# Assessing Socio and Techno-economic Impacts of Hybrid Renewable Energy System with Energy Storage for a Rural Development in Malaysia

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**Abstract-** The electrification prospect in some rural areas in Malaysia is limited because of no access to grid connection. This challenge has aroused concerns among researchers and energy providers in finding an alternative source of energy. A hybrid renewable energy system (HRES) deems as a good alternative to overcome the problem. This study employs a linear programming model in estimating socioeconomic and techno-economic analysis of HRES at Tanjung Labian. The target location is a residential area in Sabah, with the major source of income comes from timber as most of the residents are engaged in forestry activities. The socioeconomic evaluation of this study reveals the minimum values of expected demand not served (EDNS) and loss of load probability (LOLP) from the hybrid PV-diesel with battery configuration and the result contributes to the highest number of students who passed the examination. Additionally, the results of the study also reveal that hybrid PV-diesel with battery configuration is the most economical and most environmentally friendly system when it is compared to other configurations. The results of this work may encourage the adoption of a hybrid renewable energy system with a battery system by replacing and upgrading existing standalone diesel generators system in Malaysia.

**Keywords** Environment; Linear programming model; Photovoltaic; Socioeconomic; Techno-economic.

**Nomenclature**

**Abbreviation/Symbols, Full Name**

| | | | |
|---|---|---|---|
| AC | Alternating Current | $C_{NPC}$ | Net Present Cost |
| AD | Number of Days for Battery Autonomy | $C_{TAC}$ | Total Annualized Cost |
| AI | Artificial Intelligence | $EL$ | Average Daily Load Energy |
| CC | Cycle Charging | $E_S$ | Total Annual Energy Supplied to the |

| | | | |
|---|---|---|---|
| | | | Load |
| CRF | Capital Recovery Factor | $G_T$ | solar radiation incident on PV panels |
| COPT | Capacity Outage Probability Table | $G_{T,STC}$ | Incident Radiation at Standard Test Condition |
| DC | Direct Current | $K_n$ | Single Payment Present Worth Factor |
| DR | Demand Response Programming | $L_{prim,DC}$ | Average DC Primary Load in the Current Time Step |
| DOD | Battery Depth of Discharge | $\bar{L}_{prim,DC}$ | Highest DC Primary Load Experienced by the System During the Year, |
| EDNS | Expected Demand Not Served | $L_{req,DC}$ | Required Operating Reserve on DC Bus |
| F.O.R | Forced Outage Rate | $L_n$ | Useful Lifetime |
| GA | Genetic Algorithm | $LL$ | Total Load Lost. |
| GWO | Grey Wolf Optimizer | $n$ | Unit Number of System Component |
| HRES | Hybrid Renewable Energy System | $P(C_i)$ | Probability of Load Loss |
| ICTs | Information Communication Technologies | $P(L_i > C_i)$ | Duration of the Loss of Capacity |
| LCOE | Levelized Cost of Energy | $P_{G-out}$ | Output Power of the Generator |
| LF | Load Following | $P_{G-rated}$ | Nominal Power of Diesel Generator |
| LOLP | Loss of Load Probability | $P_k$ | Probability of Capacity Outage |
| NASA | National Aeronautics and Space Administrations | $P_{PV}$ | Average PV Array Output in the Current Time Step |
| NPC | Net Present Cost | $P_{wind,DC}$ | Average DC Wind Power Output in the Current Time Step |
| O&M | Operation and Maintenance | $Q$ | Quantity Components |
| $P_L$ | Total Load Demand | $r_{load}$ | Operating Reserve as a Per Cent of Load in the Current Time Step |
| $P_T$ | Total Generated Power | $r_{peakload}$ | Operating Reserve as a Per Cent of Annual Peak Load Variable |
| PSO | Particle Swarm Optimization | $r_{solar}$ | Operating Reserve as a Per Cent of Solar Power Output Variable |
| PV | Photovoltaic | $r_{wind}$ | Operating Reserve as a Per Cent of Wind Power Output Variable |
| SOC | State of Charge | $Y_{pv}$ | Rated Capacity of PV Panels |
| URFC | Regenerative Polymer Electrolyte Membrane | $\alpha_p$ | Temperature Coefficient of Power |
| $A_G$ | Coefficient of Fuel Consumption Curve | $\alpha_p$ | Temperature Coefficient of Power |
| $B_G$ | Coefficient of Fuel Consumption Curve | $f_{pv}$ | Derating Factor of PV Panels |
| $C_{ann,capital}$ | Annualized Capital Cost | $\eta_{batt}$ | Batteries Efficiency |
| $C_{ann,O\&M}$ | Annualized O&M Cost | $\eta_{inv}$ | Inverter Efficiency |
| | | $\lambda$ | Expected Failure Rate |
| | | $\mu$ | Represents Expected Repair Time |

## 1. Introduction

Energy is an essential element that ensures quality and comfort to people, while at the same time drives a nation forward. Most of the countries in the world are highly dependent upon non-renewable fossil fuels which made the country extremely vulnerable to degradation of fuel as well as leave a significant impact on the environment which causes global warming and climate change [1,2]. Due to these shortcomings of using fossil fuels, many countries are now have resorted to using renewable energy technologies especially solar energy for the generation of electricity [3]. The preference usage of solar energy is because of the numerous benefits of being a clean and free source of energy [4]. Furthermore, the economic incentives offered by government could be one of the reasons for the usage of solar energy [5].

Malaysia is a country that has great potential to develop solar energy technology and it has numerous remote areas where the electrification to these areas is very limited. Usually, diesel generators are being used to cater for the load demand to ensure that there is not interruption of power supply [6]. Therefore, the application of solar energy is feasible and it can be proven based on a study done in [7] which showed the high potential of solar energy to be applied at the various remote areas in Malaysia.

Despite the undeniable benefits of integrating solar energy with the current system, there are still some challenges that should not be overlooked such as variability, intermittency and uncertainty availability of the solar energy output [8, 9]. Besides, numerous installed solar energy system can lead to massive wastage of solar energy as it cannot be fully loaded [10].

For these reasons, the employment of one type of renewable energy source might not be the best solution as it is considered unreliable. Thus, the energy designers opt to use the hybrid energy system where it can be an integration of two renewable energy resources as well as an integration of the renewable energy system with the non-renewable energy system [11]. The employment of a hybrid renewable energy system (HRES) is effective to increase reliability along with its indexes such as expected demand not served (EDNS) and loss of load probability (LOLP). Aside from the hybrid energy system, the battery has recently attracted much interest in the electricity industry [12]. The battery can provide a crucial approach when dealing with the unpredictability of the output and intermittency of renewable sources [13]. In other words, the excess of solar energy will be absorbed by the battery and it will provide the energy back to the grid in the event of insufficiencies of solar energy [14].

Several previous pieces of literature have discussed the application of hybrid systems. Authors in the works of [15-17] have applied wind and solar energy together with diesel generators and battery to support the electrification in Nigeria and Pakistan, respectively. The simulation results indicated that hybridization of PV and wind was only suitable on a relatively high wind speed area. The efficiency of hybrid PV-wind is further investigated by [18] where the objective of the study was to harness wind energy with the support of solar energy. Authors in [19] established a study of hybrid PV-wind-diesel by considering technical and economic feasibility. The paper suggested using mini-grid based electricity as the energy supplier on the basic level, especially on off-peak hours. In [20], a study had utilized several types of renewable energy, namely, biogas, wind energy, solar energy, and pumped hydro to supply the electrical needs at one of the remote areas in Africa. The authors did not consider using diesel generators because of maintenance and transportation constraints.

Some studies accessed the performance of HRES according to the techno-economic aspect [17, 18, 21-26]. Outcomes of these studies revealed the superiority of HRES in reducing the overall system cost as well as decreasing the harmful gasses emission to the environment. A study was conducted in [27] where 100% of the renewable energy system supplied the demand in a residential house. Despite reducing levelized cost of energy (LCOE) or net present cost (NPC) as their objectives, the authors have included another two evaluation metrics, namely, unmet electricity load and levels of capacity shortage. To evaluate the optimal component sizing in the microgrid, the authors in [28] had developed the demand response (DR) programming by reducing the number of required batteries and inverter as well as reducing the PV cells capacity. A study in [29] used MATLAB/Simulink to model the PV panel array system in a strip mall where regenerative polymer electrolyte membrane (URFC) and diesel generators served as the primary and secondary back up, respectively. The usage of URFC reduced overall system cost and occupied space whilst maintained 100% renewable energy penetration.

