DESIGN OF SUSTAINABLE STAND-ALONE ENERGY SUPPLY SYSTEM FOR SMALL AND REMOTE ISLANDS IN INDONESIA: THE CASE OF AIR SENA VILLAGE

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ABSTRACT

Air Sena is a small remote village located in southern of Matak Island, Kepulauan Anambas Regency. The village is struggling to comply its electricity demand with 704 population and 202 households. Current energy demand in the village is supplied by diesel generator with capacity of 2 x 140 kVA. However, diesel generator burdens the society with high operational cost, green gas emission, and environmental quality degradation. The study is aimed to design a sustainable energy supply system in Air Sena based on local resources with stand-alone hybrid system using HOMER software. Based on simulation and optimization result, with \$0.40/L fuel price scenario, hybrid of PV-diesel generator-converter-battery is the most feasible options with 24.7% renewable energy penetration. While with scenario fuel price \$0.70/L, hybrid of PV-wind turbine-diesel generator-converter-battery is the optimum option, with 48% renewable energy penetration.

Keywords: sustainable, stand-alone, energy system

INTRODUCTION

Complexity to increase the efficiency of energy supply system is one of a long history issue in energy development in the world. The increasing demand toward a more sustainable energy system which provides a secure, affordable and low-carbon energy services requires to consider a complex system in relation to social, technological, economic and environmental aspects (Bale, Varga, & Foxon, 2013). Global energy supply system efficiency in 2005 is still 34%, due to its complexity starting from energy extraction, delivery, conversion, and its distribution to final consumers (IIASA, 2012). Among several challenges in the development of energy supply system are varies of geographical conditions and the imbalance between supply resources and demand, where energy resources are not always available where it’s needed. Indonesia has challenges the typical problems to meet its energy demand due to various geographical conditions and distributed population, especially for small and remote islands.

Air Sena Village is one of small and remote island regions that struggles to comply its energy demand, especially from electricity sector. Air Sena is located in the southern of Matak Island which is administratively part of Siantan Tengah Sub Regency Kepulauan Anambas Regency Riau Island

Province. The village geographical position is at 3^0 24’ 7” North Latitude and 106^0 28’ 0” East Longitude, and consisted of 714 population and 202 households (BPS, 2015). Existing electricity demand in Air Sena is supplied by diesel generator with capacity of 2 x 140 kVA. The current system supplies about 150 households and public facilities in the village for 6 hours per day service. The existing electricity supply system is considered as unreliable, inaccessible, and unaffordable option for the villagers in term of sustainable electricity system perspectives.

Considering its access to electricity as a key factor to achieve sustainable development effort (Ilskog & Kjellstro¨m, 2008), it is substantial for the village to have a reliable, accessible and affordable electricity supply system according to sustainable electricity principles. Furthermore, energy cost reduction could contribute to improve performance in many sectors of the economy in the region (U.S. Department of Energy , 2015). As overall, the implementation of sustainable electricity system is expected to have impact on economic development, supporting human growth and progress, and also to be able to protect local and global environment (IPCC, 2012; Sims, et al., 2007). The expected output from the research are: (1) to explain existing electricity supply system and future profile of electricity demand in Air Sena Village; (2) to identify local energy resources to be utilized for the design of sustainable electricity supply system; and (3) to design a sustainable electricity supply system in the village.

Air Sena Village is chosen as case study, and expected to be a model of the development of electricity supply system to small and remote island in Indonesia. However, the sources of energy considered in the system are limited to diesel generator, solar and wind energy, considering technology maturity and energy resources availability in the case study location. The work is expected to give alternative perspective and consideration to related stakeholders to determine a sustainable option to increase a reliable, accessible and affordable electricity supply system for small and remote island in Indonesia.

Materials and Methods

Research Model

This work is a case study research, using primary data through field survey and energy audit. Secondary data also collected from related institution regarding the study of energy resources potential in the case study location. The data is analyzed with HOMER software. The detail about the research model is demonstrated by figure 1.

