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Economics and Environment Assessment of Microgrid Configurations for Rural Area with Standalone and Integrated Energy Storage System

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Abstract

Nowadays, with the rising in electricity demand, Energy Storage System (ESS) plays an important role in solving power crisis especially in small area such as an island. The microgrid concept with energy storage system (ESS) has rising its popularity and interest because it capable to store energy during off-peak hours and supply it back to the grid during peak demand. The objective of this paper is to optimize energy storage system in a real case during peak demand in rural area which is located in a rural area in Tanjung Labian, Sabah. The optimization was modelled and analysed using HOMER by including renewable and conventional energy resources such as solar PV, diesel generators, batteries, and inverter. This paper is divided into two sections. The first section is to investigate the optimum microgrid system by modelling combination of renewable energy and ESS. The optimization model includes parameters such as life cycle, reliability, cost, and size that would give the minimum cost of microgrid system. In the second section, a further investigation was carried out by determining the economics of energy from the best combination of renewable energy and ESS. The results shown that the present of ESS in the system able to reduce the cost and dependency on standalone system through the optimized diesel-PV-battery system modelling having an approximation of 20% less cost as to compared without battery-available system. The perfection of modelling ESS with optimization characteristics will be the key features to the next generation technologies.

Keywords: Optimization, HOMER, Energy Storage System (ESS), Economics.

Introduction

Microgrid is known as a small-scale grid that able to supply load with different combination of resources and can be connected or isolated from the utility grid. During peak demand, microgrid is usually supported by generator or renewable energy such as solar, wind turbine and often used as backup power or supplement the main power grid. It is usually difficult to install power grid from the main land to far island due to various issues including transportation, economics and reliability issues. Microgrid can be found in certain places such in university, hospital, military bases, islanding, airport and large industrial facilities. The rising of population growth rate and urbanization levels causes increasing in electricity demand and emission of carbon dioxide emission. Therefore, application of renewable energy leads to more sustainable and minimizes fuel consumption and harmful gases emission (Aghamohammadi & Abdolahinia, 2014).

To reduce supply crisis and meet the growing demand, renewable energy (RE) with energy storage system (ESS) has become an alternative to act as back up during peak demand. Energy storage system will assist renewable energy in various ways, especially helping the system stability during power crisis. The stability of the system will give serious impact on the overall electric system by storing energy during off-peak and minimize cost (HOMER, 2020). Energy storage is a core component in most remote supply systems, and it needs to be considered in order to ensure the safe and efficient sustainable during operation. There are numerous types of energy storage are available commercially in various stage of implementation. The main type of energy storage can be classified such as mechanical, thermal or electrical type (Kassam, 2010; Kerdphol *et al.*, 2015). Each type has its own properties time to charge or discharge, the lifetime and cost operated system. Hence, it is important to know each characteristic and identify on how energy storage capable to minimize operation at minimum cost. Hence, the needs suitable combination of energy storage and renewable energy is important to ensure reliable power supply at load demand.

There are many types of modern optimization method to find the best microgrid system such as size optimization, lifetime characteristics or economic performance by net metering scheme (Faisal *et al.*, 2018; Li & Hennessy, 2013; Saviuc *et al*., 2019). However, many studies do not consider the reliability of ESS as electricity back-up during power crisis and the need of ESS in microgrid. Moreover, they stated that by installing ESS technology in microgrid is inefficient due to various issue, such as charging or discharging cost, reliability, life cycle and overall cost management. In addition, the inclusion of ESS is not attractive especially when price electricity in the smart grid is very low.

A study of the effect of heat recovery factor in three different scenarios of combined heat and power (CHP) have carried out by using HOMER in a residential area located in Iran (Somayeh *et al.,* 2018; Mehdi *et al*., 2018). The scenarios include generator and boiler which consume diesel as the first scenario, while using natural gas as their fuel done in second scenario. The third scenario implemented by diesel being used in a generator and the boiler consumed natural gas. The first case has been concluded as the most economical while the third scenario (hybrid microgrid) surpassed the environmental concerns as to compared to the remaining scenarios with the least carbon dioxide production of 3604 kg/year.

