Techno-economic-enviro optimization analysis of diesel/PV/wind with pumped hydro storage for Mentawai Island microgrid

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ABSTRACT

This paper presents a techno-economic analysis and environment assessment of hybrid photovoltaic (PV), wind turbine (WT), and diesel genset (DG) with pumped hydro storage (PHS) for a rural microgrid system. The analysis is carried out for a case study with Mentawai community load demand of 165.44 kWh/day at a peak load of 20.46 kW. The Homer simulation results show that there are eight feasible configurations, which the optimal hybrid system configuration to supply community load is the configuration with PV/DG/PHS. An optimal system has been achieved for the lowest NPC of Indonesian rupiah (IDR) 3,00 B consist of 15 kWp PV modules, 1 unit of PHS and a solar inverter with a size 25 kW. The net present cost and payback period are in accordance with criteria for the economic feasibility analysis method of a project. However, the cost of energy is greater than the electrical utility tariff, but this value can be considered for applications in the remote island area. Therefore, the project still feasible to be implemented. Since the renewable fraction of the system is increased hence this proposed system will have the lowest carbon emission.

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1. INTRODUCTION

The decreasing availability of fossil energy resources and the increasing awareness of efforts to conserve the environment, has led researchers to keep thinking of looking for new renewable energy (NRE) alternatives by utilizing the potential of local resources. Among renewable energy sources, the integration of solar power generation is the most developed and reliable alternative [1]. The location of Indonesia which is on the equator theoretically will receives a significant amount of solar radiation throughout the year [2]. This condition is very advantage for establishing solar energy to electrify and decarbonise rural communities in Indonesia as a tropical country. Solar, wind, and microhydro power plants have also become priority sources of renewable energy that will be developed in Indonesia to achieve the NRE target of 23% by 2025 and 31% by 2050 [3]. Regarding environment consideration, Indonesia has committed by 2030 to reduce 29% of carbon emissions as the agreement of united nations climate change conference held in Paris, 2015 [4]. The main advantage of solar and wind hybrid systems is that when the production of solar and wind power is used together can increase the system reliability [5].

Solar and wind energy are intermittent energy, meaning that energy unable to provide electricity 24 hours/day or continuously [6], [7]. To make intermittent energy fully reliable as a power supply for base load and to keep up with fluctuations in demand, the electricity generated must be stored to allow energy delivery on demand. Therefore, energy storage is essential for independent PV/wind power generation, and a solution to the intermittent problem of energy production. Integrating NRE power plants in load centers can reduce power losses and increase the voltage of the electrical network [8]. Apart from that, it is easy to maintain and operate but has a significant impact on reducing pollution and the greenhouse effect [9], [10]. Besides that, there are some disadvantages of using solar and wind energy, especially in terms of the relatively low output efficiency [11], [12]. Several factors affect the electrical power generated, such as the type of inverter used, the level of light intensity, the working temperature of the solar panels, and the storage system.

Energy storage technology research continues to develop accompanied by the use of sustainable renewable energy for remote areas. There are various energy storage technologies currently used in distributed generation based on renewable energy, such as batteries [13], gear [14], compressed air [15], supercapacitor [16], and pumped hydro [17]. Pumped water storage technique, which is the most widely used energy storage technology today, with more than 300 plants (more than 127 GW) installed worldwide [18]. Several previous researchers have focused on developing efficient, reliable, and economical energy control and management systems to solve the problem of integrating solar and hydro hybrid power plants on either islanded systems or existing conventional power systems. Mengi and Altas in 2015 conducted a study on the optimal hybrid generation control system to meet the demand for water supply in Bolivia using the hybrid optimization by genetic algorithm (HOGA) program [19]. After that, Dursun and Kilic have compared three different artificial intelligence (AI-based) power management control system strategies, in particular the effect on energy efficiency for standalone hybrid systems [20]. This system uses solar panels, wind turbines as well as proton exchange membrane fuel cells (PEMFC) as backup sources. The results suggest that power generation by a hybrid system is more reliable and cheaper than a single-source system alone.

