirements for the development of Solar Power Plants and Wind Power Plants, the data required includes daily electricity demand, solar irradiation values, average wind speed, discount rate, and the price of each equipment component. To perform the simulation in HOMER Pro, the electricity demand calculation yields the following results:

Table 1. Estimated Electricity Demand for Gili Raja Island

No.	Data	Total	Data Source
1	Number of Families Without Electricity (family)	409	BPS-Statistics of Sumenep Regency
2	Number of Residents Without Electricity (person) (assuming 4 family members/household)	1,636	
3	Demand (kWh)	1,172	Ministry of Energy and Mineral Resources
4	Total Annual Demand (kWh)	1,917,392	

In the HOMER Pro software, in addition to the electricity demand, the data that needs to be provided includes the discount rate and the price of each component. In this study, the discount rate used is 6.1%, which refers to the green bond issued by a bank in Indonesia in 2023. The price references for each component are as follows:

Table 2. Cost Estimation for Each Component

No.	Data	Investment ($/kWh)	Fixed O&M ($/kWh/year)	Data Sources
1	Solar PV	960	7.5	Ministry of Energy and Mineral Resources
2	Wind Turbine	1650	40	Ministry of Energy and Mineral Resources
3	Lithium Nickel Manganese Cobalt Battery (NMC)	293.5	5.87	Ministry of Energy and Mineral Resources
4	Lithium Iron Phospate Battery (LFP)	401	8.02	IRENA
5	Lead Acid Battery	110.5	2.21	IRENA
6	Inverter	93	-	Tokopedia e-commerce

In its optimization process, HOMER calculates various scenarios from different combinations of generation technologies. For each scenario, the optimization results in the optimal size of each technology to achieve the lowest LCOE value. In the HOMER software, the LCOE value is obtained from equations 1 and 2 [11], which are as follows:

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}} \quad (1)$$

In which,

$C_{ann,tot}$ = *Total annualized cost of the system* ($/yr)
c_{boiler} = *Boiler marginal cost* ($/kWh)
H_{served} = *Total thermal load served* (kWh/yr)
E_{served} = *Total electrical load served* (kWh/yr)

$$C_{ann,tot} = CRF(i, R). C_{NPC,tot} \quad (2)$$

$C_{NPC,tot}$ = T*otal net present cost* ($),
i = *Annual real discount rate* (%)
R = *Project lifetime* (yr)
CRF = *A function returning the capital recovery factor*

For the total net present cost, it represents the entire cost of the technology over its lifetime, including the investment cost, replacement cost, operation and maintenance cost, fuel cost, emission penalty cost, and the cost of purchasing electricity from the grid.

1.7. Funding Schemes

Funding is one of the crucial aspects of developing power plant projects, particularly renewable energy plants. To meet this funding need, solar PV and wind power business models have continued to evolve. According to NREL, the solar PV business model has entered its second generation with developments as follows:

Journal of Technology and Policy in Energy and Electric Power
Volume 1, Number 1, December 2024
https://doi.org/10.33322/jtpeep.v1i1/100

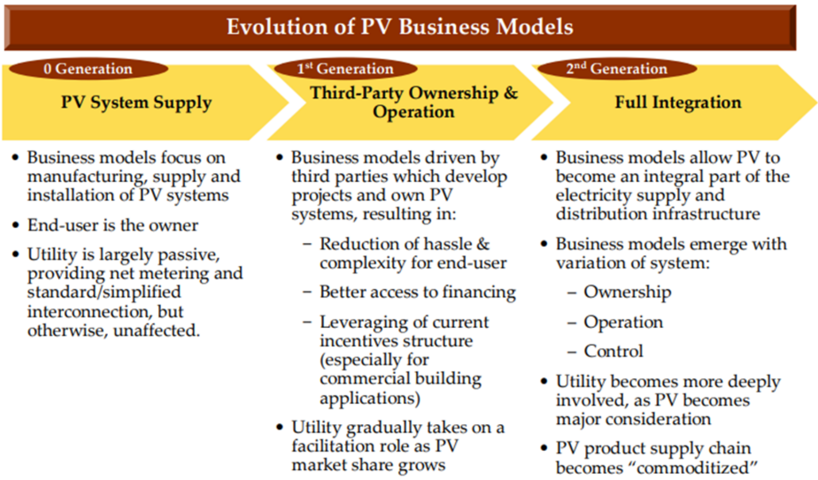


Figure 4. Development of Solar PV Business Models [13]