Meanwhile, a study in Karachi of technical-economic-environmental sensitivity analysis of electricity production and thermal loads of residential areas through off-grid wind-solar-fuel cell system considering the spill effect of emission penalty and annual interest rate on cogeneration of electricity production has been carried out (Mehdi *et al.,* 2018; Habib Ur Rahman *et al.,* 2018). The use of dump loads for converting excess electricity into heat and also heat recovering in fuel cells. This paper produced a great potential for supplying sufficient power and heat by renewable energies and having dump loads as an essential role to provide the thermal demand.

Therefore, this paper will examine the optimization of energy storage system in the microgrid by using HOMER software. The U.S National Renewable Laboratory (NREL) has developed software named HOMER to make easier for user to evaluate any possible configurations of optimization and sensitivity analysis. In HOMER, user able to input power consumption in hourly or monthly data. It also able to input the load demand in daily basis, the solar radiation and daily temperature. This allows users to evaluate optimization of microgrid in various factors such the renewable penetration, the economics, environmental-friendly and the stability. HOMER also able to simulate from small to large scale paper (Singh & Tiwari, 2017).

Problem Formulation

Simulation is performed to find the best optimization model which able to operate at lowest operating cost. If the results are not in the best optimization, the new combinations of RE+ESS are modelled. The optimization parameters include the size of components, capacity, life cycle, economics, and reliability. Model of each component in the system such as PV, battery and diesel generator are shown below.

System Modelling

PV Model: The output power of PV module can be determined by the rated capacity of the PV array in its power output under standard test conditions, solar radiation and ambient temperature.

$$P_{PV}=P_{stc}\frac{G_c}{G_{stc}}[1+\alpha(T_c-T_{stc})] \quad \textbf{(1)}$$

P_{PV} is output of the PV array, G_{stc} is solar radiance under standard condition, 1 kW/m^2. G_c is solar irradiance on the PV array, α is the temperature coefficient of power. T_c is PV cell temperature and PV T_{stc} temperature are 25^{o}c.

Lead-Acid Battery Model: The lead-acid battery plays an important role in microgrid system. The operating strategy of battery give an impact to overall operation. The SOC of battery at a certain time should be in range.