A literature review article on energy storage technologies is provided in the references [21]. Among these technologies, rechargeable lead-acid batteries, especially those with deep dissipation rates, and high stability, are generally used in standalone renewable energy systems. Currently, batteries have become at the forefront of use as a storage medium for renewable energy generation. However, the battery has known limitations [22], such as high initial investment, relatively short life, possible environmental damage and explosions due to lead and sulfuric acid, and difficulties for maintenance in isolated areas. As an alternative to storage technology based on pumped water is the right choice. Based on economic studies pumped hydro energy storage technology is more economical than batteries for standalone applications [23].

The reduction in electricity subsidies and the introduction of incentives for the use of solar power plants led to increased development and construction of solar power plants above houses and buildings [24]. Solar and wind power plants in generating electricity are very dependent on weather conditions. To maintain the stability of the electricity supply, it is necessary to pair it with a storage system such as batteries or pumped water and also with other generators such as thermal generators. The choice of solar, wind and hydropower plants have its own advantages when compared to other NRE generators, including easier and cheaper to integrate with existing electricity systems, can utilize existing land (reduce land investment costs), does not contain carbon emissions and maximally available in a tropical climate area [25]. But the unpredictability and random of sunlight and wind speed are still an obstacle to using this hybrid energy [26], [27]. Energy storage devices are generally used to smooth variations NRE generators output due to unpredictability resources [28]. This paper presents the utilization of hanseatic power solutions (HPS) as energy storage to solve the problem by using a power management control system from a solar-wind with hydro storage microgrid power system and a backup power from a diesel generator.

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2. RESEARCH METHOD

2.1. Load profile of Mentawai Island microgrid

This study uses Peipei load data, Southwest Siberut, Mentawai Islands, and West Sumatra. Peipei Hamlet is traversed by the Peipei river which is 16 km long and ± 10 m wide. The solar pumped storage is placed in the lowest area in Peipei Hamlet. From the jetty to the sub-district office it descends, as well as from the upstream direction of the Pei-pei River to PHS it also decreases. The cross-section of the Peipei river which passes through Peipei Hamlet is very winding, indirectly it will slow down the speed of the water flow so that the river will quickly fill up if the rainfall is high. Based on this information, the authors assume that this location is suitable for case studies and that there is no need to build a tower to raise the upper reservoir because the location is a basin and hilly zone. The geographical location of the study area in Mentawai Island as show in Figure 1. The design of solar/wind with pumped hydro storage will be implemented for powered of Mentawai Island microgrid demand around 165.44 kWh/day with peak load

20.46 kW and load factor 0.34 as shown in Figure 2. The random variability is used 10% for day-to-day and 20% for timestep.