Up to date, some studies adopted the use of artificial intelligence (AI) approaches to design the HRES. The authors in [30, 31] implemented a genetic algorithm (GA) in designing a hybrid energy system. The main objective of this study was to achieve the minimum cost value . Moreover, a study was performed in [32] where preference-inspired co-evolutionary algorithm and entropy weight method was developed in the HRES design. From the result, the hybrid wind, PV, battery and diesel generator was identified as the best configuration according to the economy, reliability, practicability and environmental sustainability. On the other hand, authors in [33] had hybridized particle swarm optimization (PSO) algorithm and grey wolf optimizer (GWO) where the reliability and economic were considered as their objective functions. Authors in [34] hybridized the GA algorithm and PSO algorithm for the HRES development to obtain the lowest value of LCOE.

The majority of the above-mentioned works of literature have to take the techno-economic aspect as their main objective in finding the optimal design system. However, the employment of renewable energy sources must not be limited to techno-economic analysis only as other metrics can also be considered. Generally, this study has shown the superiority of hybrid systems by offering the lowest values of NPC and LCOE. Nevertheless, the socioeconomic aspect has not been considered in the previous literature, despite its importance in real implementation. Due to this matter, this study utilizes linear programming model that estimates education which is related to the number of students who passed the examination as the socioeconomic impact for installing HRES at Tanjung Labian, Sabah.

Education attainment for instance enrolment in school, the number of students who passed examination and literacy rate is one of the essential components to improve the social development of the population in rural areas. Students who passed the examinations will have a high chance to be enrolled in higher education institute and this is the starting point for them to generate more income as well as to attain empowerment in the future. According to [35], reliable access to electricity plays a stronger role to improve the welfare of people in remote areas and authors in [36] has indicated the poverty headcounts, mortality and longevity, years or school attainment as well as unemployment rates as the example of welfare indicators.

It is presumed that the advancement of the number of students who passed the examination is affected by the reliability of electricity which is specified by the indexes of LOLP and EDNS. For instance, the occurrence of the power outage at the night before the examination will disrupt the study process of students. As the result, they do not have sufficient time to study and this will cause them to fail for subjects that they attend for the following examination day. Also, the power outage that happened during the examination session can contribute to student's inconvenience which can influence the number of students who passed the examination.

In this study, the system performance is evaluated according to economic, technical, environmental and socioeconomic aspects through the modelling of three system configurations which are standalone diesel generators, hybrid PV-diesel without battery as well as hybrid PV-diesel with battery. The results from these configurations are compared with the optimum configuration in clarifying the optimal size of PV systems before the installation can be made. Apart from that, the performance of hybrid systems is compared with standalone diesel generators to estimate the effective usage of PV and batteries in the microgrid. Finally, the conclusion will summarize the effectiveness of every system configuration according to its advantages and disadvantages. It is expected that the hybrid PV and battery system has the greatest potential to be adopted in the current system, especially to upgrade and replace the existing standalone diesel generators system in Malaysia. All of the works in this study are performed in a linear programming model.

## 2. Methodology

In this work, there are several analyses are conducted so that every possible scenario can be executed. Those analyses are as follows:

### *2.1 Site Specifications and Data Collection*

The location of the proposed HRES is at Tanjung Labian with a latitude of 5.1663°N and a longitude of 119.2321°E. It is located in Sabah which is the second largest state in Malaysia. The 5000 population of Tanjung Labian are mostly involved in forestry activities and the major source of income is coming from timber. Apart from that, they also engaged in seafood exports and tourism activities.

The development of HRES in the linear programming model requires real-time data of solar radiation, temperature as well as load profile data at Tanjung Labian. Due to the faulty measuring tools at Tanjung Labian, the collection of real-time solar radiation and temperature data seems to be impossible. Hence, this study overcomes this shortcoming by acquiring the temperature data as well as solar radiation data from the National Aeronautics and Space Administrations (NASA). The detail descriptions of the above-mentioned data can be shown in the following subsections.

#### *2.1.1 Solar Radiation Data*

Figure 1 illustrates the data of solar radiation for Tanjung Labian which is acquired from the NASA. The daily average solar radiation ranges between 4.87 kWh/m2/day and 6.44 kWh/m2/day with an annual average of 5.57 kWh/m2/day.

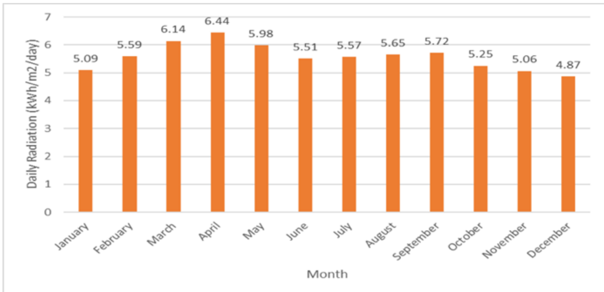


**Fig. 1.** Monthly Average Daily Solar Radiation Profile at Tanjung Labian.

#### *2.1.2 Temperature Data*

The temperature data for Tanjung Labian can also be taken from NASA and it can be portrayed in Fig. 2. The average daily temperature is between 25.64°C and 26.77°C and its annual average is 26.34°C.

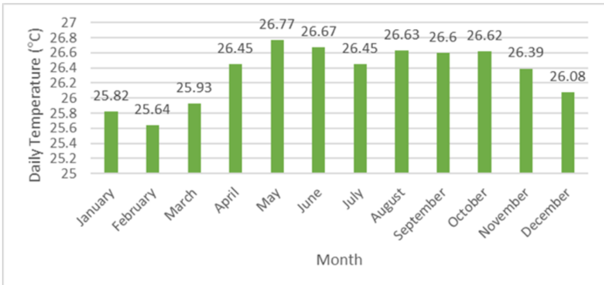


**Fig. 2.** Monthly Average Daily Temperature Profile at Tanjung Labian.

*2.1.3 Load Data*

This work gathers the load data at Tanjung Labian from the work of [37]. The hourly average daily load profile of Tanjung Labian can be shown in Fig. 3 and it is obvious from the figure that there is a variation of load reading throughout the day.

From the load pattern, the minimum demand occurs in the morning as most of the residents are working outside their homes. Night-time records the maximum load demand as the entire family spend their time at their residence. According to the measurement and assumptions, the energy demand at Tanjung Labian is estimated at around 3825.1 kWh/day with a peak demand of 417.52 kW.

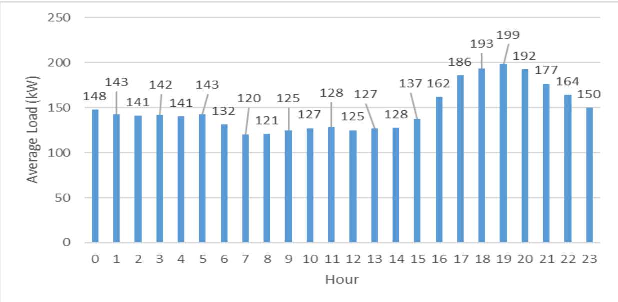


**Fig. 3.** Hourly Average Daily Load Profile at Tanjung Labian.

Furthermore, Fig. 4 represents the monthly average daily load profile at Tanjung Labian and the months of October until December record higher load demand. This is because of the Northeast Monsoon which brings heavy rainfall to the states of Malaysia which include Sabah. As the result, the population of Tanjung Labian cannot engage in their forestry and seafood export activities which contributes to higher load demand in their homes in those months.