$$SOC_{min} \leq SOC \leq SOC_{max} \quad \textbf{(2)}$$

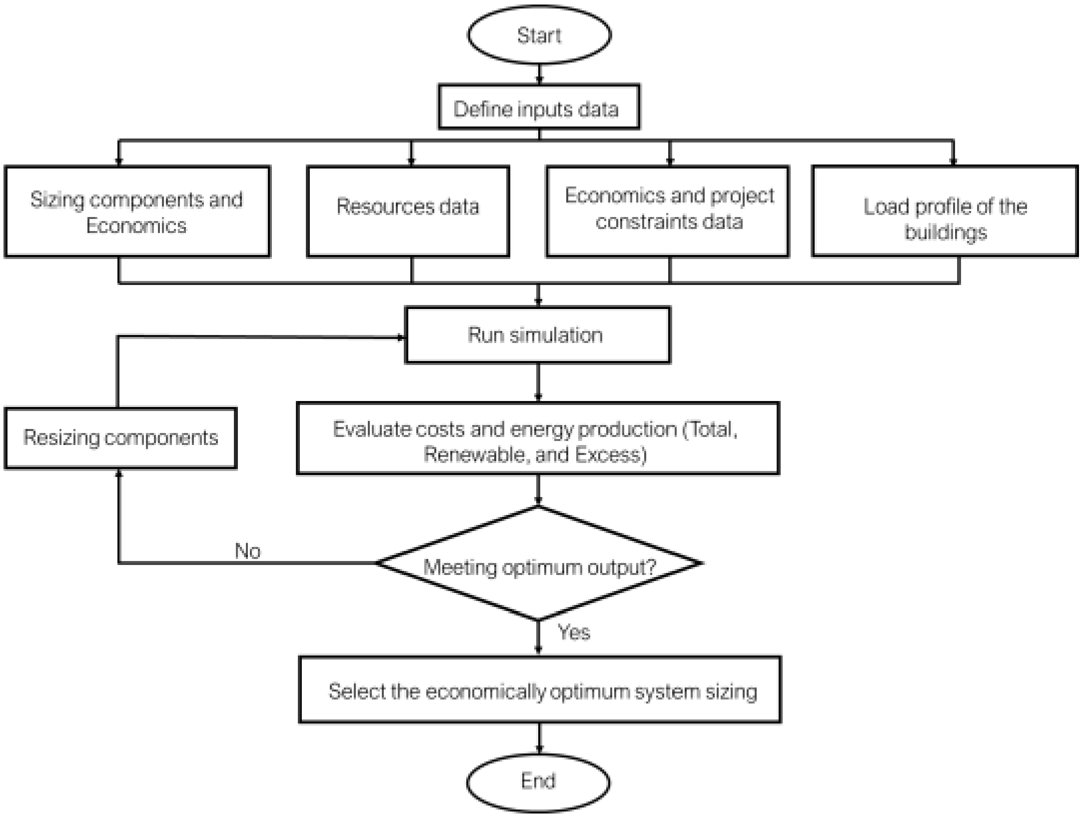
In which, SOC has upper and lower limit which SOC_{min} and SOC_{max} respectively. In addition, there is also a limit for battery output power. $P_{cha-max}$ is requirement for charging while $P_{discha-max}$ is the maximum for discharging. When the battery is charging, P_{bat} is positive. Otherwise, P_{bat} is negative when discharging.

$$P_{cha-max} \leq P_{bat} \leq P_{discha-max} \quad \textbf{(3)}$$

Diesel Generator Model: Diesel generator is used as backup power when there is not enough output from PV. The fuel curve of generator is assumed as straight line. The given equation is a generator's fuel consumption in units/hour as a function of its electrical output.

$$F_0 \times P_{rated,gen} + F_1 \times P_{gen} \quad \textbf{(4)}$$

F_0 and F_1 is the fuel curve intercept and slope coefficient respectively. $P_{rated-gen}$ is the rated capacity of the generator and P_{gen} is the electrical output power.



Objectives Function and Constraints

In HOMER, the best possible system configuration is the one that able to operate at minimum cost. In finding the optimal system, it includes the consideration such in the dispatch strategies system, size and capacity of the component. Therefore, in order to determine the optimal value that suits best the system, the following constraint need to be satisfied**:**

Generation cost: The generation comprises of two parts which the cost from diesel generator and from the renewable energy. In HOMER, the generator fuel consumption is as follow:

$$F = F_0 P_{rated\_gen} + F_1 P_{gen} \quad \textbf{(5)}$$

F_0 denotes as the intercept confident of fuel curve, *F_1* is the gradient of the curve, *$P_{rated\text{-}gen}$* is the rated capacity and *P_{gen}* is the generator electrical output. In HOMER, the generation is calculated as:

$$C_{gen,fixed} = C_{om,gen} + \frac{C_{rep,gen}}{R_{gen}} + F_0 Y_{gen} C_{fuel,eff} \quad \textbf{(6)}$$

For renewable energy, the generation cost is $C_{gen,fixed}$. The operating and maintenance equipment for generation life is $C_{om\text{-}ren}$ and $C_{rep,gen}$ respectively. The intersection fuel curve coefficient is denoting as F_0, the generator lifetime in hours is R_{gen}, the generator capacity is label as Y_{gen} (kW), While $C_{fuell,eff}$ is included the pollution generated cost due operation generation cost.