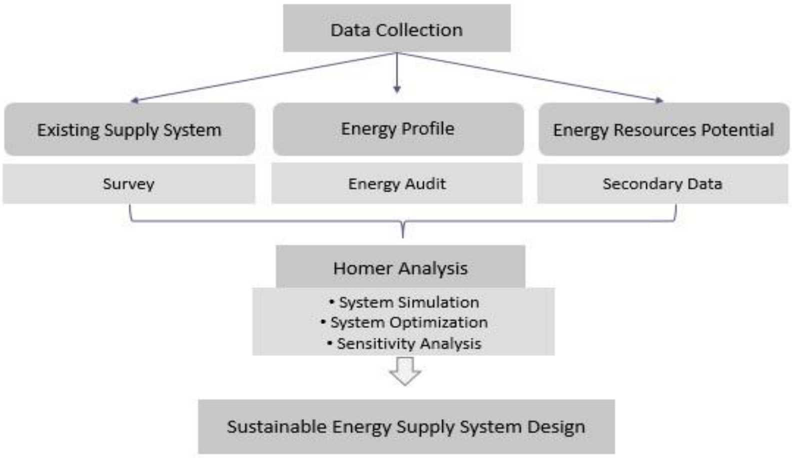


Figure 1. Research model

System Description

According to resources availability in the case study, the feasible system configuration considered to be analyzed in the research are solar photovoltaic (PV), wind turbine, diesel generator, battery, and inverter. The system structure is intuitively demonstrated in figure 2.

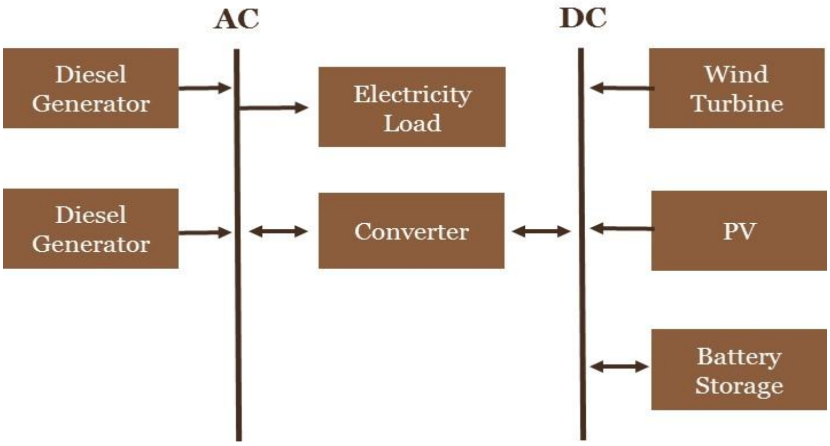


Figure 2. System configuration model

Energy Demand

Future electricity demand is measured by conducting energy audit to about 25% of energy consumers (households, industrials, and public facilities) in Air Sena Village. Energy audit is conducted to avoid over and/or under estimation to the energy demand, considering energy demand as a sensitive factor in the micro hybrid system design (Lambert, Gilman, & Lilienthal, 2006). Over estimation in energy demand could cause inefficiency and burdening the capital and operational cost of the system. Meanwhile, under estimation in energy demand could cause system failure to meet the energy demand and unable to satisfy consumers energy requirements. The aspect measures in energy audit are load profile and distribution, load pattern, base load, and peak load, including hourly, daily, and monthly variability. Load profile and distribution will determine the most feasible option of sustainable energy supply system in the village, including whether the system will be centralized, semi-centralized, or distributed. Hourly energy demand profile illustrated by figure 3, while for its variability for each month in a year period presented by figure 4.

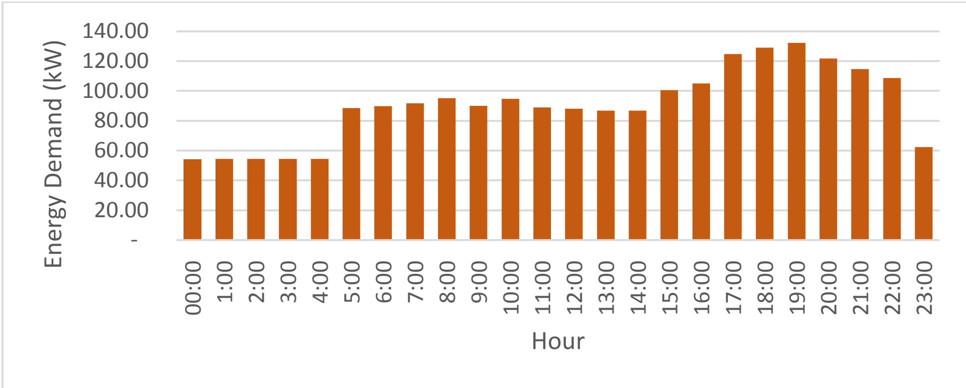


Figure 3. Energy demand profile in Air Sena Village (kW)