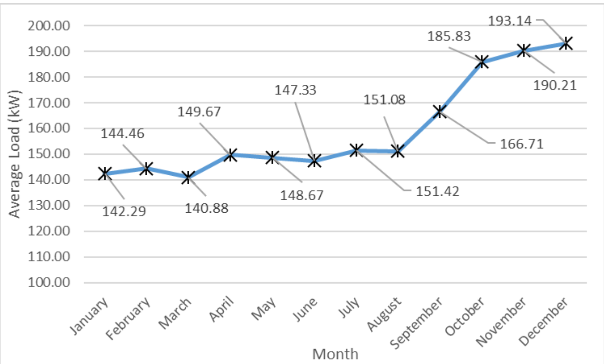


**Fig. 4.** Monthly Average Daily Load Profile at Tanjung Labian.

*2.2 Hybrid Renewable Energy System (HRES) Design*

In the design of HRES, there are several components to be considered. For Tanjung Labian, the hybrid system consists of a Photovoltaic (PV) system that acts as a main source of energy together with the batteries and diesel generators as the backup. Besides, the converter is also one of the important components to be contemplated. A brief description of every component in HRES can be presented as follows:

*2.2.1 Photovoltaic (PV) Panels*

PV panels serve as the main energy source in HRES. They are employed during the day time when there is sunshine. During night-time, the task to supply load will be taking over by batteries or diesel generators. In the linear programming model, PV panels are modelled with the derating factor and lifetime of 80% and 25 years, respectively [11]. This is because of very little maintenance needed by PV panels and it can last for a very long time. For economic inputs, the replacement cost as well as capital cost of 1 kW of PV panels are set at $2000 [37]. Meanwhile, a small operation and maintenance (O&M) cost is estimated to be $10/year.

*2.2.2 Battery*

In this study, Hoppecke 24 OPzS type of battery is considered as each cell is made up of 2V. The batteries are designed to be connected in 6 strings where there are fifty batteries in each string. Hence, the total number of batteries used are equivalent to 300 units with a lifetime estimation of 10 years. The capital cost is taken as 1200 $/unit with its replacement cost of 1170 $/unit [37].

*2.2.3 Diesel Generators*

Diesel generators are used to cater to the load demand when there is no output power from the PV system as well as the minimum capacity of batteries. This study utilizes three generators with a capacity of 500 kW for generator 1 (G1), 500 kW for generator 2 (G2) and 350 kW for generator 3 (G3). The replacement cost, O&M cost and capital cost for all generators can be shown in Table 1.

**Table 1.** Costs for Diesel Generators

| Generator | Capital Cost ($/kW) | Replacement Cost ($/kW) | Operation & Maintenance Cost ($/hr) |
|---|---|---|---|
| G1 | 320 | 300 | 0.05 |
| G2 | 420 | 400 | 0.07 |
| G3 | 220 | 200 | 0.03 |

The diesel price is depending on the location of the site. In rural areas, the diesel price could be more than 1.5 times the normal prices. This is because of the incurred cost for storage problem as well as fuel for transportation [37]. Hence, the fuel price considered in this work is at 0.8 $/L.

### 2.2.4 *Converter*

The converter in the HRES system is rated according to PV size as it is important to ensure a full power supply from PV panels. The capital cost is regarded as $890/kW, replacement cost is considered as $800/kW and the O&M cost is $10/year. Meanwhile, the lifetime of the converter to operate is taken for 15 years [19].

## 2.3 *Summary of Installed System Components*

The technical parameters of all components which are installed in HRES can be summarized in Table 2.

**Table 2.** Technical Parameters for Components in HRES.

| Equipment | Factor | Value |
|---|---|---|
| **PV** | Rated Power (Kw) | 1,200 |
| | Temperature Coefficient (°C) | -0.5 |
| | Operating Temperature (°C) | 47 |
| | Derating Factor (%) | 80 |
| | Lifetime (Years) | 25 |
| | Efficiency (%) | 13 |
| **Battery** | Maximum Capacity (Ah/Cell) | 3,574.64 |
| | Nominal Capacity (kWh/Cell) | 7.15 |
| | Nominal Voltage (V/Cell) | 2 |
| | Lifetime per battery (Years) | 10 |
| | Round Trip Efficiency (%) | 86 |
| **Diesel Generators** | Rated Power (Kw) | 1x350 & 2x500 |
| | Minimum Load Ratio (%) | 30 |
| | Minimum Running Hours (h) | 30,000 |
| **Converter** | Rated Power (kW) | 1200 |
| | Lifetime (Years) | 15 |
| | Inverter Efficiency (%) | 95 |
| | Relative Capacity (%) | 100 |
| | Rectifier Efficiency (%) | 85 |

## 2.4 *System Configuration*

The system configurations which are analysed in this study are presented in three cases: 1) standalone diesel generators, 2) hybrid PV-diesel without battery and 3) hybrid PV-diesel with battery. The standalone diesel generator system is depending upon the diesel generators to meet the load demand.

Besides, hybrid PV-diesel without battery is a system where PV panels are prioritized to cater to the load demand and diesel generator will be operated when there is low solar radiation. The hybrid PV-diesel with battery configuration will let the PV panels to cater to the load demand and the system configuration can be depicted in Fig. 5. The excess energy produced from PV panels is used to charge the battery until it is fully charged. Hence, the battery will supply the demand if there are insufficiencies of energy from PV panels. Later, the diesel generators accommodate the load if the battery cannot supply the increased demand. The flow for energy management processes for hybrid PV-diesel with battery configuration is illustrated in Fig. 6.

**Fig. 5.** Schematic Diagram of Hybrid PV-Diesel with Batteries Design.

## 2.5 *Operating Strategies*

In the renewable energy system, a dispatch strategy is a control algorithm specifically for energy storage devices or for generators to supply energy when there are insufficiencies of renewable supply [38]. Two control algorithms are widely used as operation dispatch strategies in the HRES which are load following (LF) and cycle charging (CC) strategies. LF strategy allows the generators to cater to the demand when the PV panels unable to accommodate the load. Meanwhile, the surplus energy from PV panels is used to charge the battery. On the other hand, the CC strategy allows diesel generators to serve the load demand while charging the batteries at the same time. In this study, the LF strategy has been utilized because it can produce less excess energy than the CC strategy [37].

## 2.6 *Optimization of Hybrid Model and Economic Evaluation Criteria*

An optimal hybrid system can only be achieved according to an objective function. This study considers the total life cycle cost of available electricity generation resources as the objective function. Note that a hybrid system consists of diesel generators, PV panels and a battery. Thus, the objective function is given by equation (1) [11]

$$C_{ann} = \sum_{n} (C_{ann,capital} + C_{ann,replacement} + C_{ann,O\&M}) \qquad (1)$$

where $n$ signifies the number of a system component in a system which consists of solar PV panel, battery and diesel generators. Meanwhile, $C_{ann,replacement}$, $C_{ann,O\&M}$ and $C_{ann,capital}$ denote the annualized replacement cost, annualized O&M cost as well as annualized capital cost for each system component, respectively. Equation (1) can be further represented in equation (2) [11].

**Fig. 6.** Flowchart of Energy Management Process.

$$C_{ann(n)} = Q \times C_{ann,capital} + C_{ann,replacement} \times K_n\left(i, L_n, y_n\right) \quad (2)$$
$$CRF(i, N) + C_{ann,O\&M}$$

$Q$ is the quantity components whilst CRF is the capital recovery factor of annual interest rate (i) and the year of cash flow (N) as shown in equation (3) [11]. Furthermore, the formulation of $K_n$ as shown in equation (4) is known as the single payment present worth factor where $L_n$ signifies the useful lifetime and $y_n$ depicts the number of component replacement during the project lifetime [11].

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3)$$

$$K_n(i, L_n, y_n) = \sum_{x=1}^{y_n} \frac{1}{(i+1)^{x \times Ln}} \quad (4)$$

An optimal hybrid system must able to satisfy the specified constraints, so it will appear as an optimal system. The sudden increase of load demand and sudden decrease of renewable power output are the two main scenarios that cause the system to not meet the constraints. To avoid these scenarios, a system must be capable to provide a minimum amount of operating reserve which is known as the required operating reserve. The formulation of the required operating reserve for DC buses are shown in equation (5)

$$L_{req,DC} = (r_{load} \times L_{prim,DC}) + (r_{peakload} \times \bar{L}_{prim,DC}) + (r_{wind} \times P_{wind,DC}) + (r_{solar} \times P_{PV}) \quad (5)$$

where $L_{req,DC}$ is identified as a required operating reserve on DC bus, $r_{load}$ is known as an operating reserve as a per cent of load in the current time step variable and $L_{prim,DC}$ is recognized as the average DC primary load in the current time step. Furthermore, $r_{peakload}$ denotes the operating reserve as a per cent of annual peak load variable,

$\bar{L}_{prim,DC}$ signifies the highest DC primary load experienced by the system during the year, $r_{wind}$ depicts the operating reserve as a per cent of wind power output variable and $P_{wind,DC}$ represents the average DC wind power output in the current time step. Apart from that, $r_{solar}$ and $P_{PV}$ indicate the operating reserve as a per cent of solar power output variable and the average PV array output in the current time step, respectively.

