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Techno-economic Analysis of a Stand-alone Photovoltaic-Diesel Hybrid System for Rural Area in Sarawak

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Abstract: Photovoltaic hybrid power generation is an alternative solution for supplying electricity to rural areas, especially in Sarawak, Malaysia, where grid connection is almost impossible due to the cost and geographic location. Diesel generator systems are still used by local communities in these remote areas, and the implementation of photovoltaic diesel hybrid systems can reduce dependency on diesel generator units. The work presented in this paper explores the possibility of integrating solar energy resource with diesel generator to meet the load demand of rural communities in Sarawak. In further detail, the configuration and size of the PV-diesel system are analyzed in based on the lowest net present cost (NPC) and the cost of electricity (COE). The analysis is based on mathematical modeling and simulation using Hybrid Optimization Model for Electric Renewables (HOMER) software. Eight different configurations of two energy resources-photovoltaic panels and diesel generators-are studied and compared. The option with the highest optimization values is considered to be the most feasible electrification solution for the particular rural area. The outcomes of the analysis show that the PV-diesel hybrid configuration proves to be more cost-effective compared to an existing generator-based system in that it reduces fuel dependency and has the lowest NPC and COE among all configurations studied.

Keywords: PV-Diesel Hybrid, HOMER, Net Present Cost, Cost of Electricity

1. Introduction

The majority of the population in West Malaysia has access to the electricity grid. However, some of the population in rural areas in the east region do not yet have access to sustained electricity and traditionally rely on diesel generators as well as small-scale renewable energy electrification. Although the electricity access rate in Malaysia is 100% nationally, there still remain pockets of rural areas, especially in the states of Sabah and Sarawak, without access to modern energy infrastructure [1].

The rural community usually uses diesel generators for the electrification of the areas, but such solution has disadvantages such as high fuel and maintenance costs [2]. The limited hours of generator operation limit any significant activity for socio-economic improvement due to the price of diesel and maintenance issue. Electricity will bring light to these communities which results in improvements in education, health and communication; and it surely

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enhanced the income level of the household. In addition, the maintenance and operational costs for this type of configuration are seen as an extra burden, as well as the costs to buy and to deliver diesel fuel over long distances either by river or disrupted road access.

Solar energy is considered a practical approach to overcome the electrification issue due to the abundance of solar irradiation in this region. The weather conditions are favorable for the development of photovoltaic (PV) systems, as Sarawak lies directly on the equatorial zone and receives sunshine throughout the year. This makes the area highly suitable for the implementation of PV systems as an alternative energy source. The annual average daily solar irradiation for Malaysia was recorded as being between 4.21 kWh/m2 to 5.56 kWh/m2. The highest irradiation was recorded at 6.8 kWh/m2, which occurred in August and November, while the irradiation lowest value of 0.61 kWh/m2 occurred in December [3], [4].

However, the solar energy fluctuates and is intermittent, and typically supplies only a few hours of power after nightfall. The dependence on solar element needs to be solved by hybridizing this energy source with several other energy components such as diesel generators and battery systems to generate electricity with lower implementation costs and provide a stable electricity supply to the Sarawak region, particularly in rural areas [5].

2. System Modeling

The economic system modelling was formulated from power generation models and cost criteria models. The cost criteria model was leveraged upon the annualized costs of system components, which included initial set-up, operation and maintenance, part replacements, and the fuel cost of the generators. The cost objective function for the optimization problem was to reduce the NPC and COE by simulating and comparing various system configurations. The theoretical concept for optimization in this analysis was based on mathematical modeling that included the model of power generation, the system components, the costs, and energy optimization. The theorical aspects are given below and are based on the works of authors in [6], [7], and [8].

2.1 Mathematical Model for System Components

Solar irradiation is the input parameter for photovoltaic generation model. The energy output from PV panel is depends on beam and diffuse radiation that falls on the PV panels and it can be modeled by the general equation [6], [7], and [8].

$$E_{pv} = G(t).A_{pv}.P.\eta_{pv} \tag{1}$$

An assumption was made that temperature effects on PV cells will be ignored.

where,

$G(t)$ is the hourly irradiance in in kWh/ m^2 ,

A_{pv} is the surface area, in m^2 ,

P is the PV penetration level factor,

η_{pv} is the efficiency of PV panel.