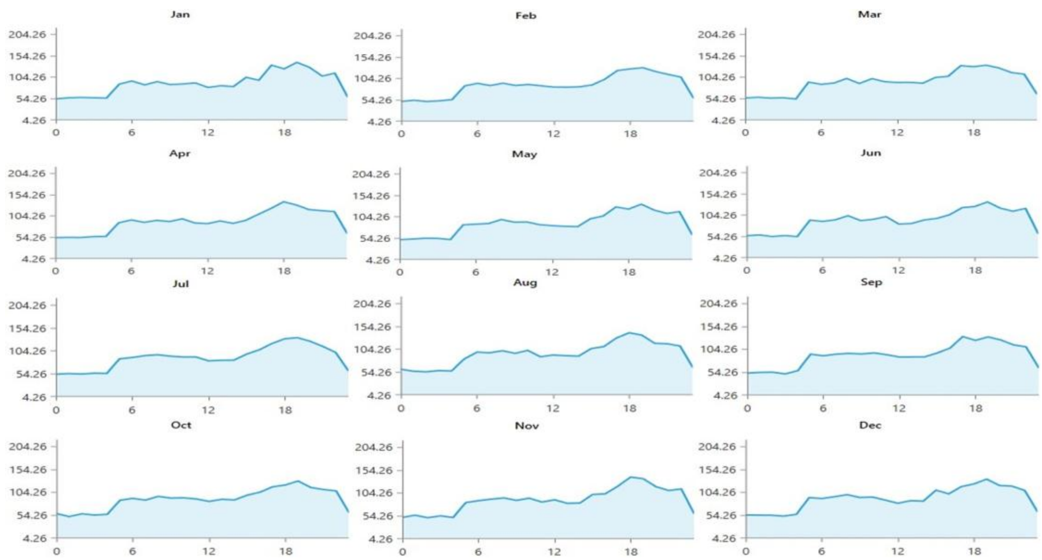
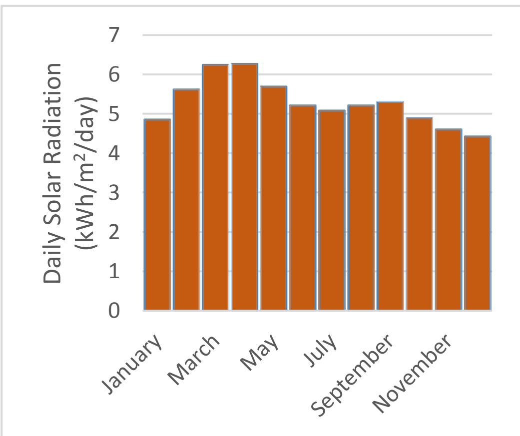


Figure 4. Load variability in one year period (kW)

Energy Resources

Renewable energy potential identification is conducted on solar energy and wind energy in the research location. Solar and wind data obtained from National Aeronautics and Space Administration (NASA) as presented in the table 5 and 6.



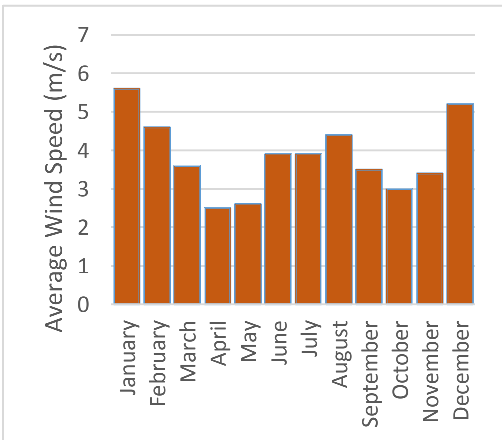


Figure 6. Monthly average wind speed (NASA, 2016)