In China, several funding mechanisms have been implemented for solar PV projects [14], including:

1. Conventional Bank Loans
   Under this scheme, the China Development Bank establishes policies requiring commercial banks and local governments to provide soft loans to consumers. However, due to risks and unpredictable returns, loans are offered only for short terms (1-5 years), which is inconsistent with project lifespans of around 20-25 years.
2. Investment Funding for the Solar PV Industry
   This scheme involves venture capital providing support to the solar PV industry, not only through funding but also by facilitating access to insurance companies and identifying markets for solar PV sales.
3. Lease Financing
   In this scheme, a leasing company (lessor) purchases the solar PV system, and the lessee pays monthly installments until the system is fully paid off.
4. Internet Financing
   In this approach, funds are crowdsourced from the general public. Public investors contribute capital to build solar PV systems and receive monthly returns from electricity production profits.

Additionally, five funding options for electrification programs in rural areas [15] including:

1. Donations
   Under donation-based funding, project costs are covered by donors or sponsors, while users typically pay for operation and maintenance costs.
2. Cash Payments by Users
   In this option, users directly pay for project construction costs as well as operation and maintenance costs. It targets high-income users but has limitations, such as users opting for smaller-capacity systems to save costs or replacing damaged components with incompatible and lower-quality parts, reducing the system's efficiency.
3. Energy Service Company (ESCO)

Under this model, an energy company purchases and installs solar PV systems and takes responsibility for operation and maintenance. The company or government may fund the project, and users pay monthly fees. This model has received positive responses in countries like the Dominican Republic, Togo, and Argentina. However, users are not the system owners, which may result in less user engagement in system maintenance.

4. Credit or Leasing Systems
   Users gradually pay for the solar PV system by making an initial down payment. Developers typically secure loans from banks or third parties to fund the project. Once payments are complete, ownership transfers to the user.
5. Fee-for-Service
   In this model, the company owns the solar PV system while users own the batteries. Users pay affordable monthly rental fees based on system capacity. Maintenance is the company's responsibility, making it popular since users avoid large upfront investments.

For hybrid solar PV-wind power plants, alternative public funding options [16] including:

1. Grants and Subsidies
   Governments or international donors provide grants to partially fund initial construction costs, reducing the financial burden on projects and making them more accessible to investors.
2. Venture Capital
   Venture capital offers funding for high-risk, high-reward projects, often targeting new technologies or projects with significant growth potential.
3. Debt Financing
   Projects secure long-term loans from banks or financial institutions, repaid through revenues generated from plant operations.
4. Asset-Backed Securities
   Power plants issue securities backed by cash flows from electricity sales, enabling lower-cost, long-term financing and bundling multiple projects into one offering.
5. Results-Based Financing
   Funding is linked to achieving specific project milestones, such as energy production targets or carbon emissions reductions. Financial incentives are provided only after results are achieved.
6. Carbon Financing
   Hybrid wind and solar projects generate additional revenue by selling carbon credits on global carbon markets, helping reduce operating costs and enhance financial viability.
   Electrification on Gili Raja Island uses an internal ESCO (Energy Service Company) funding scheme through the state utility company, PLN. This approach allows PLN to efficiently manage solar PV systems by involving third parties with specialized expertise, while internal funding supports large-scale projects, reducing reliance on external donors. This combination provides a sustainable solution for advancing electrification and clean energy transition in Indonesia.