The hourly energy output from diesel generator can be calculated according to the equation

$$E_{dg}(t) = P_{rated}(t).\,\eta_{dg} \tag{2}$$

If more than one generator attached, the energy output will be the sum of all generated power by each generator.

$$E_{dg\_total}(t) = \sum_{dg=1}^{N_{dg}} E_{dg}(t) \qquad E_{dg\_tot}(t) = \sum_{dg=1}^{N_{dg}} E_{dg}(t) \tag{3}$$

where,

η_{dg} is the efficiency of the diesel generator,

P_{rated} is the generator rated power,

$E_{dg\ tot}(t)$ is the total power from all generators,

$E_{dg}(t)$ is the hourly energy of each generator.

The battery state of charge (SOC) is the cumulative sum of the daily charging and discharging rate. The battery bank serves as energy source when discharging and as a load when charging. At any time, t, the SOC is related to the previous SOC, while for the period of t-1 to t, it is related to the energy production and consumption situation. During the charging process, when the total output of all PV exceeds the load demand, the available battery bank capacity at a time, t, is described by [6], [7], and [8].

$$E_{bat}(t) = E_{bat}(t-1) - E_{cc-out}(t).\eta_{chg} \tag{4}$$

where,

E_{bat} is the energy stored in battery at hour t,

$E_{bat}(t-1)$ is the energy stored in battery at hour t-1,

$E_{cc-out}(t)$ is the energy discharge from charge controller at hour t,

η_{chg} is the battery charging efficiency.

he battery is triggered to support the energy demand. As such, the available energy in battery bank at a time t, is expressed as [6], [7], and [8]:

$$E_{bat}(t) = E_{bat}(t-1) - E_{req}(t) \tag{5}$$

where,

$E_{req}(t)$ is the hourly energy demand required at time, t.

2. 2 Annualized Economic Cost Model of All Components

The annualized economic cost model of all component can be modeled by equation [6].

$$C_{ann\_tot} = \sum_{con,bat,dg,pv=1}^{N_{con,bat,dg,pv}} capital + opening + replacement \tag{6}$$

where,

$C_{ann\ tot}$ is the total annualized economic cost model of all components,

$N_{c,bat,dg,pv}$ is the number of each component.

2.3 System Optimization Model

The optimization problem for the PV-diesel hybrid system is derived based on previous power generation, component, and economic cost model. The cost function includes operating cost of the generator units, converter, battery, and PV panel can be finally described as in [8].

$$Cost = \sum_i C_{pv,i}N_{pv,i} + \sum_j C_{dg,j}N_{dg,j} + \sum_k C_{bat,k} + N_{bat,k} + \sum_l C_{con,l} + N_{con,l} \tag{7}$$

where,

$C_{pv,dg,bat,con}$ is the cost for each component,

$N_{pv,dg,bat,con}$ is the number of each component.

Subject to following constraints,
Load demand is less or equal to power generated from PV and generator,

$$Load \leq \sum_i E_{pv,i}N_{pv,i} + E_{dg,j}N_{dg,j} \tag{8}$$

$E_{pv,i}$ is the power generated by PV panel,

$E_{dg,i}$ is the power generated by generator,

N_{pv} is the number of PV panel,

N_{dg} is the number of generator.

The generator has to operate within generation limit,

$$P_{dg,i,\min} \le P_{dg,i} \le P_{dg,i,\max} \tag{9}$$

where,

P_{dg} is the power of generator.

Battery state of charge,

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \tag{10}$$

where,

SOC is the state of charge of the battery.

3. Optimization Algorithm and Method Implemented in Homer

HOMER simulation software was developed by the United States National Renewable Energy Laboratory (NREL) used to simulate and suggest a feasible system for all possible combination of a component by making energy balance calculations in time steps of yearly data [9]. In each interval or time step, HOMER compares the electric and thermal demand in that time step to the energy that the system can supply and calculates the flow of energy to and from each component of the system [10]. This analysis uses the latest version of HOMER, namely Homer Pro, which features a new optimization algorithm to examine the least-cost system for rural application. Figure 1 shows a flowchart of the optimization framework in HOMER Pro [11], [12].