The linear programming program records the cost efficiency of a system based on the value of NPC obtained from every system configuration. It comprises O&M cost, capital cost, fuel cost and replacement cost [39]. Note that an optimal system is selected from a system that has the lowest value of NPC. The formulation of NPC can be shown in equation (6) where CRF represents the capital recovery factor as defined earlier in equation (3), $C_{TAC}$ is the total annualized cost ($/year) and $C_{NPC}$ is net present cost.

$$C_{NPC} = \frac{C_{TAC}}{CRF\left(i,n\right)} \tag{6}$$

Apart from that, the value of LCOE can also be deliberated as the life cycle cost of a system. It is the average cost per kWh of electricity generation by the system and it can be determined using equation (7) where $E_S$ is the total annual energy supplied to the load in kWh.

$$LCOE = \frac{C_{TAC}}{E_S} \tag{7}$$

## 2.7 Environmental Evaluation

The environmental aspect of every system configuration is estimated according to the emission of nitrogen oxides, carbon monoxide, sulfur dioxide, unburned hydrocarbons, carbon dioxide and particulate matter to the atmosphere. The measurement of emission is considered important because it is highly connected with the main environmental issues such as acid rain and the greenhouse effect.

In this study, emissions of all pollutants are coming from the production of electricity from diesel generators. It is measured in yearly emissions (kg/yr) and the equation to calculate the annual emissions of pollutants is shown in equation (8)

*Annual Emission= Emission Factor x Total Annual Fuel Consumption* (8)

where the emission factor is the amount of pollutant emitted per unit of fuel consumed (kg/L). Note that the emission factor for nitrogen oxides, carbon monoxide, sulfur dioxide, unburned hydrocarbons and particulate matter are specified with the values of 0.0026 kg/L, 0.0136 kg/L, 0.0022 kg/L, 0.0007 kg/L and 0.0001 kg/L, respectively. Meanwhile, the emission factor of carbon dioxide is measured according to an assumption that carbon in the fuel which is not released as unburned hydrocarbon or carbon monoxide is considered carbon dioxide.

## 2.8 Reliability Evaluation

Aforementioned, the socioeconomic factor (number of students who passed the examination) is measured according to reliability assessment. Note that there are two types of reliability indexes used by this study which are LOLP and EDNS.

LOLP is the probability for the daily peak load of every system configuration to exceed the generating power capacity for some time [40]. It is being estimated according to equation (9)

$$LOLP = \sum_{i=1}^{n} P(C_i)P\left(L_i > C_i\right) \tag{9}$$

where $P(C_i)$ is the probability of load loss and $P\left(L_i > C_i\right)$ signifies the duration of the loss of capacity. Another index to be measured is EDNS and it can be shown in equation (10) where $LL$ represents the total load lost in MW and $P_k$ is the probability of capacity outage.

$$EDNS = LL \times P_k \tag{10}$$

The measurement of reliability indexes (LOLP, EDNS) can only be achieved through the development of the capacity outage probability table (COPT) which consists of availability and non-availability states of generating capacity where these states are arranged according to ascending order of outage magnitude. A binomial distribution will be used in the case of a system that has identical units [41].

After the estimation of LOLP and EDNS, the linear regression has been applied in finding the association between the dependent variable (number of students who passed the examinations) and the independent variable (LOLP or EDNS) for every configuration.

## 2.9 Socioeconomic Evaluation

The energy assessment is a major influence on the socioeconomic condition of a country and the lack of energy access contributes to many negative socioeconomic impacts, especially towards the rural population. Concisely, the number of students who passed the examination at Tanjung Labian, Sabah is assessed according to the following steps in Fig. 7 [11]:

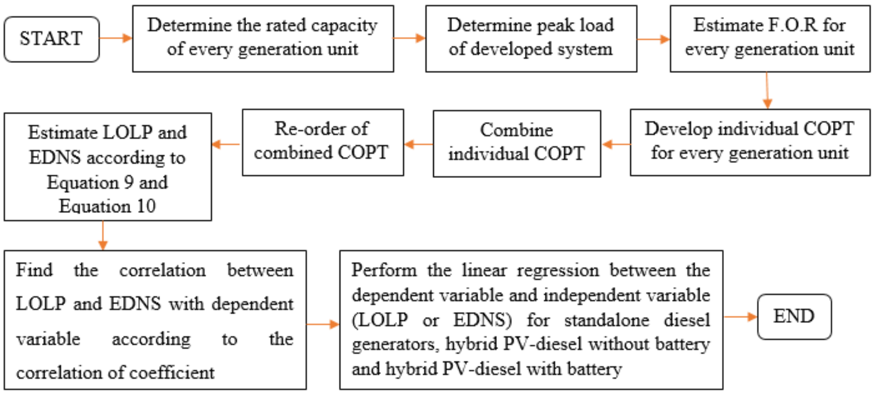


**Fig. 7.** Procedures of Socioeconomic Assessment.

## 3. Results and Analysis

This section describes the results of every configuration in the aspects of economic, environment, technical (sensitivity analysis) and socioeconomic.

### *3.1 Economic Analysis*

Aforementioned, the important economic metrics that will be investigated are the NPC and LCOE values. Apart from that, the capital cost, replacement cost, O&M cost and fuel cost for every system configuration can also be measured. The economic results can be shown as follows:

#### *3.1.1 Standalone Diesel Generator*

The introduction of the first scenario which is standalone diesel generators configuration is very crucial to properly determine the impact of injecting PV in the system. From the simulation of the linear programming model, the diesel generator of G3 with a capacity of 350kW produced 99.02% of total energy production, while 0.98% of energy is produced by a 500kW diesel generator known as G1. The reason why G1 is selected to supply load instead of G2 is due to its specification of lower O&M cost, replacement cost and capital cost as portrayed by Table 1.

This scenario depicts the NPC value of $6,933,648 and LCOE value of 0.3153 $/kWh which is the lowest cost compared to other configurations based on similar operating conditions. Table 3. also shows that the system O&M cost, replacement cost, fuel cost and capital cost for 25 years project period are $1,458,041.85, $298,815.85, $4,879,380.43 and $447,000.00, respectively. The renewable fraction for this scenario is 0% since this scenario depends only on the diesel generator to generate electricity. From the observation, there is a small amount of excess energy, representing about 1.02% of total electricity generation.

**Table 3.** Economic Evaluation for Standalone Diesel Generators.

| Component | O&M Cost ($) | Replacement Cost ($) | Fuel Cost ($) | Capital Cost ($) |
|---|---|---|---|---|
| G1 | 15,752,40 | 0.00 | 46,065.83 | 160,000.00 |
| G2 | 0.00 | 0.00 | 0.00 | 210,000.00 |
| G3 | 1,442,289.45 | 298,815.85 | 4,833,314.60 | 77,000.00 |
| System | **1,458,041.85** | **298,815.85** | **4,879,380.43** | **447,000.00** |

#### *3.1.2 Hybrid PV-Diesel without Battery*

By using the hybrid PV-diesel without battery configuration, the system O&M cost, replacement cost, fuel cost and capital cost to be $1,663,689.39, $795,599.82, $3,963,632.64 and $3,915,000.00, respectively, as shown in Table 4. Furthermore, the total NPC for one unit of 1200 kW PV, one unit of 350 kW diesel generator and one unit of 500kW diesel generator was $10,069,530. The LCOE for this configuration is 0.4579 $/kWh which is the most expensive cost of energy among other configurations.

**Table 4.** Economic Evaluation for Hybrid PV-Diesel without Battery.

| Component | O&M Cost ($) | Replacement Cost ($) | Fuel Cost ($) | Capital Cost ($) |
|---|---|---|---|---|
| G1 | 15,358.59 | 0.00 | 44,958.75 | 160,000.00 |
| G2 | 0.00 | 0.00 | 0.00 | 210,000.00 |
| G3 | 1,270,273.28 | 256,479.34 | 3,918,673.89 | 77,000.00 |
| PV | 189,028.76 | 0.00 | 0.00 | 2,400,000.00 |
| Converter | 189,028.76 | 539,120.48 | 0.00 | 1,068,000.00 |
| System | **1,663,689.39** | **795,599.82** | **3,963,632.64** | **3,915,000.00** |

The reason is that the solar power generated by the PV is not fully utilised, where it supposed to charge the battery. Hence, 57.9 % of excess energy is considered a loss. There was no storage to store the demand balance when the PV cannot accommodate the demand. As a result, the diesel generators will take over the task to cater to the demand. As mentioned earlier, this configuration is depending on PV or diesel generators to meet the load demand. Therefore, the PV integration in the system has caused the energy production to be 66.2% from PV panels, 33.4% from G3 and 0.40% from G1.