2. Methodology

This study involved a comprehensive methodology that encompassed a literature review, data collection, simulation and optimization using HOMER Pro software, data analysis, and the compilation of a final report. The methodological framework is illustrated in the following flowchart :

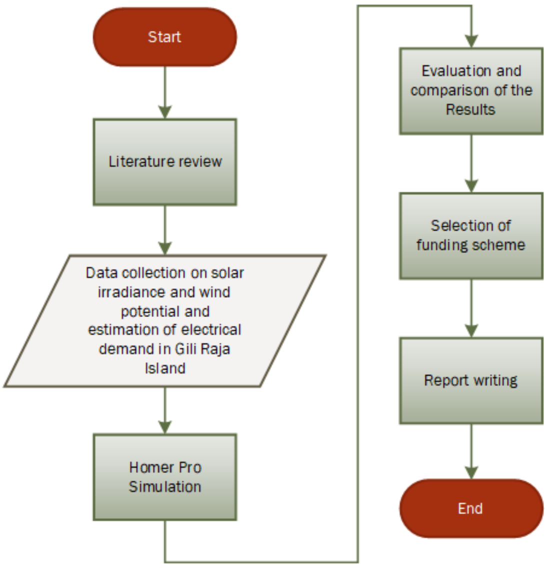
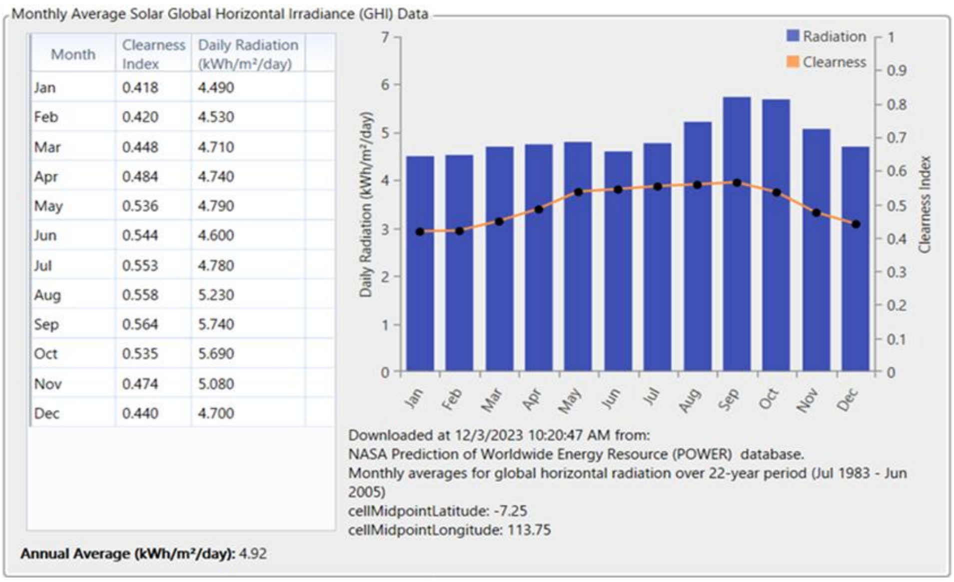


Figure 5 . Research Flowchart

3. Results and discussion

In this study, simulations will be conducted to determine the optimal configuration of a hybrid system comprising solar photovoltaic (PV), wind turbines, diesel generator, and various battery energy storage (BES) technologies, including lead-acid, NMC, and LFP, using HOMER Pro software. The objective is to meet the electricity demand of unelectrified households on Gili Raja Island. By specifying the simulation location in HOMER Pro, the solar irradiance and average wind speed data for Gili Raja Island can be obtained. Based on data from NASA Prediction of Worldwide Energy Resources (POWER), the average Global Horizontal Irradiance (GHI) on Gili Raja Island is as follows :



Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.418	4.490
Feb	0.420	4.530
Mar	0.448	4.710
Apr	0.484	4.740
May	0.536	4.790
Jun	0.544	4.600
Jul	0.553	4.780
Aug	0.558	5.230
Sep	0.564	5.740
Oct	0.535	5.690
Nov	0.474	5.080
Dec	0.440	4.700

Figure 6. Estimated GHI in Gili Raja Island

The average wind speed data for Gili Raja Island was also sourced from NASA's Prediction of Worldwide Energy Resource (POWER) database. The specific values are presented below :

https://doi.org/10.33322/jtpeep.v1i1/100

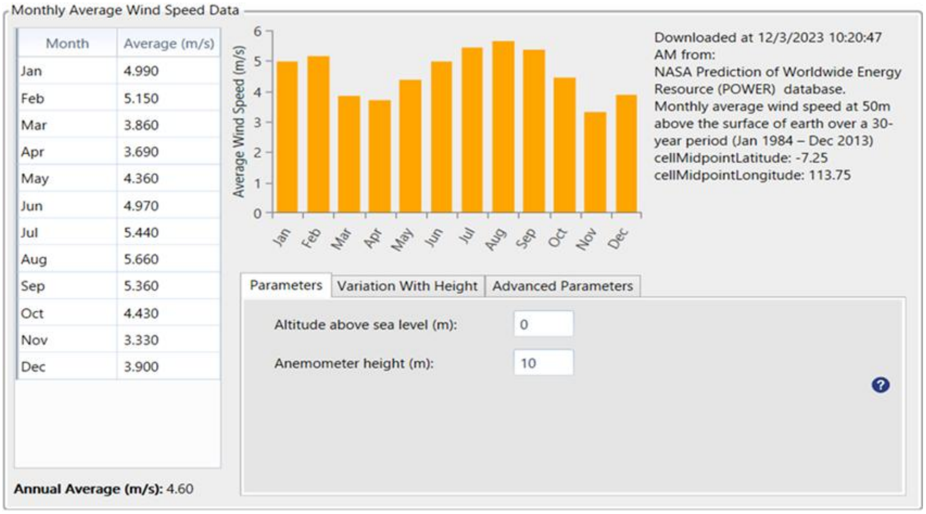


Figure 7. Estimated Average Wind Speed in Gili Raja Island

The simulated system consists of the following components: solar PV, wind turbines, diesel generator, inverter, battery, and load.

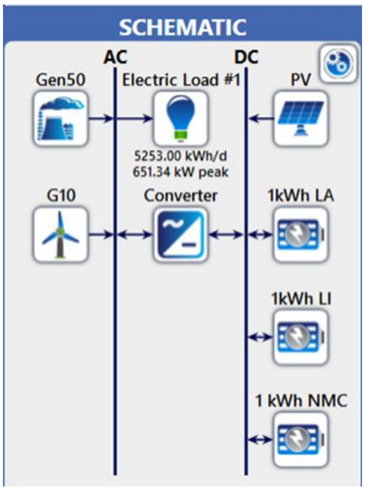


Figure 8. Simulated System Configuration

Various scenarios were simulated and optimized in this study, each with unique combinations of solar PV, wind turbines, diesel generator, and battery types. The optimization process using HOMER Pro resulted in 10 optimal scenarios, providing the required capacities for solar PV, wind turbines, diesel generator, battery, and inverter, as presented below :

Table 3. Optimized Capacity Requirements Result

Scenario	Solar PV (kW)	Wind-Turbine (kW)	Diesel-Gen (kW)	Lead Acid (kWh)	LFP (kWh)	NMC (kWh)	Inverter (kW)
1	1,876	210	450			3,695	635
2	2,313		450			4,079	646
3	1,592	270	450	10,491			650

4	1,971		450	12,054			647
5	1,797	280	450		4,335		617
6	3,003			16,825			1270
7	2,359		450		5,082		721
8	4,203	50		12,317			754
9	2,325	660				8,481	708
10	3,908					9,354	2272