Data Analysis

Data analysis and system design primarily use HOMER software. HOMER is energy supply system simulation tool developed by US National Renewable Energy Laboratory (NREL). HOMER uses mathematical and algorithm optimization model to identify optimum power system configuration. There are three main pillars output in HOMER analyzing, which are simulation, optimization and sensitivity analysis. In the simulation, HOMER determines technical feasibility and its life cycle cost in the period of time, HOMER also examines the feasibility of configuration system of each determined components and parameters. In the optimization, HOMER presents the most feasible and optimum configuration based on the input components and parameters. *Net Present Cost* (NPC) values determines the most feasible and optimum configuration. In sensitivity analysis, HOMER analyzed how the result affected by different input components and parameters (Hafez & Bhattacharya, 2012).

The system designs considering sustainability aspects in term of technical, economic, and environment sustainability (The World Bank, 2008). Technical sustainability assessed system reliability, technology maturity, the optimization of local resources utilization, and operational and maintenance simplicity. Economic sustainability assessed electricity rate affordability, impact to productive activity and economic growth, and system maturity in term of economic independence. Environmental sustainability assessed through the impact of supply system development for environment preservation and its role on climate change mitigation.

System Inputs

Generic flat plate PV is selected as PV technology in the system, with 25 years of lifetime and with 80% derating factor. Initial capital, replacement and operational and maintenance (O&M) cost assumption for PV panel are $2,000.00, $1,800.00, $5.00 respectively per 1 kW peak. The cost is expected to decrease as install capacity values increases. Where at 100 kW peak install capacity, the price will decrease 10%. The initial capital, replacement and O&M is $180,000.00, $162,000.00, $500.00 respectively per 100 kW peak. The simulation values for PV in the study are 0, 50, 100, 150, 200, and 400 kW peak.

Wind turbine selected in the system is 1 kW rated capacity, 20 years of lifetime, 24 m hub height. The cost for initial capital, replacement and O&M are $2,500.00, $2,000.00, $10.00 respectively. The cost is expected to decrease as capacity increases, with initial capital, replacement and O&M are $200,000.00, $160,000.00, $1,000.00 respectively per 100 kW. The number of option values of wind turbine simulation are 0, 5, 25, 50, 100, and 200 kW.

Diesel generator capacity selected in the system is 2 x100 kW. The lifetime of each diesel generator are 15000 hours with 25% minimum load ratio. Search capacity in the simulation are 0, 50, and 100 for 100kW for first diesel generator and 0, 15, 30, 50, 75 and 100 for 50kW for second diesel generator. initial capital, replacement and O&M are $500.00, $450.00, $0.02 per 1 kW and $45,000.00, $40,000.00, $2.00 per 100 kW. The assumption is based on diesel generator average price from ESMAP study in 2009 (ESMAP, 2009).

Initial capital, replacement and O&M cost assumption for battery storage in the system are \$300.00, \$300.00, \$3.00 respectively per 1 kW and \$25,000.00, \$25,000.00, \$300.00 respectively per 100 kW. The amount of battery storage for simulation are 0, 25, 50, 75, 100, and 200. While Initial capital, replacement and O&M cost assumption for converter are \$800.00, \$800.00, \$0.00 respectively per 1 kW and \$70,000.00, \$70,000.00, \$0.00 respectively per 100 kW. The size of converter considered in the system are 0, 25, 50, 75, 100, and 200.

Discount rate assumed in this system is 7%, this assumption is based on average of Bank Indonesia discount rate in last 5 years (Bank Indonesia, 2016; Indonesia Investments, 2016). While the expected inflation is 5%, this number is based on the average of Indonesia inflation rate in last seven years and the forecast of Indonesian inflation in 2016 – 2020 by Trading Economic (Bank Indonesia, 2016; Trading Economics, 2016). There are two scenarios tested under sensitivity analysis values in this system. The first scenario is when fuel price is \$0.40/L, the assumption is based on current diesel energy price under government subsidizing. The second scenario is when fuel price \$0.70/L, considering the uncertainty of the fuel price.