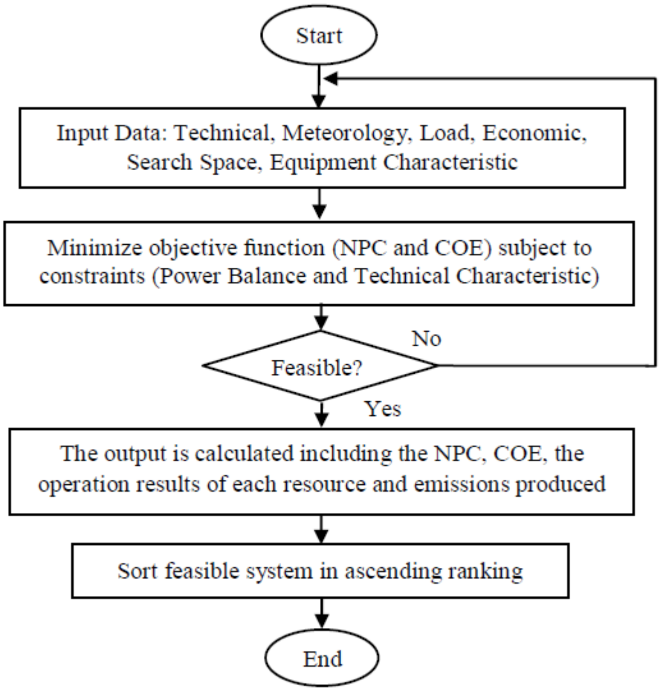

Fig. 1 - Framework for HOMER Optimization

HOMER Pro has two optimization algorithms called optimizer and grid search algorithm. The grid search algorithm simulates all of the viable configurations. An optimizer algorithm is based on propriety derivative-free algorithm that used to calculate the least costly system [9]. A derivative-free algorithm is a mathematical-based optimization that does not use derivative information in the classical sense to find an optimal solution [13]. According to [14], given the unconstrainted optimization problem,

$$\min \{f(x): x \in R^n\} \quad (11)$$

where f: $R^n \rightarrow R$ may be noisy or non-differentiable, and particularly in the case where the evaluation of f is complex and computationally time-consuming to evaluate, the problem of finding an optimal point in this particular situation is referred to as derivative-free optimization. More reviews and explanations on derivative-free algorithms can be found in [14] and [15].

There are two strategies used in PV-diesel hybrid optimization, namely the load following (LF) and cycle charging (CC) dispatch strategies. Figure 2.0 illustrates the optimization algorithm in various case of supplying loads based on the work in [6] and [16].