Furthermore, the optimization results also provide the cost data and CO2 emissions associated with each of the 10 scenarios :

Table 4. Optimized Cost and Emission Results for Various Scenarios

Scenario	LCOE ($/kWh)	NPC ($)	CAPEX ($)	OPEX ($/yr)	Fuel cost ($/yr)	Emisi CO^2 (kg/yr)
1	0.189	5,645,158	3,700,164	52,959	53,901	106,095
2	0.193	5,777,417	3,887,588	49,367	50,251	98,910
3	0.202	6,052,014	3,603,144	50,327	26,941	53,029
4	0.209	6,240,947	3,693,454	45,240	22,190	43,678
5	0.234	6,983,828	4,392,499	69,625	60,884	119,839
6	0.242	7,243,670	4,860,304	59,707	-	-
7	0.245	7,315,219	4,779,097	66,686	51,096	100,573
8	0.265	7,931,917	5,548,711	60,745	-	-
9	0.278	8,302,265	5,875,556	93,618	-	-
10	0.308	9,187,006	6,708,662	84,221	-	-

Based on the optimization results from HOMER Pro, the highest Net Present Cost (NPC) is observed in the scenario utilizing only solar PV with NMC batteries, while the lowest NPC is achieved in the scenario combining solar PV, wind turbines, diesel generators, and NMC batteries. Similarly, in terms of the Levelized Cost of Electricity (LCOE), the highest LCOE is observed in the scenario with only solar PV and NMC batteries, whereas the lowest LCOE is obtained in the solar PV, wind turbines, diesel generators, scenario with NMC batteries.

If carbon dioxide (CO2) emissions are considered as a key aspect in meeting the electricity demand of Gili Raja Island, the use of diesel generator—which produces CO2 emissions—becomes a critical factor. The scenario with the lowest LCOE, involving solar PV, wind turbine, diesel generators, and NMC batteries, generates CO2 emissions of 106,095 kg per year. In contrast, scenarios that do not produce CO2 emissions exclude the use of diesel generator. For instance, in Scenario 6, the electricity demand is met using only solar PV and lead-acid batteries, or in Scenario 8, where solar PV, wind turbines, and lead-acid batteries are employed.

To ensure proper funding for the construction, operation, and maintenance of the electrical system on Gili Raja Island, selecting an appropriate funding scheme is essential. In this study, the construction of the renewable energy is aimed at providing electricity to households that have not yet gained access to electricity. Given the government's and PLN's obligations related to Public Service Obligations (PSO) to provide electricity services to all Indonesian citizens, the development of electrical facilities on Gili Raja Island is a mandatory task for PLN and the government. Therefore, the Energy Service Company (ESCO) model is deemed the most suitable funding scheme for this project.

The availability of electricity is expected to add value by fostering the growth of household industries, thereby increasing electricity sales. For funding sources, PLN can leverage existing financial instruments, such as Green Bonds. To qualify for Green Bond funding, PLN has established a framework that aligns with international green finance principles, including the ICMA Green Bond Principles, LMA Green Loan Principles, and ASEAN Green Bond Standards [17].

4. Conclusion

Several simulation scenarios for the electricity generation portfolio on Gili Raja Island have been conducted, utilizing a range of technologies including wind turbines, solar PV, diesel generators, and energy storage systems (lead-acid, NMC, and lithium-ion). The scenarios were designed to meet the user demand of 5,253 kWh per day or 1,917 MWh annually, optimized using HOMER software to identify the configuration with the lowest Levelized Cost of Energy (LCOE).

The optimization results indicate that the combination of wind turbines, solar PV, diesel generators, and NMC batteries achieves the lowest LCOE at $0.189/kWh and a Net Present Cost (NPC) of $5,645,158. However, this portfolio still depends on diesel generators, resulting in annual carbon emissions of 106,095 kg. This dependency is inconsistent with the government’s net zero emissions target for 2060.