RESULTS AND DISCUSSION

Air Sena Village Profile

Air Sena Village is located in one of remote archipelago regency in Indonesia, Kepulauan Anambas Regency (figure 7). Kepulauan Anambas Regency is located across the northern of Indonesia, in the middle of the south china sea between Malaysia mainland and the island of Borneo. The regency geographically positioned at 2^0 10’ 0” - 3^0 40’ 0” north latitude and 105^0 15’ 0” - 106^0 45’ 0” east longitude, consisted of 255 small islands and about 46,664.14 Km^2 total land area. Kepulauan Anambas Regency In the north bordered with Vietnam and South China Sea, in the south with Bintan Island and The South China Sea, in the west with Malaysia and The South China Sea, and in the east with Natuna Regency and The South China Sea (BPS, 2015).

Figure 7. Air Sena Village location map

Air Sena Village was formed in 22nd August, 2006 based on the regulation of Natuna Regency No. 12 in 2006. The village consists of five community association (RW) and eight neighborhood (RT) with the total area about of 10 km^2 (BPS, 2015). Based on the characteristics of the region, the village is included in the category of coastal areas. The predominant area of Air Sena Village is hilly with altitudes reaching 101-500 meters above sea level. While residential concentrated along the coastline (figure 8), due to the livelihoods of the majority of the villagers of Air Sena Village which is associated to coastal and marine areas. The primary access to Air Sena Village is through sea route from Tarempa, the city of Kepulauan Anambas Regency. From Tarempa Air Sena Village can be accessed by speed boat about 15 - 20 minutes and by traditional motorboat (*Pompong*) about 30 – 45 minutes. The secondary access is through land route from Matak Airport, about 15 km from Air Sena Village, it is accessible only on foot or motorcycle due to the poor condition of infrastructure.

Figure 8. Residential distribution in Air Sena Village

1.1. Existing Condition

Basically, The State Electricity Company of Indonesia (PLN) roles as primary supplier to fulfil electricity demand in Indonesia. However, PLN is not always having the ability to comply all of the energy demand in every region in Indonesia. This issue mainly due to limited capacity and another related to technical and economical disadvantages, such as limited power capacity, high grid expansion costs, limited consumers, high investment, and economically unattractive. Currently, PLN only able to provide 4,914 (39.66%) households from total of 12,392 households in Kepulauan Anambas Regency. PLN is the only supplier which could provide 24 hours service in Kepulauan Anambas Regency. The communal diesel generator, PV, and micro hydro system which is operated by local communities contributes 27.84% of electricity service. The system only works 6 hours per day, and the electricity tariff is decided the community itself. While the rest 32.5% still has no access to electricity service, or little access by their own individual diesel generator with capacity about 3-5 kW (Energy and Mineral Resources Agency of Kepulauan Anambas Regency, 2016).

Air Sena Village is one of the villages which comply its electricity need without PLN. The primary electricity demand in Air Sena Village is supplied by communal diesel generator, the diesel generator is an aid from the local government in 2012 with the amount of power 2 x 140 kVA. The system operates with the daily service from 17:30 to 23:30 of local time (WIB) each day in a week and 07:00 to 12:00 in every Sunday. The system supplies 145 households and five public facilities (74.26%), with electricity tariff IDR 2,500.00/kWh ($0.1923/kWh) + IDR 10,000.00 ($0.77) per ampere for base load. For extra electricity service, the villagers have to use their own diesel generator with the power 3-5 kVA. The maximum bill of the villagers for the electricity (48 hours supplies in a week) is up to IDR. 1,000,000.00 per month, the minimum bill is IDR. 40,000.00 per month, while the average bill is about IDR. 200,000.00 per month. The decision regarding the duration of electricity supplies is based on collective agreement of Air Sena Villagers and the Village Government of Air Sena, considering the sustainability of the use of diesel generator and the expense spent during the operation of the diesel generator. While the rest 25.74% households, operates their own individual diesel generator with capacity 3-5 kW.

Simulation and Optimization

Since Air Sena Village located remotely from PLN electricity grid and has limited consumers, the alternative options to comply Air Sena electricity demand is by providing a stand-alone energy hybrid system based on local resources. The system considered the penetration of renewable energy, yet at the same time also deliberated economic minimization. There are two scenarios presented in this simulation and optimization results. The first scenario is with the fuel price assumption at \$0.40/L, the assumption is based on the current fossil based fuel price under government subsidy. The second scenario is with the fuel price assumption at \$0.70/L, the assumption is considering the uncertainty of the world fossil based fuel price.