### *3.1.3 Hybrid PV-Diesel with Battery*

The third configuration is the hybrid PV-diesel with a battery. The results depict the NPC value of $7,754,518 and LCOE value of 0.3526 $/kWh. Meanwhile, O&M cost, replacement cost, fuel cost and capital cost are represented by the values of $886,418.87, $1,445,507.17, $1,511,113.43 and $4,275,000.00, respectively, as shown in Table 5. All of these costs are calculated from the usage of one unit of 1200 kW PV, one unit of 350 kW diesel generator, one unit of 500 kW diesel generator and 6 string size batteries. Note that 83.8% of energy is the production of PV and the rest of the energy is coming from diesel generators G3 and G1.

**Table 5.** Economic Evaluation for Hybrid PV-Diesel with Battery.

| Component | O&M Cost ($) | Replacement Cost ($) | Fuel Cost ($) | Capital Cost ($) |
|---|---|---|---|---|
| G1 | 1,575.24 | 0.00 | 4,603.69 | 160,000.00 |
| G2 | 0.00 | 0.00 | 0.00 | 210,000.00 |
| G3 | 506,786.11 | 80,990.15 | 1,506,509.74 | 77,000.00 |
| PV | 189,028.76 | 0.00 | 0.00 | 2,400,000.00 |
| Battery | 0.00 | 825,396.54 | 0.00 | 360,000.00 |
| Converter | 189,028.76 | 539,120.48 | 0.00 | 1,068,000.00 |
| System | 886,418.87 | 1,445,507.17 | 1,511,113.43 | 4,275,000.00 |

The NPC and LCOE values of hybrid PV-diesel with battery is lower than hybrid PV-diesel without battery. This is because of the presence of the battery that absorbs the surplus energy generated from PV. As the result, the excess energy produced from hybrid PV-diesel with a battery is 15.5% lower than hybrid PV-diesel without a battery. To properly design HRES, the battery must be included in the design to ensure that surplus energy from the PV can be stored for later use. Besides, it is crucial to include a battery in the system to avoid stability problems.

### *3.1.4 Optimised Hybrid PV-Diesel with Battery*

The configuration of optimized hybrid PV-diesel with battery can be investigated in the linear programming model in confirming whether existing hybrid PV-diesel with the battery has been optimally selected or not before the installation can be set up. The economic evaluation of the optimized hybrid PV-diesel with battery is displayed in Table 6. The optimal selection of PV, diesel generator and battery are selected based on the least value of LCOE and NPC. From the results, this optimal configuration has minimal NPC and LCOE of $5,328,966 and 0.2423 $/kWh, respectively.

**Table 6.** Economic Evaluation for Optimized Hybrid PV-Diesel with Battery.

| Component | O&M Cost ($) | Replacement Cost ($) | Fuel Cost ($) | Capital Cost ($) |
|---|---|---|---|---|
| G1 | 105,619.82 | 12,687.97 | 266,086.92 | 32,000.00 |
| G2 | 86,945.35 | 9,621.21 | 181,336.07 | 21,000.00 |
| G3 | 354,428.93 | 66,910.20 | 1,691,440.46 | 44,000.00 |
| PV | 94,514.38 | 0.00 | 0.00 | 1,200,000.00 |
| Battery | 0.00 | 430,459.92 | 0.00 | 360,000.00 |
| Converter | 47,257.19 | 134,780.12 | 0.00 | 267,000.00 |
| System | 688,765.67 | 654,459.42 | 2,138,863.45 | 1,924,000.00 |

This configuration needs all diesel generators when supplying the load especially at nighttime when the PV is unavailable, and the battery is fully discharged. In the previous configurations, diesel generator G2 has not been utilized to serve the demand. However, this optimized hybrid PV-diesel with the battery has utilized diesel generator G2 to generate 3.59% of total electricity production. This was the cheapest cost that the system can provide compared to previous configurations. Meanwhile, this system will not cause any stability issue since it includes a battery in the design that can be used to store surplus energy from PV for later use. As a result, the excess energy for this configuration is reduced to 1.85%.

### *3.2 Environmental Analysis*

It is undeniable that energy storage technologies manage to reduce the emission of harmful gas and the waste of energy. The addition of battery in the standalone diesel generators and hybrid PV-diesel without battery would significantly reduce harmful gas emission to the environment.

**Table 7.** Emission of Harmful Gas by Every System Configuration.

| | Emission | | | |
|---|---|---|---|---|
| | Standalone Diesel Generator | Hybrid PV-Diesel without Battery | Hybrid PV-Diesel with Battery | Optimized Hybrid PV-Diesel with Battery |
| **Carbon Dioxide (kg/yr)** | 1,015,309 | 868,093 | 346,378 | 445,058 |
| **Carbon Monoxide (kg/yr)** | 5,253 | 4,491 | 1,792 | 2,302 |
| **Unburned Hydrocarbons (kg/yr)** | 279 | 238 | 95.1 | 122 |
| **Sulfur Dioxide (kg/yr)** | 2,482 | 2,122 | 847 | 1,088 |
| **Particulate Matter (kg/yr)** | 44.9 | 38.4 | 15.3 | 19.7 |
| **Nitrogen Oxides (kg/yr)** | 1,007 | 861 | 343 | 441 |

From Table 7., the configuration of the standalone diesel generators has emitted the highest rate of harmful pollutants to the atmosphere. Moreover, the combination of PV and battery in the current standalone diesel generators system enhanced the reduction of harmful emissions. Though, the optimized hybrid PV-diesel with battery releases a higher rate of harmful pollutants compared to hybrid PV-diesel with battery configuration. This is due to the reason that optimized hybrid PV-diesel with battery configuration has utilized all three diesel generators while hybrid PV-diesel with battery only uses two diesel generators. The utilization of diesel generators contributes to the emission of harmful pollutants to the environment. Hence, the optimized hybrid PV-diesel with battery records the higher rate of harmful pollutants emission than hybrid PV-diesel with battery.

### *3.3 Technical Analysis*

The technical analysis for every system configuration can be evaluated according to sensitivity analysis that varying several system parameters. In this study, four parameters which are load demand, fuel price, battery capital cost and PV capital cost have been varied. The load demand has been varied in 3825 kWh/day and 7624 kWh/day and the price of fuel is considered to be in the range of 0.2$/L until 2.4$/L. Meanwhile, the capital cost for PV and battery is reduced to 60%. The results of sensitivity analysis can be illustrated in Table 8.

#### *3.3.1 Sensitivity Analysis Result with Variation in Load Demand*

The first case is the base scenario where all other parameters are kept constant and the load demand is varied between 3825 kWh/day and 7624 kWh/day. As can be seen in Table 8, when the load demand is at 7624 kWh/day, the capacity of PV needed is 900 kW which is 300 kW more than the PV capacity required by the load demand of 3825 kWh/day. Apart from that, the load demand of 7624 kWh/day has demanded the usage of two diesel generators whilst the load demand of 3825 kWh/day only requires the employment of one diesel generator. Consequently, the initial capital cost, operating cost, total NPC and LCOE in the load demand of 7624 kWh/day is increased approximately $0.76 million, $287,595, $5.26 million and $0.007/kWh, respectively, as compared to the load demand of 3825 kWh/day.

#### *3.3.2 Sensitivity Analysis Result with Variation in Fuel Price*

This work has varied the fuel price to be in the ranges of $0.2/L, $1.8/L and $2.4/L. From Table 8. Th3 fuel price at the load demand of 3825 kWh/day influences the values of NPC and LCOE. From the results, the higher price of fuel will lead to a higher cost of electricity. The same trend can be seen at the load demand of 7624 kWh/day. On top of that, the NPC value for the load demand of 7624 kWh/day is increased about $2.8 million for the fuel price of $0.2/L, $9.34 million for the fuel price of $1.8/L and $11.79 million for the fuel price of $2.4/L as compared to the load demand of 3825 kWh/day. Likewise, the values of LCOE are observed to increase in the proportion of $0.0247, $0.04, $0.065 at the fuel price of $0.2/L, $1.8/L and $2.4/L, respectively.