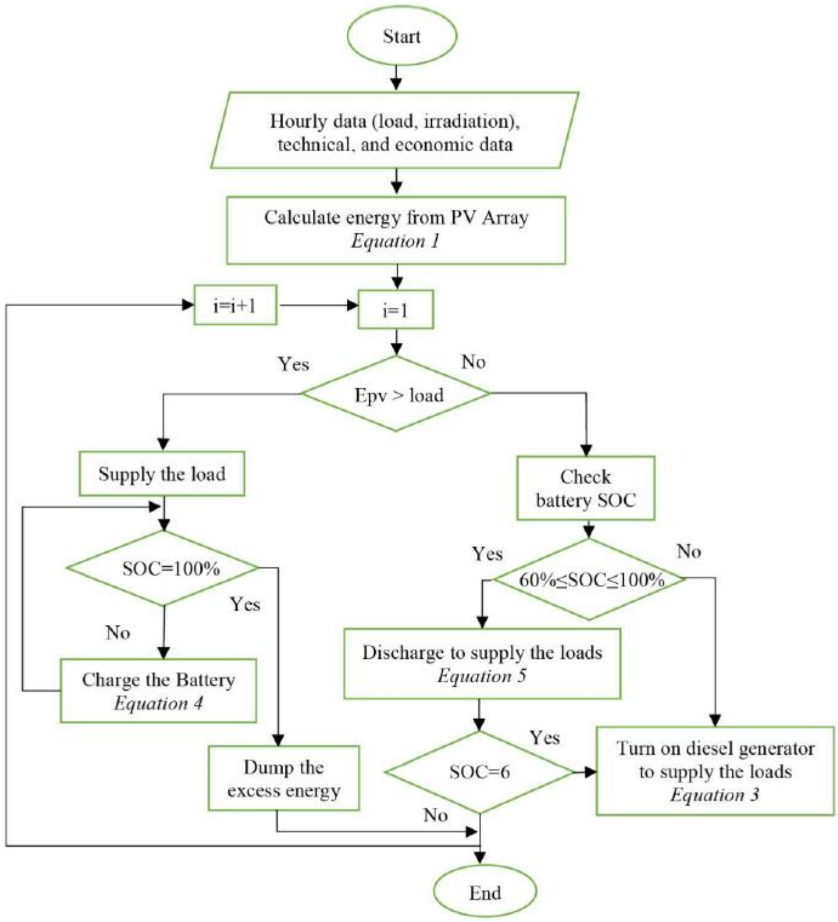

Fig. 2 - Optimization Algorithm PV-Diesel Hybrid System

In the event of unavailability of PV output, the LF strategy is used, in which the diesel generators are employed to supply the electricity load. The PV panels are used to supply the load and charge the batteries in the event of excess power. Meanwhile, in the CC strategy, diesel generators are used to feed the load demand and at the same time to charge the batteries. The LF strategy was considered in this analysis as it helps to reduce excess energy. The system operates in different modes accordingly to the climate conditions. When solar irradiation is available, the control system priorities the PV panels to supply the loads. Meanwhile in the case of excess energy, the system will charge the batteries. Under these conditions, any further excess energy should be either dumped or utilized for ancillary service. If there is less energy output from the PV panels, the battery will supply the loads until the minimum SOC occurs, at which point the system will employ the diesel generator to supply the load. The decisions of the control system to operate any of the energy components and to charge or discharge the batteries take place on an hourly basis and based on the energy balance computation.

Meanwhile, in the CC strategy, generators are used to supply the electricity load and at the same time to charge the batteries. The LF strategy was considered in this analysis as it helps to reduce excess energy. This system configuration operates in different modes based on climate situations. When solar irradiation is available, the control system priorities the PV panels to feed the loads. Else, the system will charge the battery in the case of excess energy occurred. Under these conditions, any further excess energy should be either utilized for ancillary service or dumped. If there is less energy output generated by PV panels, the battery banks will supply the electricity load until the minimum SOC occurs, at which situation the system will employ the generator to supply the load. Figure 2 illustrates the optimization algorithm in various case of supplying loads based on the work in [6] and [16].

Based on the energy consumption of the Bario community, it was decided to implement a PV-diesel hybrid configuration combining PV panels, diesel generators, battery storage, and converter. The system configuration used in this hybrid system is a mixed-bus system where the energy from the PV panels and the battery banks feed into the direct current (DC) bus and the energy from diesel generators feeds into the alternating current (AC) bus as depicted in Figure 3 [16], [17].

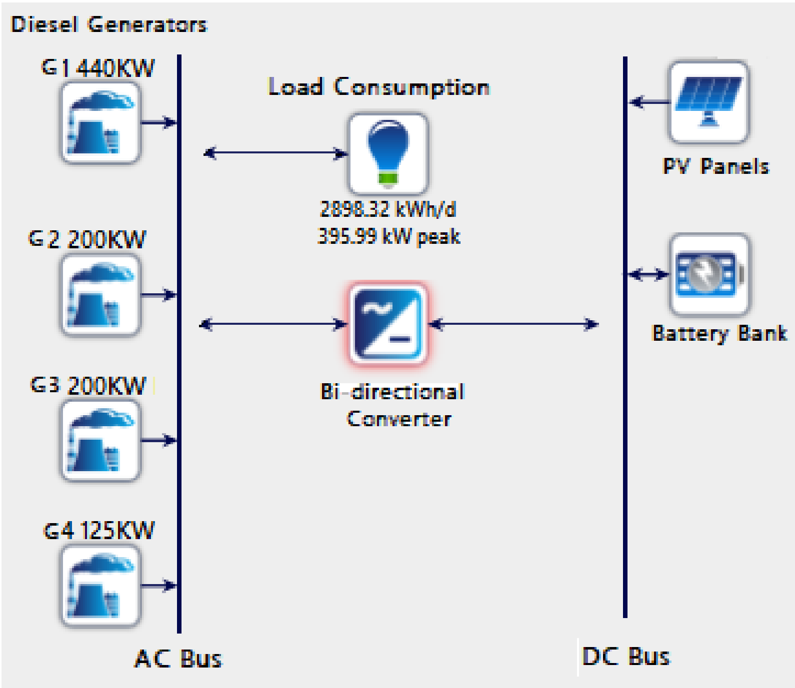

Fig. 3 - The Tested PV-Diesel Hybrid Configuration

To find the most viable system with lowest cost criteria, the input variables were prepared and gathered through data preparation stage. The priority cost criteria analyzed were the NPCs and COEs of the system configurations. Other cost criteria analyzed were capital costs, operating costs, and diesel fuel costs. Eight system configurations were proposed: PV/four generators/battery, PV/three generators/battery, PV/two generators/battery, PV/one generator/battery, PV/battery, two generators/battery, two-generator system, and a PV/two generator system. The component costs, load size, technical data, interest rate, and control strategy were then simulated using the HOMER optimization software. The method used for the system's cost analysis is represented in Figure 4.