Hybrid system typically could contribute up to 75-99% electricity production from renewable energy resources (ARE, 2014). However, the common fraction of renewable energy contribution to hybrid system is about 11-25%, in order to be able to maintain system voltage and frequency stability (Infield, 1999; Shaahid, et al., 2007). The 1st scenario of simulation and optimization presented that the configuration of PV-diesel generator-converter-battery storage is the most feasible option, with 24.7% renewable energy penetration. While the 2nd scenario offered the configuration PV-wind turbine-diesel generator-converter- battery storage as the optimum option, with 48% renewable energy penetration (table 1).

The 1st scenario system requires \$2,367,903.00 net present cost (NPC) for 25 years operation, with \$0.1804/kWh levelized cost of energy (COE). 1st scenario offered slightly lower energy price than the existing system (\$0.1923/kWh). The 2nd scenario system needs \$2,995,780.00 NPC and slightly higher energy price than the existing system, with COE as much as \$0.2259/kWh (table 1). Basically, the value of COE in hybrid system will depend on various aspect, such as interest rate, technology price, fuel price, and other miscellaneous costs. According to (Adaramola, Paul, & Oyewola, 2014) study in northern part of Nigeria present the COE at \$0.346/kWh, with 3% interest rate and fuel price at \$1.10/L. Another study conducted by (Adaramola, Agelin-Chaab, & Paul, 2014) in the southern of Ghana accounted COE at \$0.276/kWh, with 16% interest rate and fuel price at \$0.95/L. While the study performed by (Zhang, Ma, Ye, Chen, & Xiong, 2016) in The City of Shenzhen presented lower COE as much as 0.122, 0.105 and 0.141 \$/kWh for three different scenarios with 6% of interest rate.

Table 1. Simulation and optimization results

Scenario	RE Fraction (%)	Configuration	Capacity (kW)	NPC ($)	COE ($/kWh)
1st Scenario	24.7	PV Wind DG I DG II Converter Battery	150 - 1 x 50 1 x 50 75 25	2,367,903.00	0.1804
2nd Scenario	48	PV Wind DG I DG II Converter Battery	150 200 1 x 50 1 x 30 100 200	$2,995,780.00	0.2259

Diesel generator still contributes as a major electricity producer in 1st scenario, since the assumption of fossil based fuel price at $0.4/L and the system design run based on cost minimization (figure 9). The highest PV electricity production is in March and April, as March and April is the highest global solar radiation in the location (figure 5). The 2nd scenario shows a slightly balance electricity production between diesel generator and renewable energy, with 48% renewable energy penetration. The increase renewable energy sharing seen due to the high assumption of fuel price at $0.7/L. Wind turbine electricity production is quite fluctuated, as the fluctuation of wind speed its self (figure 6). The highest electricity production from wind turbine is January and December, while the lower production is May and April. While energy production from PV is slightly flat, with a small increase in March and April (figure 10).