#### *3.3.3 Sensitivity Analysis Result with Variation in PV and Battery Capital Cost*

This work varied the capital cost of PV and battery in between the factor of 1 and 0.6. The factor of 1 is the actual capital cost of PV panel and battery whilst the factor of 0.6 is the 40% reduction of the capital cost of PV panel and battery. This signifies the capital cost variation in between $1200 per kW and $2000 per kW for PV panel while the capital cost for the battery is in the range of $720 per unit and $1200 per unit. As observed from Table 8., when there is capital cost variation of PV and battery at load demand 3825 kWh/day and a fuel price of $0.2/L, the system seems to depend on the configuration of standalone diesel generators. However, the system relies on the hybrid PV-diesel with battery configuration at the increased fuel price of $1.8/L and $2.4/L. Nevertheless, this case is not similar to the load

**Table 8.** The Result of Sensitivity Analysis

| Sensitivity Variables | PV (kW) | G1 (kW) | G2 (kW) | G3 (kW) | Battery (Units) | Converter (kW) | Initial Capital ($) | Operating Cost ($/yr) | Total NPC ($) | LCOE ($kWh) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Variations of Load Demand** | | | | | | | | | | |
| **3825 kWh/day** | 600 | 0 | 0 | 350 | 300 | 300 | $1.90M | $198,902 | $5.04M | $0.229 |
| **7624 kWh/day** | 900 | 500 | 0 | 350 | 300 | 300 | $2.66M | $486,497 | $10.3M | $0.236 |
| **Variations of Fuel Price at Load Demand of 3825 kWh/day** | | | | | | | | | | |
| **$0.2/L** | 0 | 0 | 0 | 350 | 0 | 0 | $77,000 | $104,428 | $1.72M | $0.0783 |
| **$1.8/L** | 900 | 0 | 0 | 350 | 300 | 300 | $2.50M | $327,027 | $7.66M | $0.348 |
| **$2.4/L** | 900 | 0 | 0 | 350 | 300 | 300 | $2.50M | $413,241 | $9.01M | $0.410 |
| **Variations of Fuel Price at Load Demand of 7624 kWh/day** | | | | | | | | | | |
| **$0.2/L** | 300 | 500 | 0 | 350 | 120 | 300 | $1.25M | $207,858 | $4.52M | $0.103 |
| **$1.8/L** | 1,200 | 500 | 0 | 350 | 300 | 600 | $3.53M | $855,534 | $17.0M | $0.388 |
| **$2.4/L** | 1,200 | 500 | 0 | 350 | 300 | 600 | $3.53M | $1.10M | $20.8M | $0.475 |
| **Variation of Solar PV Capital Cost and Battery Capital Cost at Load Demand of 3825 kWh/day and Fuel Price of $0.2/L** | | | | | | | | | | |
| **1** | 0 | 0 | 0 | 350 | 0 | 0 | $77,000 | $104,428 | $1.72M | $0.0783 |
| **0.6** | 0 | 0 | 0 | 350 | 0 | 0 | $77,000 | $104,428 | $1.72M | $0.0783 |
| **Variation of Solar PV Capital Cost and Battery Capital Cost at Load Demand of 3825 kWh/day and Fuel Price of $1.8/L** | | | | | | | | | | |
| **1** | 900 | 0 | 0 | 350 | 300 | 300 | $2.50M | $327,027 | $7.66M | $0.348 |
| **0.6** | 900 | 0 | 0 | 350 | 300 | 300 | $1.64M | $327,027 | $6.79M | $0.309 |
| **Variation of Solar PV Capital Cost and Battery Capital Cost at Load Demand of 3825 kWh/day and Fuel Price of $2.4/L** | | | | | | | | | | |
| **1** | 900 | 0 | 0 | 350 | 300 | 300 | $2.50M | $413,241 | $9.01M | $0.410 |
| **0.6** | 1,200 | 0 | 0 | 350 | 300 | 300 | $2.00M | $384,658 | $8.06M | $0.366 |
| **Variation of Solar PV Capital Cost and Battery Capital Cost at Load Demand of 7624 kWh/day and Fuel Price of $0.2/L** | | | | | | | | | | |
| **1** | 300 | 500 | 0 | 350 | 120 | 300 | $1.25M | $207,858 | $4.52M | $0.103 |
| **0.6** | 600 | 500 | 0 | 350 | 240 | 300 | $1.40M | $175,996 | $4.17M | $0.0951 |
| **Variation of Solar PV Capital Cost and Battery Capital Cost at Load Demand of 7624 kWh/day and Fuel Price of $1.8/L** | | | | | | | | | | |
| **1** | 1,200 | 500 | 0 | 350 | 300 | 600 | $3.53M | $855,534 | $17.0M | $0.388 |
| **0.6** | 1,200 | 500 | 0 | 350 | 300 | 600 | $2.43M | $855,534 | $15.9M | $0.363 |
| **Variation of Solar PV Capital Cost and Battery Capital Cost at Load Demand of 7624 kWh/day and Fuel Price of $2.4/L** | | | | | | | | | | |
| **1** | 1,200 | 500 | 0 | 350 | 300 | 600 | $3.53M | $1.10M | $20.8M | $0.475 |
| **0.6** | 1,200 | 500 | 0 | 350 | 300 | 600 | $2.43M | $1.10M | $19.7M | $0.450 |

demand of 7624 kWh/day where the system is depending on the hybrid PV-diesel with battery configuration even at the cheapest fuel price. This means that the reduction of PV and battery capital cost along with high fuel price and high load demand has caused the standalone diesel generators to include the PV panel and battery in the system.

For the case of load demand at 3825 kWh/day and fuel price of $0.2/L, the reduction of capital cost for PV and battery does not reduce the NPC and LCOE values. However, the increment of fuel price at $1.8/L and $2.4/L has decreased the values of NPC and LCOE when there is a reduction in PV capital cost and battery capital cost. At the load demand of 7624 kWh/day, the reduction to 60% of capital cost for PV and battery has reduced the NPC and LCOE values for the fuel price of $0.2/L, $1.8/L and $2.4/L.

### *3.4 Socioeconomic Analysis*

The socioeconomic aspect of every configuration can be analyzed by firstly estimating the reliability indexes. Aforementioned, LOLP and EDNS are employed as the reliability indexes and the evaluations of all indexes are based on COPT. Hence, the socioeconomic analysis requires several steps that can be shown as follows:

*3.4.1 Determine the Rated Capacity of Every Generation Unit as well as the Peak Load Of the Developed System:*

Table 9. have shown the rated capacity of every generation unit. This study has elected diesel generators, battery and PV panel as the generation units of the system. Meanwhile, the peak load demand in Tanjung Labian is equivalent to 417.51 kW.

**Table 9.** Rated Capacity of Every Generation Unit.

| **Generation Unit** | | **Rated Capacity** |
|---|---|---|
| **Generator** | DG1 | 500 kW |
| | DG2 | 500 kW |
| | DG3 | 350 kW |
| **PV Panel** | PV | 1,200 kW |
| **Battery** | Battery | 2,145 kWh (300 batteries connected in 6 strings) |

*3.4.2 Determine the F.O.R for Every Generation Unit*

The work in [20] has been an indicator for this study when selecting the F.O.R for every generation unit. The F.O.R for the generation unit of the diesel generator is 0.06, the PV panel is 0.03 and the battery is 0.04.

*3.4.3 Develop Individual COPT for Every Generation Unit*

Table 10. until Table 12. depict the COPT for diesel generators, PV panel and battery. The tables clearly show that the probability of no outage is estimated according to binomial expression.