The 2018 monthly solar radiation data for Bario, Sarawak coordinated at 3°44.7' N, 115°27.0' E is analyzed based on mean global solar radiation and monthly clearness index [18]. The solar radiation reaches its highest value of 5.39 kWh/m$_2$/day in June, and a yearly average of 5.11 kWh/m$_2$ was recorded at the studied location [19]. The clearness index indicates the clearness of the atmosphere at the selected site and was generated by HOMER. The average clearness index in this remote area was recorded as 0.47 annually. The highest clearness index value of 0.534 was recorded in June and the lowest of 0.472 was recorded in December [17], [19]. The solar radiation data was automatically generated by HOMER once the location was selected [18].

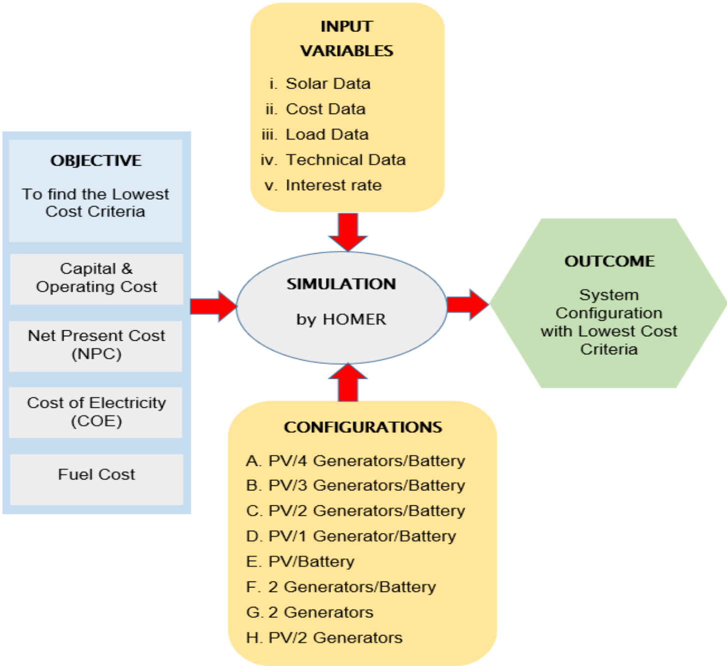

Fig. 4 - Method for Cost Analysis

4. Result and Discussion

Eight different configurations were proposed for further economic analysis in order to determine the most optimized system. The optimization inputs are also based on 5.11 kWh/ m2/day of solar radiation, a 0.47 clearness index, RM 2.18/liter diesel prices, 80% maximum renewable energy penetration, and interest rate of 6.0%. The complete analysis results are depicted in Table 1.

Table 1.0 - Optimization Results Based on Different Configurations

Configuration	PV	Converter	P1 440kW	P2 200kW	P3 200kW	P4 125kW	Battery	Net Present Cost (RM)	Cost of Electricity (RM)	Operating Cost (RM)	Initial Cost (RM)
A	✓	✓	✓	✓	✓	✓	✓	10,131,480.00	0.7408	508,884.20	3,552,875.24
B	✓	✓	✓	✓	✓		✓	9,934,297.00	0.7264	512,389.30	3,310,375.24
C	✓	✓	✓	✓			✓	9,618,797.00	0.7033	517,997.50	2,922,375.24
D	✓	✓		✓			✓	9,396,797.00	0.7182	501,919.20	2,908,228.37
E	✓	✓					✓	13,622,900.00	1.0700	309,862.50	9,617,149.24
F		✓		✓	✓		✓	10,146,190.00	0.7419	732,875.90	788,275.35
G				✓	✓			10,131,510.00	0.7408	732,689.80	776,000.00
H	✓	✓	✓	✓				10,161,290.00	0.7430	676,566.60	1,415,267.61

The PV and battery system (Configuration E) produced the lowest operating cost of RM309,862.50, while the generator and battery system of Configuration F was the highest with a cost of RM723,875.90 between all configurations. The ranking for each configuration is shown in Figure 5.