Among the alternative scenarios, Scenario 6 offers a fully clean energy portfolio using only PLTS and lithium-ion battery storage. This configuration eliminates operational emissions entirely, aligning with net zero objectives. However, the LCOE for this portfolio is $0.242/kWh, with an NPC of $7,243,670—28% higher than the lowest LCOE portfolio.

To implement the proposed energy infrastructure on Gili Raja Island, the Energy Service Company (ESCO) funding model is recommended. Under this scheme, PLN would manage the costs of construction, operation, and maintenance, while users pay monthly fees based on their energy usage. This approach aligns with PLN's Public Service Obligation (PSO) to provide electricity access nationwide. Moreover, a zero-emission portfolio presents opportunities to secure renewable energy-specific funding such as Green Bonds, which offer low-interest loans and can reduce the overall cost of development.

References

[1] PT PLN (Persero), “STATISTIK PLN TAHUN 2022,” Jakarta, Indonesia, 2023. [Online]. Available: www.pln.co.id

[2] BPS, “KECAMATAN GILIGENTING DALAM ANGKA 2023,” Sumenep, 2023.

[3] A. Wibowo, *Instalasi Panel Listrik Surya*. Semarang: Yayasan Prima Agus Teknik, 2022.

[4] IRENA, *Electricity storage and renewables : costs and markets to 2030*. International Renewable Energy Agency, 2017.

[5] N. Yuniarti, *Modul Pembelajaran Pembangkit Tenaga Listrik*. Yogyakarta: Jurusan Teknik Elektro FT UNY, 2019.

[6] Kementerian ESDM, *Panduan Pengelolaan Lingkungan Pembangkit Listrik Tenaga Bayu*. Jakarta: Kementrian Energi dan Sumber Daya Mineral, 2021.

[7] Dewan Energi Nasional, “OUTLOOK ENERGI INDONESIA 2022,” Jakarta, 2022.

[8] M. J. Barasa Kabeyi and O. A. Olanrewaju, “Diesel Power plants: Design and Operation and

Performance Enhancement," in *Proceedings of the International Conference on Industrial Engineering and Operations Management*, Michigan, USA: IEOM Society International, Jul. 2022, pp. 3164–3164. doi: 10.46254/EU05.20220425.

[9] ADB, "Handbook on Battery Energy Storage System," Manila, Philippines, Dec. 2018. doi: 10.22617/TCS189791-2.

[10] E. Rakhimov, D. Khoshimov, S. Sultonov, F. Jamoldinov, A. Imyaminov, and B. Omonov, "Battery technologies: exploring different types of batteries for energy storage," *BIO Web Conf*, vol. 84, p. 05034, Jan. 2024, doi: 10.1051/bioconf/20248405034.

[11] UL Solutions, "Homer Pro Infosheet," USA, 2022.

[12] Kementerian ESDM, "Technology Data for the Indonesian Power Sector: Catalogue for Generation and Storage of Electricity – March 2024," 2024.

[13] L. Frantzis, S. Graham, R. Katofsky, and H. Sawyer, "Photovoltaics Business Models," 2008. [Online]. Available: http://www.osti.gov/bridge

[14] S. Zhang, "Innovative business models and financing mechanisms for distributed solar PV (DSPV) deployment in China," *Energy Policy*, vol. 95, pp. 458–467, Aug. 2016, doi: 10.1016/j.enpol.2016.01.022.

[15] M. Anisuzzaman, T. Urmee, M. Anisuzzaman, and T. P. Urmee, "Financing Mechanisms of Solar Home Systems for Rural Electrification in Developing Countries," 2006. [Online]. Available: https://www.researchgate.net/publication/228412560

[16] M. Z. Hussain, "Financing renewable energy Options for Developing Financing Instruments Using Public Funds," Washington, D.C., 2013.

[17] PT PLN (Persero), "Green finance framework," Jakarta, Indonesia, 2021.