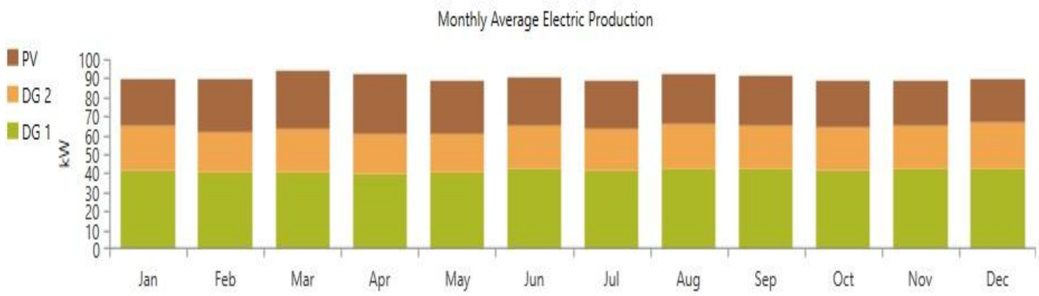


Figure 9. Monthly average electricity production: 1st scenario

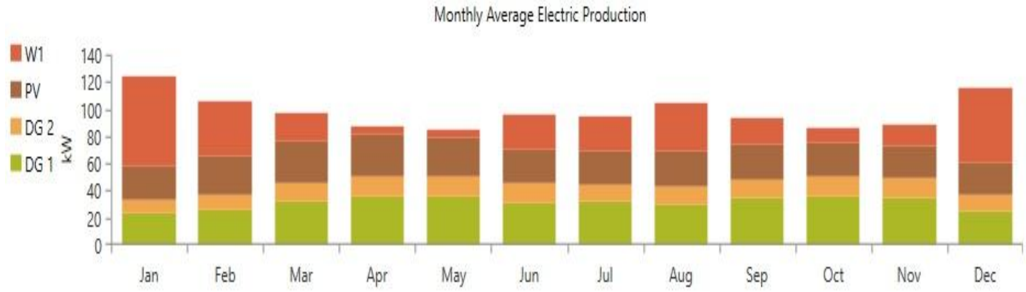


Figure 10. Monthly average electricity production: 2nd scenario

The highest cost from 1st scenario optimum system is for fuel purchasing, since diesel generator takes a big share in electricity production and consume a huge amount of fossil based fuel. The diesel generator also acquires the immense cost for replacement, operational, and maintenance (table 2). Based on annual cost, the system requires $375,000.00 of capital investment, while for the next 24 years is about $100,000.00 annually on average, except for 10th and 20th year. The detail of the system cashflow demonstrated by figure 11.

Table. 2. System Net Present Cost: 1st Scenario

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
PV	$269,899.0	$0.00	$14,808.00	$0.00	$0.00	$284,707.00
DG I 50kW	$22,525.0	$220,996.00	$169,893.00	$816,964.00	-$8,226.00	$1,222,153.00
DG II 50kW	$22,525.0	$157,781.00	$124,601.00	$464,181.00	-$6,018.00	$763,070.00
Battery	$6,288.0	$44,155.00	$1,481.00	$0.00	-$3,216.00	$48,707.00
Converter	$52,525.0	$79,508.00	$0.00	$0.00	-$16,386.00	$115,647.00
System	**$373,763.0**	**$502,439.00**	**$310,783.00**	**$1,281,145.00**	**-$33,846.00**	**$2,434,284.00**

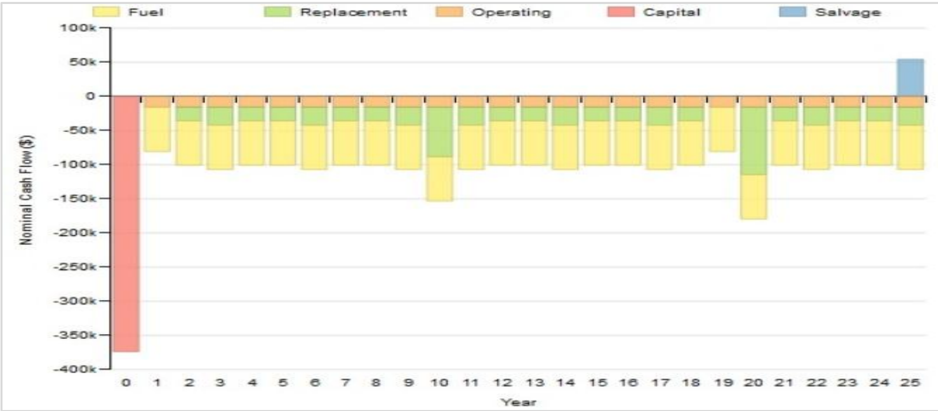


Figure 11. System cash flow by cost type: 1st scenario

The diesel generator still contributes high cost of all 2nd scenario optimum system, which more than $2 million or almost 2/3 of total system cost. Fuel purchasing is about $1.5 million or a half of total system cost (table 3). The capital investment requires for the system is $825,404.00, while for the average expenses need for the next 24 years is quite vary between $100,000.00 – $200,000.00 annually. The detail of the system cash flow demonstrated by figure 12.