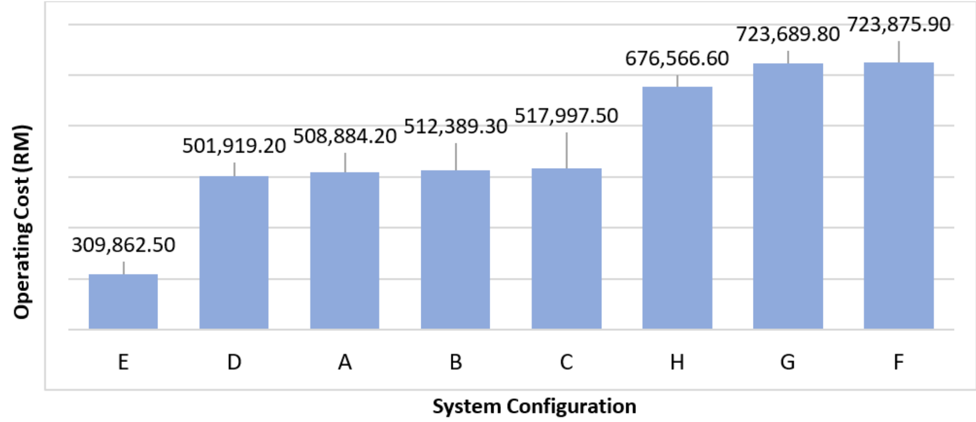

Fig. 5 - Comparison Based on Operating Cost

Configuration E is a fully renewable energy configuration and had the lowest operating costs among all configurations analyzed. In Configuration F, additional costs were imposed to cover the operating cost of the generator, including its maintenance and fuel costs. Configuration F is not ideal for a sustainable hybrid system despite the fact that the capital cost of this configuration ranked second lowest among all configurations, as shown in Figure 6.

The highest capital cost, RM9,617,149.24, was recorded for the PV and battery of Configuration E. In this weather and solar irradiance-dependent configuration, the system needs more battery capacity for energy storage to satisfy the electricity demand. The least capital cost of RM776,000.00was recorded for the base case, the diesel-only system of Configuration G. Configuration F was the highest of RM9,617,149.24 between all configurations.

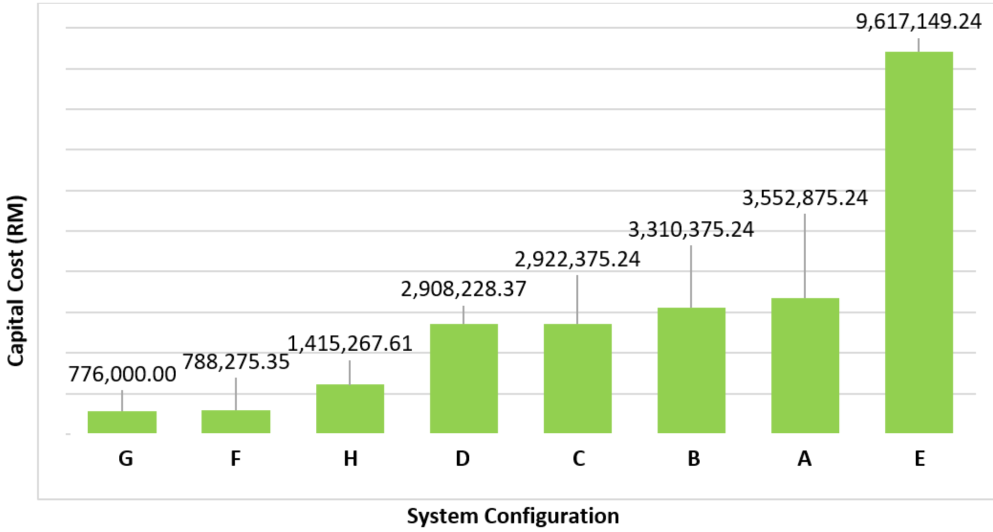

Fig. 6 - Comparison Based on Capital Cost

Configuration D had the lowest NPC among all configurations, at RM 9,396,797.00. However, as a power control strategy and to ensure no power disruption in meeting load demand, two generators had to be involved in the optimization to avoid system failure due to generator breakdown or scheduled maintenance. Configuration C, which integrates a PV array, two diesel generators, and a battery, had the second lowest NPC among all configurations at RM9,618,797.00. The 100% renewable energy penetration and lowest operating cost (RM309,862.50) is recorded using the stand-alone PV and battery system in Configuration E, but such a system comes with the highest NPC (RM13,622,900.00) and highest initial capital cost (RM9,617,149.24) in comparison with other hybrid systems. However, in terms of greenhouse gas emissions, the PV and battery system is also preferable than the base case of a diesel-only system. The base case, Configuration G, had the fourth highest NPC (RM10,131,510.00) of all systems analyzed.