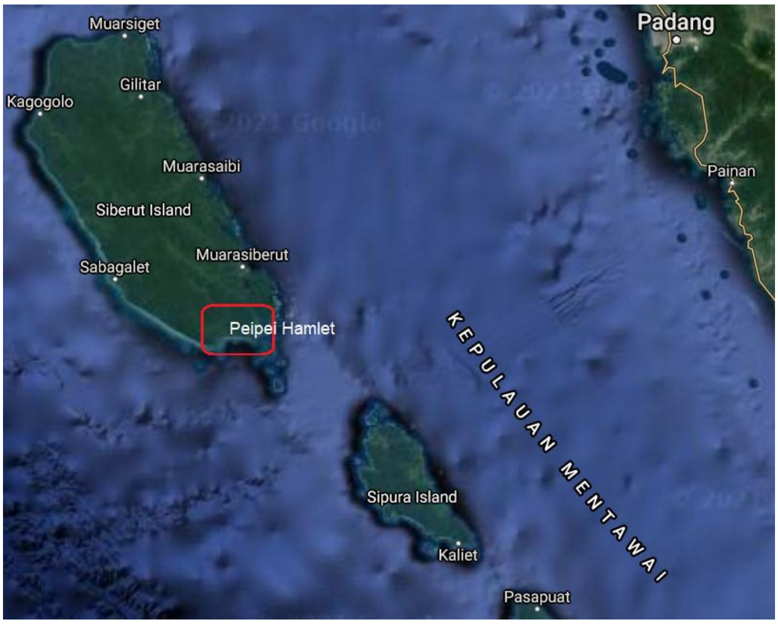

Figure 1. Geographical location of the study area in Mentawai Island, Indonesia

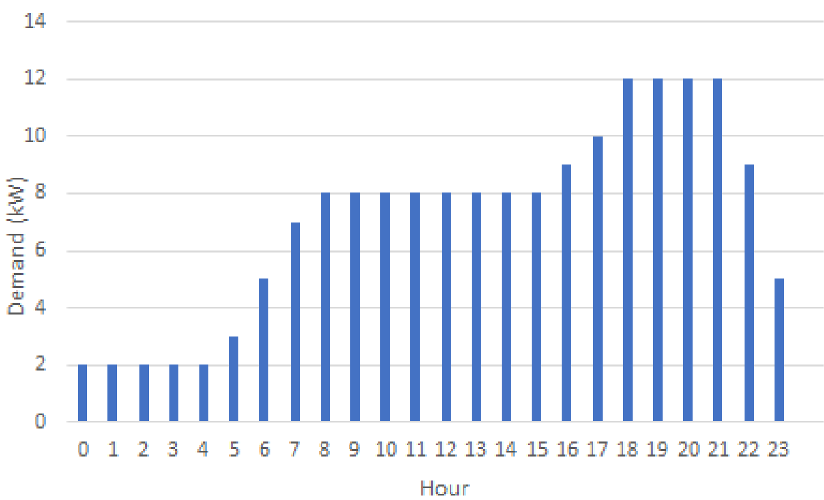

Figure 2. Daily load profile of Mentawai Island microgrid

2.2. Solar and wind resources

The amount of electrical energy produced by a solar power plant is mainly determined by the availability of sunlight, while wind power is based on the wind speed at the location where it is placed. The meteorological monthly data of solar radiation and wind speed are imported from NASA's website for the location of Peipei Hamlet, Siberut Island, Mentawai (1°25.6'S, 98°55.5'E) given in Table 1. The average annual solar radiation received per day is 4,75 kWh/m^2/day and the average wind speed is 3.66 m/s.

These two weather parameters are used as input for Homer's software for analyzing the economic feasibility of PV/wind powered microgrid system in the Mentawai Islands. The wind speed and solar radiation profiles are close to the weather patterns in various remote islands in Indonesia. Therefore, the results of this study can become a consideration for the development of PV/wind with pumped hydro storage for Indonesia remote island applications.

Table 1. Monthly averaged radiation and wind speed

Month	Clearness index	Radiation ($kWh/m^2/d$)	Wind speed (m/s)
Jan	0.46	4.79	4.34
Feb	0.50	5.28	4.05
Mar	0.48	5.05	3.41
Apr	0.49	4.97	2.98
May	0.52	5.04	3.15
Jun	0.52	4.84	3.38
Jul	0.50	4.64	3.80
Aug	0.46	4.59	4.02
Sep	0.43	4.52	3.93
Oct	0.44	4.59	3.36
Nov	0.41	4.24	3.44
Dec	0.44	4.50	4.09

2.3. System components

The main components of the systems studied are PV systems, wind turbines, water-pumped storage, and converters. PHS is used as a storage system when the sun and wind are not available to be used to meet the load demands. The capacity of the PHS is designed to meet the load requirements with a water capacity of 7000 m^3, with a reservoir height of 12 m, assuming a hydro generator efficiency of 75%. The capacity of electrical energy stored in PHS can be calculated using the following equation:

$$Es=9,81\ \eta\ h\ Vol/3600 \tag{1}$$

where; Es=stored energy (kWh)
η =hydro generator efficiency (%)
h=falling a height (m)
Vol=reservoir volume (m^3)

While the output power of PHS depends on the rate of water discharge, as in the following equation:

$$P=9,81\ \eta\ h\ Q \tag{2}$$

where; P=power (kW)
Q=average flow (m^3/s)

The PHS was designed using 7000 m^3 water stored on a 12 m upper reservoir which equals 171.68 kWh electrical energy stored. By using (1) and (2), the PHS energy and power output are obtained as shown in Table 2. The technical specification and financial data of the proposed Mentawai Island microgrid system are tabulated in Table 3. The individual system components in the system such as size, service life and cost are determined in detail. The pumped hydro storage PV system is designed consists of power circuit or electrical installation, water pipe installation and Arduino control circuits. The list of costs for installation and operation of PHS is shown in Table 3 as well as others system component.