In HOMER, the properties storage life indicates the storage life is depends on lifetime throughput. To measure the life span of batteries, HOMER observed energy cycling passes it. The following equation is to calculate battery life in years:

$$R_{batt} = \min\left(\frac{N_{batt}.Q_{lifetime}}{Q_{thrpt}}\right), R_{batt,f} \quad \textbf{(7)}$$

The number of battery bank is label as N_{batt}, $Q_{liferime}$ is the lifetime of battery and Q_{thrpt} is the summation of total energy cycle through battery bank within one year, and $R_{batt,f}$ is the maximum life battery life. HOMER calculates the wear cost of battery is as follow:

$$C_{batt}=\frac{C_{reppbatt}}{N_{batt} \cdot Q_{lifetime} \cdot \sqrt{\eta_n}} \quad \textbf{(8)}$$

$C_{reppbatt}$ is the replacement cost of the storage bank, N_{batt} is the number of batteries in storage bank and $Q_{lifetime}$ is the lifetime in each single storage [kWh] and $\sqrt{\eta_n}$ is a roundtrip efficiency in fractional or in average of 80%.

In addition, the constraints in (1), (2) and (4) should also be satisfied.

Evaluation Criteria

In the HOMER, it provides analysis in economical based on the framework of life cycle cost (LCC) The LCC depends on capital cost, replacement cost and operating maintenance cost. HOMER able to perform simulation to find the optimum cost and design. The total net present cost determined by HOMER is as follow:

$$NPC=\frac{C_{tot}}{CRF(i,T_p)} \quad \textbf{(9)}$$

C_{tot} is the total annual cost of the system ($/year), i is the annual interest rate and T_p is the lifetime of operation, while *CRF* is the capital recovery factor which can be defined as:

$$CRF(i,n)=\frac{i(1+1)^n}{(1+i)^{n-1}} \quad \textbf{(10)}$$

n is representing the number of years. Then, the salvage cost (SV) is calculated as:

$$SC= C_{RC}\frac{T_{rem}}{T_{com}} \quad \textbf{(11)}$$

C_{RC} is the equipment replacement cost. T_{rem} is equipment remaining lifetime(year) and T_{com} is the component period life (year). The levelized of COE is as following:

$$COE=\frac{C_{tot}}{E_{tot}} \quad \textbf{(12)}$$

E_{tot} denotes as the total annual electricity consumption (kWh/year).

System Design

This project test bed was in Tanjung Labian, Sabah. It is a small island located at the eastern side of Sabah with the latitude 5.10^o N/119.13^{o}E. The main source incomes for the islanders are timber, tourism and exporting seafood (Nfah & Ngundam, 2008) as shown in figure 1. The system has been designed to include the following technologies, PV systems, converter and diesel generator to acts as back up supply.

Table 1
Site specification

Site	**800 houses**
Location	5.10 °N latitude, 119.13 ° E longitude
Average load	160.11 kW
Peak load	416.98 kW

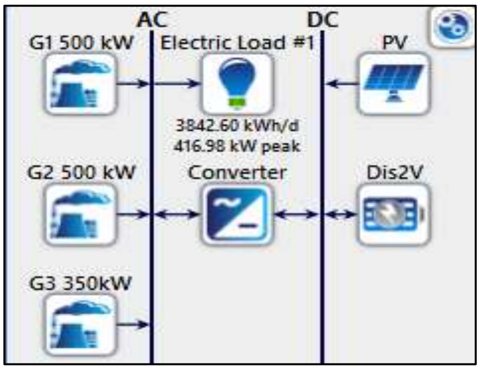
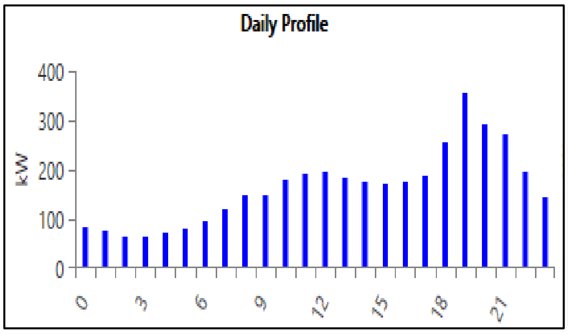