Therefore, base on lowest NPC criteria, the PV-diesel integrated with battery system is preferable for the system selection over only generator or PV and battery systems. Configurations D, C, B, A, G, F, H, and E are ranked accordingly in order of increasing NPC as presented in Figure 7. The system with the lowest COE is the most economically preferred. The combination of PV-diesel and batteries in Configuration C produced the lowest COE (RM0.7033/kWh) among all configurations. The highest COE was produced by the PV and battery system of

Configuration E (RM1.07/kWh). The other PV-diesel hybrids with battery configurations (D, B, and A) produced COEs of RM 0.7182/kWh, RM0.7264/kWh, and RM0.7408/kWh respectively.

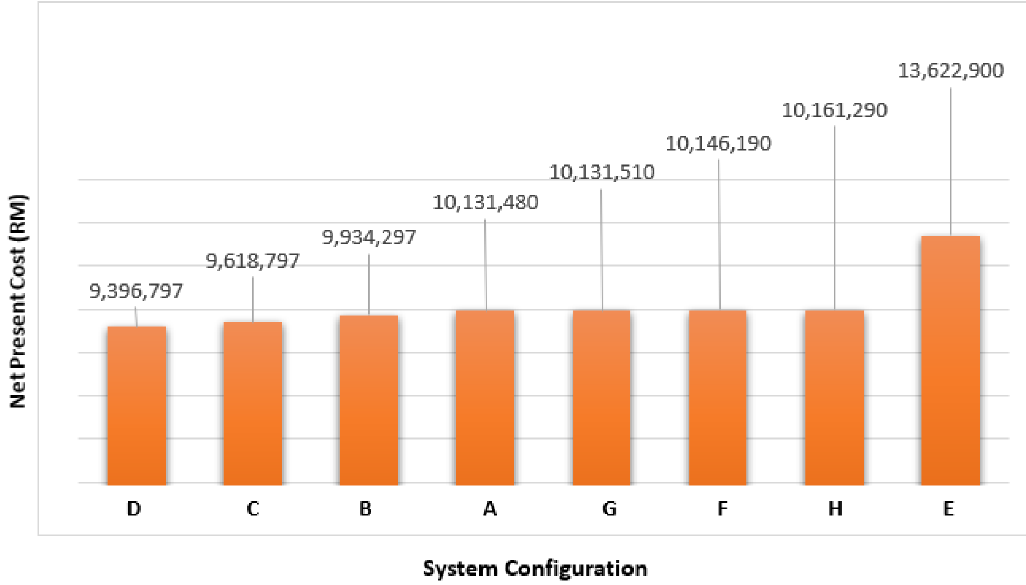

Fig. 7 - Comparison Based on NPC

The variation of COE values depicted major differences between systems with and without a generator. In this comparison, the system without a generator resulted in a higher COE value. As shown in Figure 8, the COE values of Configurations D, B, A, G, and F are in increasing order, proportional to the number of generators attached. More generators in the system result in higher COEs, and it is not preferable for a system with a higher COE to be proposed in a rural area.