Table 2. PHS store energy and output power

Q (m3/s)	Depletion time (hour)	Es (kWh)	P (kW)
1,9444	1	171,68	171,68
0,9722	2	171,68	85,84
0,6481	3	171,68	57,23
0,4861	4	171,68	42,92
0,3889	5	171,68	34,34
0,3241	6	171,68	28,61
0,2778	7	171,68	24,53
0,2431	8	171,68	21,46
0,2160	9	171,68	19,08
0,1944	10	171,68	17,17

The schematic diagram of a PV/wind/diesel microgrid system integrated with PHS in the Homer pro V3.13 application to serve the load demand of 165.44 kWh/day is shown in Figure 3. The objective of Homer optimization is to identify a microgrid configuration which has low NPC and low CoE. The constraints be considered in Homer optimizasion process consist of PV derarting factor is 88% with 15.3% module efficiency, PHS assumed that the generator turbine acts a pump in the reserve case, so that the charging, and recharging current same. Initial PHS state of reservoir 100% and minimum until empty 0%. WT used with capacity 3 kW, with hub height 17 m and a converter efficiency 97.45%.

Table 3. Components costs in Homer simulation

PV System	
Type Sharp ND-250QCS 1 kW	IDR. 10,000,000
Installing MCBs, busbars and fuses cost	IDR. 1,000,000
Total cost	IDR. 11,000,000
O&M Cost per year (5% of PV Cost)	IDR. 500,000
WT	
Generic Wind Turbine 3 kW	IDR. 12,000,000
Replacement Cost	IDR. 3,000,000
Total cost	IDR. 15,000,000
O&M Cost per year (10% of WT Cost)	IDR. 1,200,000
Inverter	
Type Solar Inverter Sinecxel 30 kW	IDR. 50,000,000
O&M Cost	IDR. 0,0
Replacement Cost	IDR. 50,000,000
Pumped Hydro Storage	
Hydro Turbine Generator/Motor	IDR. 30,000,000
Water Dam 7000 m^3 and pipe installation	IDR. 70,000,000
Replacement Cost	IDR. 50,000,000
O&M Cost per year	IDR. 500,000

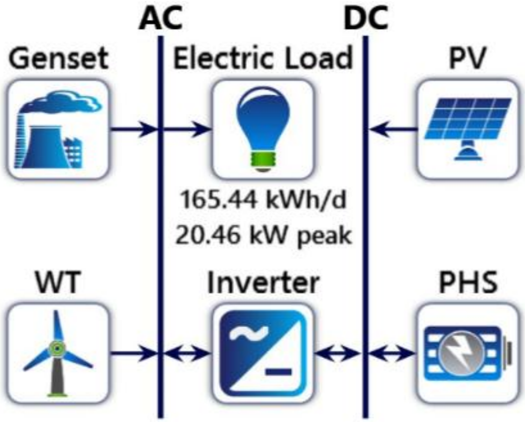

Figure 3. The main components of the microgrid system design

The output of the simulation results is in the form of an optimal system design model to be analyzed. Economic feasibility analysis uses three methods, namely, net present cost, payback period, and cost of energy. The net present cost calculated using the following expression:

$$NPC=CC+RC+O\&M\ Cost+FC-Salvage \quad (3)$$

where; NPC=net present cost (IDR)
CC=capital cost (IDR)
RC=replacement cost (IDR)
O&M cost=operation and maintenance cost (IDR)

The payback period is the number of years of payback for the investment cost of a project. This payback period calculation is carried out to determine the financial risk to the project that will be carried out. The payback period value can be calculated using the following equation:

$$Payback\ Period=ICR/Inc_{year} \quad (4)$$

where; RIC=renewable investment costs (IDR)
Inc_{year}=per year income (IDR)

Cost of energy (COE) is the average value of electrical energy per kWh produced by the system in a project. COE has criteria if it is less than the basic cost of providing electricity, then it is feasible to continue, if it is greater then it is not feasible to continue. The calculation of the COE value can be done using the following equation:

$$CoE=TAC/kWh_{Tot\_Prod} \quad (5)$$

where; TAC=total annualized cost (IDR)
kWh_{Tot_Prod}=total kWh production (kWh)

3. RESULTS AND DISCUSSION

A comparative analysis of economic benefits for various configurations is given in Table 4. The optimized results with the smallest NPC and CoE were obtained in the configuration with PV, diesel genset, and PHS. Meanwhile, the wind turbine is less than optimal due to the low wind potential in the western region of Indonesia. Diesel generator integration has a greater influence on COE than PHS. Low annual NPC for PV+PHS (IDR 2,387) and high for base case i.e. microgrid with diesel generator only (IDR 3,134). This Homer simulation results use to determine the main component variables of PV modules, wind turbine with the pumped hydro storage system when operating. The optimal design configuration consists of 15 kWp solar panels, 25 kW inverters and a pumped hydro storage unit with a nominal capacity of 171.44 kWh. The pumped hydro storage can cover the electrical energy demand during the solar module and wind turbines not produce energy.