Figure 1: Schematic for Microgrid system

Load Demand

In remote areas, usually the local spent their whole time outdoors since their main sources of income comes from fishing, tourism and exporting seafood. The use of the electricity does not high as in urban areas. The uses of load started to increase at noon as the family members will come home to have lunch. However, the peak demand will be at night when all the family members are at home. The demand data were gathered from (Nfah & Ngundam, 2008). The data had been modified to provide a more accurate portrayal demand for load modelled period. The daily load profile is shown in figure 2 can be observed that the load varies throughout the day. In the morning, the demand is low. However, as the day passes, the demand is rising, and it noticed the peak demand was at night. Random variability factor has been set to HOMER in order to estimate differences in each day, it is known as day-to-day variability and time-to-step-time variability. Malaysia is tropical country which do not have various season. Therefore, approximately 5% has been set for the variability.



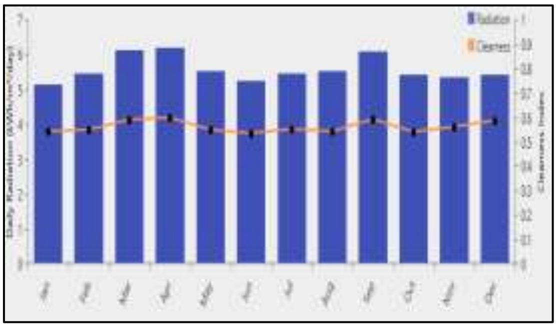


Figure 2: Daily Load Profile

Figure 3: Solar Radiation Data

Solar Radiation and Temperature

The data of solar radiation was provided by Malaysian Metrological Department which can be downloaded through HOMER. Solar radiation for Tanjung Labian was selected and the data showed that the range of solar radiation is between 4.8 kWh/m^2 to 5.57 kWh/m$^{2.}$ In figure 3, it can be seen that the solar estimated annual average scale for Pulau Banggi is 5.57 kWh/m^2. Generally, the annual average temperature for Tanjung Labian is 26.3^{o}C. The temperature data is downloaded from NASA.

System Components

Tanjung Labian power system is implemented with several components such diesel generator, PV array, batteries and converter. It is about to supply electricity for 800 houses (Nfah & Ngundam, 2008).

Diesel Generators

Diesel generator will be used to meet the demand when there is no output from PV panel and batteries (Hossain et al., 2017). The recent diesel price in Malaysia is RM 2.18 per litre ($ 0.7 per litre). The capital cost and replacement cost for this paper is 220 $/kW while the maintenance cost is 0.030 $/kW. The generator price is stated by (Anwari *et al*., 2012). As in (Shaahid & El-Amin, 2009), the diesel price is depending on locations; where in the remote area the fuel price could be 1.5 times higher than normal prices. This is due to the expensive cost of transportation to the location.

PV array and Converter

PV system is used to supply base load during daytime and at the same time charging the energy storage. The capital cost and replacement cost for PV is 2000 $/kW and the maintenance cost are 10 $/year (Anwari *et al*., 2012). The used of converter is to convert electrical energy to desired forms. The rated of converter is depends on PV array to ensure to fully supply PV. The capital cost and replacement cost are 890 $/kW and 800 $/kW respectively while the maintenance cost is 10 $/kW (Anwari et al., 2012).

Battery Energy Storage

Battery acts as backup to supply electricity during peak demand and during nighttime. The battery consists of 6 string with 240 batteries units. The capital cost of battery is 1200 $/unit and 1170 $/unit for replacement.

Operating Strategies

In HOMER, there are two main operating strategies can bet set which are cycle charging (CC) and operating charging (OC). In cycle charging, diesel generator is used to supply the base demand also needed to charge the battery. Generator operates at its full maximum capacity, if there is excess electricity it will be used to charge the battery. However, in this paper load following was assumed to operate the system. In load following strategy, PV is used to supply the base load and charging the battery until it fully charged. If there is not enough power, the battery still able to meet the demands until it reaches the certain set-point of charges. Only after that, the generator will take place to supply the loads. Generator is use as backup power. Load following strategies is an ideal system with a lot of RE power.