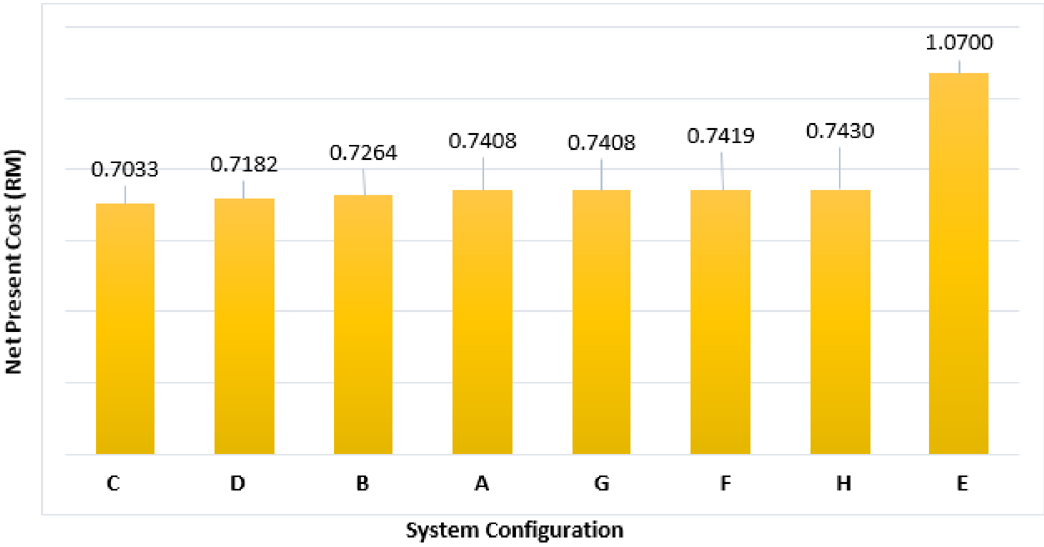

Fig. 8 - Comparison Based on COE

Lower consumption of diesel is considered to be favourable for all generator-based systems. Neglecting Configuration E, which consists only of PV and battery components, Configuration A, B, and C consume 215,592 liters diesel annually, the lowest among all generator-based configurations. Regardless of the generators used in these systems, the fuel consumption remains the same, except for in the case of the 200 kW generator combined with the PV and the battery in Configuration D. This configuration consumes 2.63% more fuel annually compared to Configurations A, B, and C. As explained earlier, Configuration D was not considered in the selection of feasible hybrid system due to its operating strategy to obtain power reliability in supplying electricity to the community.

Configuration H is considered to be a fuel-dependent system, as the PV array would not be able to generate electricity during nightfall or in lower solar irradiance conditions. Therefore, it ranked among the highest fuel consuming systems. Configuration F and G consumed the highest volumes of fuel (316,847 liters/year) and shared the same power production fractions. A complete comparison of fuel consumption for each configuration is demonstrated in Figure 9.

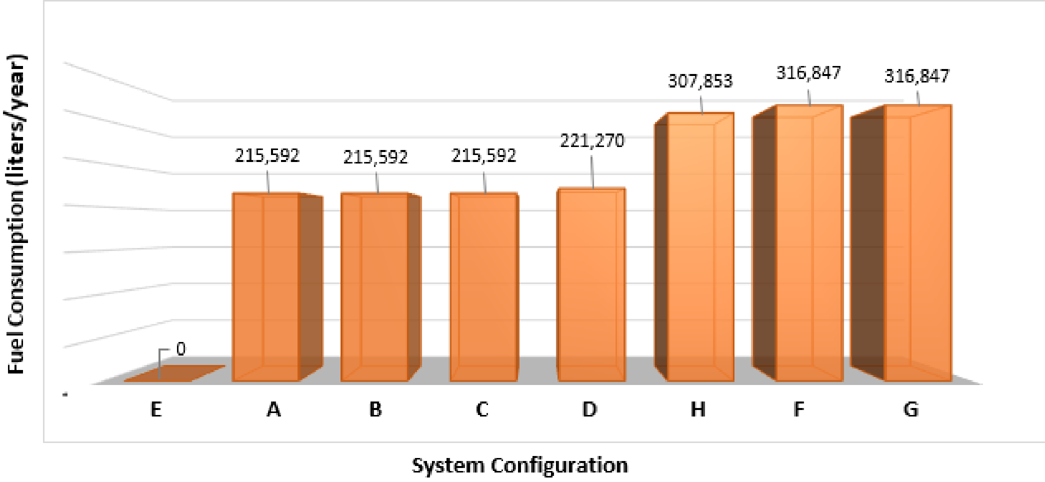

Fig. 9 - Comparison Based on Fuel Consumption

5. Conclusion

The findings from this analysis are concluded as follows.

- The simulation indicated that the PV array and two diesel generators with the integration of the battery system had the lowest NPC and COE among all configurations analyzed, based on a 2,898.32 kWh/day load consumption, 5.11 kWh/ m^2/day of solar radiation, a diesel price of RM2.18/liter, an 80% maximum renewable energy fraction share, and the interest rate is at 6.0%.
- The NPC for this optimal hybrid configuration is RM9,618,797.00, compared to RM10,131,510.00 for a generator-only system. The COE is RM0.7033/kWh, a decrease of 5.06% from the generator-only system. Although the initial capital cost of the hybrid system is considered high, the implementation of a PV array and two generators with a battery system causes a reduction of 101,255 liters of diesel consumption, which can save RM220,735.90 annually compared to the generator-only system for 25 years of operation.
- Based on HOMER optimization results, it is recommended that the system integrate 255 kW PV panels, 86 units of 2,500 Ah batteries, a 115 kW power converter, and two generators with the sizes of 440 kW and 200 kW to minimize the cost criteria of the proposed system.

Finally, the findings from this current work will hopefully serve as a base case for future researchers in implementing any configuration of PV hybrid system in other rural areas of the state and in Malaysia in general.

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