Table 4. Components costs in Homer simulation

Configuration	NPC (IDR)	CoE (IDR/kWh)	Operating cost (IDR)	Initial capital (IDR)
PV/DG/PHS	3.00B	2,387	125M	407M
PV/WT/DG/PHS	3.01B	2,395	124M	419M
DG/PHS	3.66B	2,908	164M	242M
WT/DG/PHS	3.68B	2,924	164M	254M
Base Case (DG)	3.94B	3,134	184M	100M
WT/DG	3.97B	3,157	185M	112M
PV/DG	4.07B	3,236	186M	197M
PV/WT/DG	4.10B	3,261	187M	209M

The result in Table 4 also shows that, although the configuration with DG requires a minimum investment of 100 M, it has a large operational cost for diesel fuel. Meanwhile, the initial investment for the hybrid PV/DG/PHS system is 407M, but the operating cost is the lowest at 125 M per year, resulting in the lowest NPC and CoE. Thus, the most optimal configuration is obtained for the system with the lowest operational costs and is relatively independent of the size of the initial investment.

3.1. Operational analysis

The total energy production produced during the year from off-grid PV system with the pumped hydro storage system during operation to meet the daily electricity load demand of 20,653 kWh/year. The total AC consumption of Mentawai Island microgrid is 60,386 kWh/year. The results of this electrical energy production are assumed if PV works optimally with the support of sunny weather factors by the solar radiation index obtained from the NASA website. Pumped hydro storage simulation results also have incoming energy of 10,081 kWh/year and energy output of 8,393 kWh/year with losses of 1,941 kWh/year. The working principle of pumped hydro storage is to drain the water from the upper reservoir when the load is peak and pump back the water from the lower reservoir when the load is low.

Energy scheduling of the optimal hybrid system for three days in July is shown in Figure 4. This figure shows the fulfillment of power generation demand which is divided by PV, PHS, and diesel systems. Wind turbine does not produce electricity due to low wind speed, while diesel is scheduled at night when PV does not produce electricity and PHS is not available enough. In addition, the PHS performance during the charging and discharging period is also demonstrated in the Figure 4.