Result and Discussion

The results will be discussed by comparing operating strategies of different system configurations such standalone, existing diesel/PV/battery system, existing system diesel/PV without battery and the optimized system. The results will include all the technical, economical and environment factors. The comparison of results of each system is provided in Table II. This study presents 6% of interest rate to the diesel price and investment cost with paper lifetime 25 years. The results for each part are separately in section 5.1, 5.2 and 5.3.

Optimization Results

Standalone System

From the results in Table II, it can be figured out that the lowest net present cost (NPC) for all system with $ 5,105.503 can be obtained in standalone diesel system. The system cost will be high due to installing RE requires lots of cost. In this system, the largest generator is used to supply the load demand and the other generator will act as back up. From Table III it can be seen, generator 1 was served the base load. The other generator will be on standby, if generator 1 unable to meet the demand, generator 2 will take immediate action backup generator 1, generator 3 will followed as well. Since the first generator is 500kW, it supplies all the demand as the peak demand is 416.98kW in this system. Renewable energy fraction is 0% as the system do not use solar photovoltaic. This shows total electricity production is 100% comes from diesel generator 1,625,623 kWh/yr.

Existing Diesel/PV/ Battery System

PV arrays produce large amount of electricity which 66.1% of the energy production can be noticed in Table III. During the daytime, the PV arrays will supply the base load and at the same time charging the energy storage system. Meanwhile, during nighttime, if the battery could not supply the demand, generator 1 will take an action and supply the load. Hence, the largest generator 1 (500kW) produce 33.9% of energy production. Another generator will be on standby. The NPC and COE for this system is twice amount compared to stand alone system which $7,765,982 and $0.3515 respectively. The NPC is higher due to present of RE system. However, the operating cost is lower by $249,590.70. Renewable fraction for this system is 28.3%. However, in this system the excess electricity is 50% per year which it can still be reduced by optimizing the system.

Existing System Diesel/PV without Battery

This condition is developed to study the advantages or disadvantages system without battery. The results show in table II, the Net Present Cost, operational and LCOE is higher than existing system with includes battery i.e. $9,106,820, $352,993.30 and 0.4122 $/kWh respectively. This combination is the most expensive among all system because the generated power from PV is not being used fully. The excess electricity which can be used to charge battery is consider as loss since this system do not include energy storage system. Hence, when PV cannot meet the demand and there is no storage to store energy, generator need to be ON to replace the PV supply the load. In addition, the CO_2 emission from generator is higher due to running hours of generator 1 is longer than system with batteries. This could cause air pollution. The analysis does not impose the penalty cost for pollution.

Optimizing System PV/Diesel and Battery

In the optimum system configuration, the selection of sizing component is observed less than the existing system. The net present cost is $5,981,107 which are lower than the existing system where $7,765,982. The operational cost and LCOE is $278,229.20 and 0.2707$/kWh respectively. The system uses 240 batteries unit. In addition, the excess electricity for this system is only 14.8%. Hence, this optimum system shows a huge different in cost and operating due to less PV and generator capacity use.

Table 2
Total cost of the system

Description	**NPC ($)**	**Operational Cost ($)**	**LCOE ($/kWh)**
Standalone Diesel	5,105,503	319,137	0.2311
Existing Diesel/PV/Battery system	7,765,982	249,590.70	0.3515
Existing Diesel/PV/ without Battery system	9,106,820	352,993.30	0.4122
Optimized Diesel/PV/battery system	5,981,107	278,229.20	0.2707

Operating Strategies

The technical challenging part for the systems is to decide their operating strategies. The simulation was carried out from the optimizing diesel/PV and battery system with two different operating strategies. Table IV shows the Net Present Cost (NPC), operating and LCOE for load following is cheaper than cycle charging dispatch by $5,964,988, $277,226.90 and 0.270 $/kWh respectively. This is because in load following; PV is used to supply the base load and charging the battery. The use of generator is load following only enough to feed the load.