Table. 3. System Net Present Cost: 2nd Scenario

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
PV	$269,899.0	$0.00	$14,808.00	$0.00	$0.00	$284,707.00
Wind Turbine	$399,495.0	$219,135.00	$39,487.00	$0.00	-$149,555.00	$508,562.00
DG I 50 kW	$22,525.00	$157,073.00	$122,212.00	$1,070,451.0	-$8,538.00	$1,363,723.0
DG II 30 kW	$13,535.00	$94,219.00	$72,723.00	$476,286.00	-$5,770.00	$650,993.00
Battery	$49,949.00	$151,823.00	$11,846.00	$0.00	-$25,756.00	$187,862.00
Converter	$70,000.00	$105,960.00	$0.00	$0.00	-$21,838.00	$154,122.00
System	**$825,404.0**	**$728,209.00**	**$261,076.0**	**$1,546,737.0**	**-$211,456.0**	**$3,149,970.0**

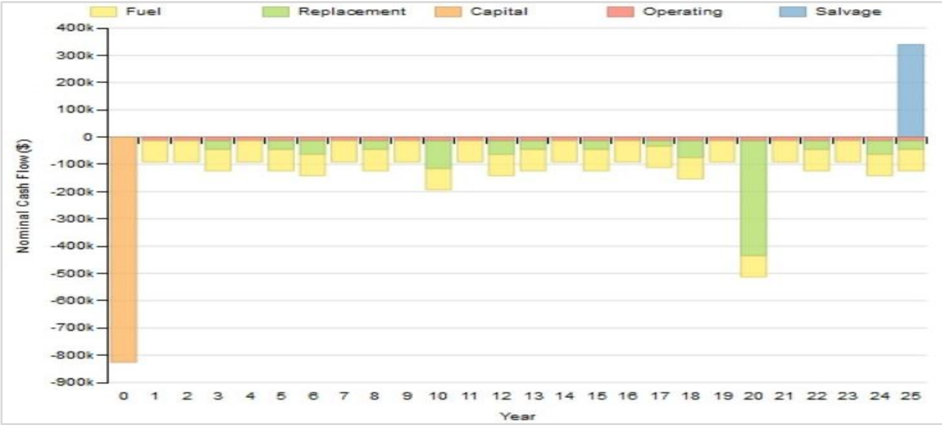


Figure 12. System cash flow by cost type: 2nd scenario

System Environmental Emission

Energy has become the center of human activities to ensure global prosperity, yet energy sector also has a significant role in affecting environmental sustainability by releasing greenhouse gas emission into atmosphere (AGECC, 2010). By 2004, energy consumption based on fossil fuel has account to contribute 56.6% of global CO_2 global emission (IPCC, 2007). Both case scenario of the study revealed a distinguish greenhouse gas emission contribution to the atmosphere. The first scenario contributes loads of emission than second scenario (table 4), since the first scenario consumed more fuel and less renewable energy penetration. The reduction of greenhouse gas emission almost two time less in the second scenario. Greenhouse gas emission reduction in the system should be taking into account, since electricity power generation sector contributes over 27% of global CO_2 emissions and accounted as the biggest global CO_2 emissions (IPCC, 2007).

Table 4. System emission

Pollutants	Units	Emissions	
		1st scenario	2st scenario
Carbon dioxide	kg/year	427,188.00	294,713.00
Carbon monoxide	kg/year	1,054.50	727.46
Unburned hydrocarbons	kg/year	116.80	80.58
Particulate matter	kg/year	79.49	54.84
Sulfur dioxide	kg/year	857,87	591.83
Nitrogen oxide	kg/year	9,409.00	6,491.20

CONCLUSION

With more than 13 thousand islands and 253 million populations, to achieve 100% electrification ratio is one of the most challenging situations for Indonesia. Grid extension from the main island is an expensive option, yet almost 30 million Indonesians living in small and remote islands are still lack of access to electricity. Accordingly, this condition inhibits the economic growth of the society in small and remote islands. Future energy development in small and remote islands should be more flexible in order to deal with varies conditions and needs of the societies. The stand-alone hybrid system proposed in this study considered as quite an interesting option to be alternative for energy supply development in small and remote island in Indonesia, especially to answer the uncertainty of fossil based fuel energy price fluctuation. The study which has been conducted in Air Sena Village is expected to be a model of the development of energy supply system to small and remote island in Indonesia. The effort to increase renewable energy penetration in energy supply system is not only expected to have impact on economic development and supporting human growth and progress, but also to be able to protect local and global environment by reducing green gas emission from energy sectors.

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