**Table 10.** COPT for 3 Diesel Generators with Rated Values of 500kW and 350 kW.

| **Units Out** | **Capacity Out (kW)** | **Capacity In (kW)** | **Binomial Expression** | **Probability of No Outage** |
|---|---|---|---|---|
| **0** | 0 | 1,350 | $p_1^3=(0.94)^3$ | 0.830584 |
| **1** | 350 | 1,000 | $2p_1^2q_1=2(0.94)^2(0.06)$ | 0.106032 |
| **1** | 500 | 850 | $p_1^2q_1=(0.94)^2(0.06)$ | 0.053016 |
| **2** | 850 | 500 | $2p_1q_1^2=2(0.94)(0.06)^2$ | 0.006768 |
| **2** | 1,000 | 350 | $p_1q_1^2=(0.94)(0.06)^2$ | 0.003384 |
| **3** | 1,350 | 0 | $q_1^3=(0.06)^3$ | 0.000216 |

where q1 denotes the forced outage rate or unit unavailability equals 0.06 while p1 signify unit availability given equals 0.94

**Table 11.** COPT for PV Panel with Rated Value of 1,200 kW.

| **Units Out** | **Capacity Out (kW)** | **Capacity In (kW)** | **Binomial Expression** | **Probability of No Outage** |
|---|---|---|---|---|
| **0** | 0 | 1,200 | $p_2$ | 0.97 |
| **1** | 1,200 | 0 | $q_2$ | 0.03 |

where q2 denotes the forced outage rate or unit unavailability equals 0.03 while p2 signify unit availability equals 0.97

**Table 12.** COPT for 6 Strings Batteries with Rated Value of 2,145 kWh.

| **Units Out** | **Capacity Out (MW)** | **Capacity In (MW)** | **Binomial Expression** | **Probability of No Outage** |
|---|---|---|---|---|
| **0** | 0 | 2,145 | $p_3^6= (0.96)^6$ | 0.782757789696 |
| **1** | 357.5 | 1,787.5 | $6p_3^5q_3 = 6(0.96)^5(0.04)$ | 0.195689447424 |
| **2** | 715.0 | 1,430 | $15p_3^4q_3^2 = 15(0.96)^4(0.04)^2$ | 0.020384317440 |
| **3** | 1,072.5 | 1,072.5 | $20q_3^3p_3^3 = 20(0.96)^3(0.04)^3$ | 0.001132462080 |
| **4** | 1,430 | 715 | $15p_3^2q_3^4 = 15(0.96)^2(0.04)^4$ | 0.000035389440 |
| **5** | 1,787.5 | 357.5 | $6p_3q_3^5 = 6(0.96)(0.04)^5$ | 0.000000589824 |
| **6** | 2,145 | 0 | $q_3^6 = (0.04)^6$ | 0.000000004096 |

where q3 denotes the forced outage rate or unit unavailability given by 0.04 while p3 signify unit availability given by 0.96

*3.4.4 Combine Individual COPT and Reordering of Combined COPT*

At this stage, an individual COPT is combined to form the system configurations of standalone diesel generators, hybrid PV-diesel without battery and hybrid PV-diesel with battery. Table 13. describes the cumulative probability of combined COPT for standalone generators which comprised of two diesel generators that have the rated value of 500 kW together with one diesel generator at the rated capacity of 350 kW.

**Table 13.** Combined COPT for Standalone Diesel Generators (G1+G2+G3) System.

| | **Capacity Out (kW)** | **Cumulative Probability** |
|---|---|---|
| **Generator** | **0** | 0.830584 |
| | **350** | 0.106032 |
| | **500** | 0.053016 |
| | **850** | 0.006768 |
| | **1,000** | 0.003384 |
| | **1,350** | 0.000216 |

Table 14. shows the cumulative probability of combined COPT for hybrid PV-diesel without battery system where it consists of individual COPT of diesel generator and PV panel in Table 10. and Table 11., respectively.

**Table 14.** Combined COPT for Hybrid PV-Diesel without Battery (G1+G2+G3+PV) System.

| | | **PV** | |
|---|---|---|---|
| | **Capacity Out (kW)** | **0** | **1,200** |
| **Generator** | **0** | 0.80566648 | 0.02491752 |
| | **350** | 0.10285104 | 0.00318096 |
| | **500** | 0.05142552 | 0.00159048 |
| | **850** | 0.00656496 | 0.00020304 |
| | **1,000** | 0.00328248 | 0.00010152 |
| | **1,350** | 0.00020952 | 0.00000648 |

Meanwhile, Table 15. portrays the cumulative probability of combined COPT for three generators, PV panel and six strings of batteries. It shows the combination of Table 14. with Table 12

After the combination of individual COPT, the combined COPT requires the re-ordering process before the estimation of LOLP and EDNS can be made.

*3.4.5 Estimate the LOLP and EDNS*

Two reliability indexes which are LOLP and EDNS are estimated and the result is shown in Table 16. In comparing the configuration performance in Table 16., standalone diesel generators and hybrid PV-diesel with the battery has the highest and lowest values of LOLP and EDNS, respectively. This signifies that standalone diesel generators are the least reliable configuration while hybrid PV-diesel with battery is the most reliable configuration. Hence, the former has the highest rate of power outage while the latter has the least tendency to experience the power outage.

**Table 16.** Reliability Indicators of System Configuration.

| **Model type** | **LOLP(/year)** | **EDNS (MW/yr)** |
|---|---|---|
| **Standalone diesel generator** | 1.9260 | 0.0003186362 |
| **Hybrid PV-diesel without battery** | 0.05686632 | 0.00000955908 |
| **Hybrid PV-diesel with battery** | 2.740914E-10 | 2.68515826E-13 |

*3.4.6 Find the Correlation Between LOLP and EDNS with Dependent Variable According to the Correlation of Coefficient*

A correlation of coefficient is used to find the correlation of LOLP and EDNS with the dependent variable (number of students who passed the examination). The data for the number of students who passed the examination is obtained from the Department of Statistic Malaysia from the year 2010 until 2014. The result from the correlation of coefficient shows that the correlation between LOLP and the number of students who passed the examination is -0.94 which indicates a strong negative correlation. The establishment of a negative correlation signifies the opposite trend between the LOLP and the number of students who passed the examination. This means that whenever the value of the former variable increases, the value of the latter variable decreases and vice versa. Meanwhile, the EDNS records the correlation of -0.69 which indicates the moderate negative correlation with the number of students who passed the examinations. Therefore, this study selects LOLP as the independent variable of linear regression because of its strong correlation with the number of students who passed the examination.

*3.4.7 Perform the Linear Regression Between the Dependent Variable and Independent Variable (LOLP) for Standalone Diesel Generators Configuration, Hybrid PV-Diesel without Battery Configuration and Hybrid PV-Diesel with Battery Configuration*

The linear regression is developed in a data analysis tool provided by Microsoft Excel. In this tool, the data for independent and dependent variables are selected and the data will be evaluated to produce the results in term of the coefficient of determination, p-value, partial regression coefficient as well as y-intercept value. The evaluation of linear regression results in a coefficient of determination value equal to 0.88. Furthermore, the independent variable of LOLP indicates a statistical significance of 0.017 in the p-value. The linear equation obtained from the regression analysis is shown in equation (11) and it is then used to estimate the number of students who passed the examination at a given LOLP.

The application of the partial regression coefficient of LOLP to the following equation (11) has shown that the percentage number of students who passed the examination will reach 48.10% in hybrid PV-diesel without battery and 49.39% in hybrid PV-diesel with battery compared to 5.68% in standalone diesel generators. The increase percentage number of students who passed the examination signifies the importance of installing the HRES in the rural areas for an improvement of socioeconomic growth.

$$\textit{Number of students who passed the examination} = 245,980.41 + (-113,069.71 \times LOLP) \qquad (11)$$