Table 3
Overall System Performance

Type of System	**Component**	**Rated Capacity (kW)**	**Production (%)**	**Production kWh/yr**	**Running hours (h/yr)**	**CO_2 emission**
Standalone system	G1	500	100	1,625,623	8,760	1,200,906
	G2	500	0	0	0	
	G3	350	0	0	0	
	Total	1350	100			
Existing Diesel/PV/Battery system	PV	1200	66.1	1,959,918	4,380	740,163
	G1	500	33.9	1,006.239	5,249	
	G2	500	0	0	0	
	G3	350	0	0	0	
	Total	1350	100			
Existing Diesel/PV without Battery system	PV	1200	56.2	1,959.0917	4,380	1,138,714
	G1	500	43.8	1,529,139	8,735	
	G2	500	0	0	0	
	G3	350	0	0	0	
	Total	1350				
	PV	400	41.4	653,306	4,380	

Optimized Diesel/PV/Battery system	G1	300	36.6	577,781	5,769	836,019
	G2	200	18.0	284,622	1,092	
	G3	200	3.95	62,404	434	
	Total	1000	100			

Table 4
Total cost for dispatch strategies

Dispatch Strategy	NPC ($)	Operating Cost ($)	LCOE ($/kWh)
Load Following	5,964,988	277,226.90	0.2700
Cycle Charging	6,132,705	287,874.00	0.2776

Sensitivity Analysis
High Diesel Price
The diesel price in remote areas can be high due to its location and the expensive transportation. The diesel price is varied from 0.7$/L to 3.00 $/L. The growth demand was assumed as 5% per year, and the results show as the fuel price increase. The NPC, operating and LCOE are expected to increase. However, the fuel price will continue increase but the total cost can be reduced as the new development technology of will lead to reduce PV and batteries prices. Decreasing in PV and batteries price will lead to the less dependence on standalone system.

Battery Sizing
Also, analysis on battery have been observed. The present of storage system is important, to ensure the stability on the system especially during the peak demand. The size of batteries gives an impact on NPC value. Increasing number of batteries, the value of NPC will be higher as the addition battery will add up cost to the NPC and the operational cost. In order to operate optimally, choosing the size of battery should be aligned with the usage of load demand. The size of battery has been varied from 60- 360 units. In this study, 240 units of batteries with 40% SOC is the optimum for the system with 7 years of lifetime.

Environmental Impact
The usage of diesel has given negative impact to environment and human health. From the Table V, the CO_2 emission in the standalone system shows the highest rate compared to other systems with 1,200,906 kg/year. The diesel price gives an impact in choosing optimization system, the optimization would be to standalone system if the diesel price is 0.7$/L. However, the standalone system will only be feasible when the increasing in diesel price starting 1.06$/L. Then, system with PV and battery is the cheapest among all. Therefore, the existing of RE sources in the system has improved economical and environment characteristics. As seen in results, the present of PV and energy storage system reduced the amount of harmful emission release.

Table 5
System behaviour for dispatch strategies

Pollutant (kg/yr)	Standalone System	Existing Diesel/PV/Batteries
Carbon Dioxide	1,200,906	740,163
Carbon Monoxide	6,213	3,829
Unburned Carbon	330	203
Matter	53.1	32.7
Sulfur dioxide	2,936	1,809
Nitrogen oxide	1,191	734

Conclusion

This study investigates the economic analysis in different system in Tanjung Labian by using HOMER. It has shown that

- the standalone system is the best economical compared to existing PV/Diesel/Battery system.
- the present of RE and storage system reduced the emission of harmful gasses.
- considering dispatch strategy, load following is the best for option where it produces more renewable penetration, cycle charging is efficient when renewable penetration is less.
- the sensitivity results are conducted based on certain parameters which are diesel price, PV size, load demand growth, battery sizing and environmental impact. It predicts the trends of RE sources in future and become less dependent on standalone system.
- this study has shown that by including energy storage to store energy capable to minimize cost, reduce the excess energy also the dependence on diesel generator.

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