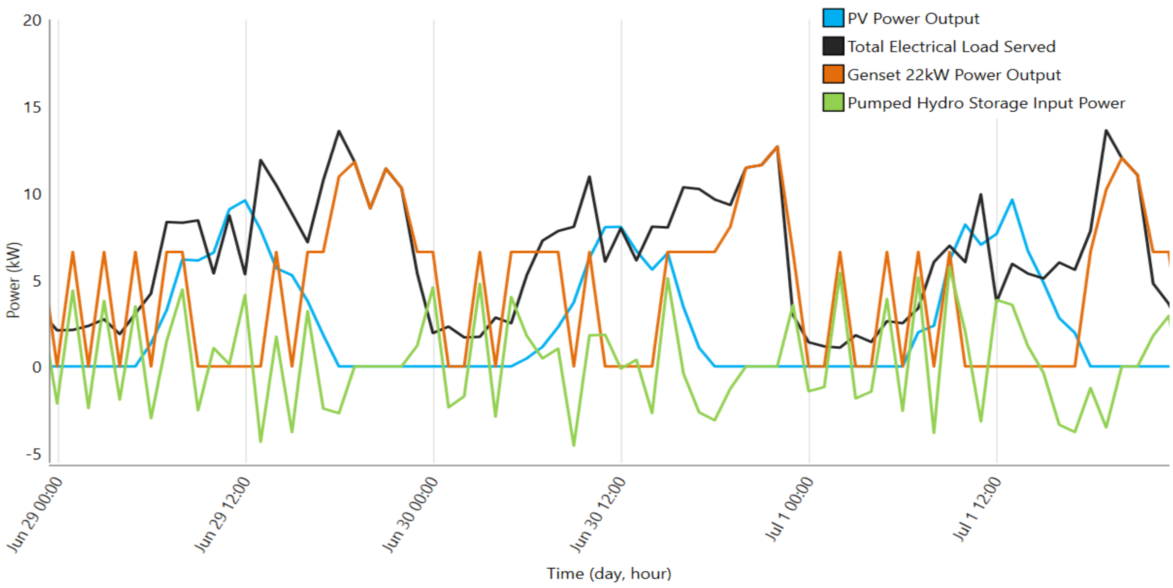

Figure 4. Energy scheduling of the optimal system through three days

3.2. Economical analysis

The NPC feasibility follow this rule: if the NPC is negative, then the project is not recommended to be implemented, if the NPC value is positive, then the project is feasible to be realized and if the NPC value is zero, it means that there is no change if the project is still being implemented or not. The payback Period which has a shorter period than the life of the project, the investment is feasible to be realized. However, if the payback period has a longer period than the life of the project, the investment is not feasible to be realized.

The first, NPC criteria of IDR. 3,00 B were declared feasible because they had exceeded the criteria of the NPC method where if the NPC was positive, the project was feasible to continue. Second, in the payback period method, it is obtained that the length of time is 10 years 4 months. This result fulfills the criteria because if the payback period is smaller than the project life is declared feasible to continue, the PV system with pumped hydro storage project is planned to last for 25 years. The cost of energy of the system designed is IDR. 2,387/kWh is lower than the basic cost of providing electricity set by the ministry of energy and mineral resources, which is IDR. 2,538/kWh. However greater than PLN tariff, but this value can be considered for applications in the remote island area. Therefore, the project still feasible to be implemented. Based on Table 5, the project is feasible to be implemented because it has met all economic feasibility criteria of a project.

Table 5. The economic feasibility simulation results

Parameters	Result	Conclusion
NPC	IDR 3,001,729,000.00	Feasible to be realized
PP	10 years and 4 months	Feasible to be realized
CoE	IDR. 2,387.00/kWh	Not feasible to be realized, but can be considered for the remote islanded area

3.3. Environmental analysis

Indonesia is committed to reducing greenhouse gas emissions (GHG) by 29% and CO_2 emissions up to 8 million tons by 2030 [29], [30]. The development of renewable hybrid generation is predicted will contribute to reducing GHG as well as CO_2 emissions. The emissions (pollutant) of the optimal hybrid system with PV/DG/PHS over one year compared to the base case with only diesel genset is shown in Table 6. The environmental impact of the optimized hybrid system in terms of carbon emissions has been reduced to 23,240 kg/year compared to the base case of 39,222 kg/year. This is in line with the Indonesian government's targets that by 2025 the installed capacity of the solar power plant will reach 1.0 GW [31].

Table 6. Environment comparison

Emissions (Pollutant)	Unit	Quantity	
		Optimized hybrid system	Base case (Diesel Genset)
Carbon Dioxide	kg/yr	23,240	39,222
Carbon Monoxide	kg/yr	5.62	9.49
Unburned Hydrocarbons	kg/yr	0	0
Particulate Matter	kg/yr	1.32	2.22
Sulfur Dioxide	kg/yr	47.6	80.3
Nitrogen Oxides	kg/yr	13.3	22.4

4. CONCLUSION

The economic feasibility analysis of hybrid PV/wind/diesel with pumped hydro storage for a rural microgrid system has been presented. The simulation test results on the Homer software produce 48 solutions with details of 22 feasible system solutions, and 26 system solutions that are not feasible due to lack of storage capacity. An optimal system has been achieved for the lowest NPC consist of 15 kWp PV modules, 1 unit of 171,44 kWh pumped hydro storage and a solar inverter with a size 25 kW. The use of generation from wind turbine is less profitable for electricity of the Mentawai Islands microgrid system because the wind speed is relatively low. The NPC of PV system with pumped hydro storage is IDR 3,00 B, cost of energy is IDR. 2,387/kWh greater than the basic normal electrical tariff, payback period under the project lifetime. Three parameters of economic feasibility have met the criteria for a project to be built, since the cost of energy for archipelagic areas can be excluded, the project feasible to be implemented. The renewable fraction of this system is 30.1%, hence this proposed system will have the lowest carbon emission. These design and development study result of PV/wind/diesel hybrid system with a water pump storage system are expected to be implemented in other isolated systems spread across Indonesia.

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