**Table 15**. Combined COPT for Hybrid PV-Diesel with Battery (G1+G2+G3+PV+Battery) System.

| | | **Battery** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Capacity Out (kW)** | **0** | **357.5** | **715** | **1,072.5** | **1,430** | **1,787.5** | **2,145** |
| **Generator & PV** | **0** | 0.630641713 | 0.157660428 | 0.016422961 | 0.000912387 | 2.85121E-05 | 4.75201E-07 | 3.30001E-09 |
| | **350** | 0.080507453 | 0.020126863 | 0.002096548 | 0.000116475 | 3.63984E-06 | 6.0664E-08 | 4.21278E-10 |
| | **500** | 0.040253726 | 0.010063432 | 0.001048274 | 5.82375E-05 | 1.81992E-06 | 3.0332E-08 | 2.10639E-10 |
| | **1,200** | 0.019504383 | 0.004876096 | 0.000507927 | 2.82181E-05 | 8.81817E-07 | 1.4697E-08 | 1.02062E-10 |
| | **850** | 0.005138774 | 0.001284693 | 0.000133822 | 7.43457E-06 | 2.3233E-07 | 3.87217E-09 | 2.68901E-11 |
| | **1,000** | 0.002569387 | 0.000642347 | 6.69111E-05 | 3.71728E-06 | 1.16165E-07 | 1.93609E-09 | 1.3445E-11 |
| | **1,550** | 0.002489921 | 0.00062248 | 6.48417E-05 | 3.60232E-06 | 1.12572E-07 | 1.87621E-09 | 1.30292E-11 |
| | **1,700** | 0.001244961 | 0.00031124 | 3.24208E-05 | 1.80116E-06 | 5.62862E-08 | 9.38103E-10 | 6.51461E-12 |
| | **1,350** | 0.000164003 | 4.10009E-05 | 4.27092E-06 | 2.37273E-07 | 7.4148E-09 | 1.2358E-10 | 8.58194E-13 |
| | **2,050** | 0.000158931 | 3.97328E-05 | 4.13883E-06 | 2.29935E-07 | 7.18547E-09 | 1.19758E-10 | 8.31652E-13 |
| | **2,200** | 7.94656E-05 | 1.98664E-05 | 2.06942E-06 | 1.14968E-07 | 3.59274E-09 | 5.98789E-11 | 4.15826E-13 |
| | **2,550** | 5.07227E-06 | 1.26807E-06 | 1.3209E-07 | 7.33835E-09 | 2.29324E-10 | 3.82206E-12 | 2.65421E-14 |

## 4. Discussions

This section discusses the main findings obtained from Section 3. The results in Section 3 will be explained in term of cost and environmental analysis on every system configuration. Apart from that, the effect of changing certain parameters in the system configuration will be investigated in this study together with the socioeconomic impacts produced by every system configuration. The estimated cost of every configuration is portrayed in term of NPC and LCOE. Each configuration also shows the harmful pollutants emission rate as well as the effect of changing the parameters of battery price, load growth, fuel price and PV price. The reliability indexes of every system (LOLP and ENDS) are quantified as the measurement of the socioeconomic effect of every system configuration.

### *4.1 Techno-Economic Effect*

In the economic aspect, the best economic property is dominated by standalone diesel generators followed by hybrid PV-diesel with battery and hybrid PV-diesel without battery as shown in Fig. 8.

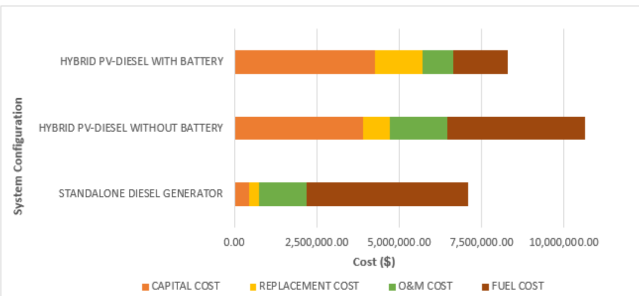


**Fig. 8.** Estimation Cost of Every System Configuration.

The estimated O&M cost, replacement cost, fuel cost and capital cost of hybrid systems are higher than standalone diesel generators system because of the inclusion of PV or battery which are merely expensive upon purchasing.

The sensitivity analysis of every configuration is estimated by varying the parameters of battery price, load growth, fuel price and PV price on the performance of every configuration. The results demonstrate the dependency on hybrid PV, diesel generators and battery particularly in the event of high load demand and high fuel price. Moreover, the high reduction in related costs of PV and battery will eliminate the standalone diesel generators option. Similar to the case of NPC and LCOE values, where the increment of load demand and fuel price along with decrement of PV and battery capital cost has endorsed the system to employ the hybrid system which includes the PV, diesel generators and battery. It is expected that the costs of the battery, as well as PV, are reduced in future which validates the idea of using a 100% renewable energy generation system.

**Table 17.** Fuel Consumption and Running Hour of Diesel Generators in System Configuration.

| | **Standalone Diesel Generator** | **Hybrid PV-Diesel without Battery** | **Hybrid PV-Diesel with Battery** |
|---|---|---|---|
| **Fuel Consumption (L)** | 387,193 | 314,527 | 119,911 |
| **Running Hours (hrs/year)** | 8,760 | 7,719 | 3,068 |

Standalone diesel generators and hybrid systems can also be quantified according to the measurements of fuel consumption and running hours of diesel generators. The result in Table 17. indicates that hybrid systems consume fewer fuels compared to standalone diesel generators. Apart from that, running hours of hybrid systems also have been reduced as the systems more depend on the generator that has a smaller rated capacity when supplying the load demand. As a result, the diesel generators will not be frequently operated and subsequently reducing the replacement, fuel, maintenance and operational costs. Hence, NPC and LCOE values will be decreased as well.

### *4.2 Environmental Effect*

The results in Section 3 shows that standalone diesel generators emit the highest amount of harmful pollutants to the atmosphere whilst hybrid systems contribute less harmful pollutants. This means that the inclusion of PV or battery in the current standalone diesel generators enhanced the reduction of harmful gas emissions. A comparison is also being made between hybrid PV-diesel without battery and hybrid PV-diesel with battery and the results show the superior performance of hybrid PV-diesel with battery. This is due to the reason that surplus energy which is generated from PV is not being utilized in charging the battery in the hybrid PV-diesel without a battery system. As a result, the surplus energy turns into excess energy and the role of supplying the load will be taken by diesel generators. Thus, a huge amount of energy is supplied from diesel generators and it will release a higher amount of harmful pollutants to the environment. In the summary, the amount of harmful pollutants emission is strongly related to the type of system configuration as well as the amount of generated energy.

### *4.3 Socioeconomic Effect*

This study evaluates the reliability effects of every system configuration on the socioeconomic impact of the number of students who passed the examination. This evaluation can be regulated by firstly estimating the values of LOLP and EDNS. They serve as indexes when estimating the reliability of every system configuration. The results show that the standalone diesel generators system has the highest values of LOLP and EDNS, in contrast with the values obtained from hybrid PV-diesel with battery. Utilization of renewable energy source which includes PV panel and the battery will increase the system reliability. Hence, any system that operates with the integration of PV panels and battery will experience the least rate of a power outage.

Next, the socioeconomic impact, namely, the number of students who passed the examination is obtained according to the linear regression equation is shown in equation (11). In summary, the reliability of every electrical system leaves a huge impact on the number of students who passed the examination. The usage of a hybrid renewable system which comprises PV panel, diesel generators and battery is more reliable than standalone diesel generators and this will considerably improve the education of the population in rural areas. Better education will lead to better living condition because there is a high tendency for them to generate more income and attain empowerment in future.

## 5. Conclusion

This work estimates the techno-economic analysis of HRES by using a linear programming model. Based on the result of this study, it can be concluded that pairing diesel generator, PV and battery to generate electricity is a cost-effective solution to successfully meet the load demand. From the simulation, a hybrid system consists of 100 kW, 50 kW and 200 kW diesel generators, 600 kW PV, 300 kW system converter and 300 batteries with a nominal voltage of 2 V is found to be an optimal hybrid configuration according to the minimum values of NPC and LCOE.

Sensitivity analysis results depict that LCOE and NPC values are noticeably sensitive to the load demand growth, fuel price, PV and battery capital cost. The integration of renewable energy resources in the generation of electricity has minimized the dependence on a standalone diesel generator, improved the system performance as well as generated less harmful pollutants. This study also validated the importance of adding the battery to reduce losses as well as to store excess energy. It also resulted in increasing system sustainability. Besides, reducing battery as well as PV costs can lead to lower values of NPC and LCOE which will enhance the use of both technologies in the current system.

The socioeconomic impact which is the number of students who passed the examination can be evaluated according to the values of LOLP. The result analysis reveals that hybrid PV-diesel with battery configuration denotes the lowest values of LOLP. Hence, this configuration is the most reliable one and it will experience the lowest rate of a power outage. A linear regression method is used to find a relation between LOLP with the number of students who passed the examination and the results revealed that the hybrid PV-diesel with the battery will contribute to the highest number of students who passed the examination.

The projection costs of PV and battery are expected to decrease with further research and development. Hence, it is possible to implement and to integrate a hybrid renewable energy system with a battery in the future. In a conclusion, the hybrid renewable energy system with the battery has the potential to be adopted in the current system, especially to upgrade and to replace the existing standalone diesel generators system in Malaysia.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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