Future Energy
Open Access Journal
ISSN 2832-0328

August 2022| Volume 01 | Issue 02 | Pages 28-45

Journal homepage: https://fupubco.com/fuen

https://doi.org/10.55670/fpll.fuen.1.2.5

Future Publishing LLC

Article

Feasibility Analysis and Economic Viability of Standalone Hybrid Systems for Marudi Electrification in Sarawak, Malaysia

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ARTICLE INFO

Article history:
Received 01 April 2022
Received in revised form
02 May 2022
Accepted 07 May 2022

Keywords:
Hybrid renewable energy system, off-grid, mini-grid, techno-economic optimization, rural electrification, feasibility analysis

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DOI: 10.55670/fpll.fuen.1.2.5

ABSTRACT

A hybrid renewable energy system is a feasible solution for off-grid electrification where grid electricity is not available due to economic or technical limitations. In this study, rural electrification is performed on a small longhouse settlement, Long Moh, in Sarawak, Malaysia, with a population of 308 from 70 households. Initially, a hybrid PV/Hydro/DG/Battery system is proposed due to the abundance of solar and hydro resources in the village. There have been a lot of studies based on PV/DG/Battery systems in Malaysia but less with the inclusion of hydropower. Through simulation and optimization process, the most optimal system in terms of Net Present Cost (NPC) is found to be a hybrid Hydro/DG/Battery system which provides a total NPC of $213,694.90, cost of electricity of $0.08/kWh, and operating cost of $9,495.56/year. The most environmentally friendly system is the proposed PV/Hydro/DG/Battery system due to less fuel consumption (12,863.63 L/year) and its high renewable penetration. The standalone diesel generator (DG) system was the least economic and most polluting system. The best system overall for rural electrification at the case study location is a hybrid Hydro/DG/battery system due to its relatively low NPC and emissions output compared to a standalone DG system.

1. Introduction

As of 2019, there has been a record of high global energy consumption of 162,189 TWh, an increase of 20.9% compared to the energy consumption a decade ago in 2009, which was 134,116 TWh. The world's primary energy source is fossil fuels, such as natural gas, oil, and coal, which influence greenhouse gas emissions and adversely affect the environment [1]. Burning fossil fuel produces large quantities of carbon dioxide, and it is the leading cause of man-made global warming. Employing renewable energy systems (RESs) such as hydro, wind, and solar has been gaining attention due to global warming and fossil fuel depletion concerns. In 2009, renewable energy consumption accounted for 8.1% of the global energy consumption, while in 2019, this figure increased to 11.4% [1]. However, as of 2018, 10.4% of the global population hasn't had access to electricity [2]. In the state of Sarawak in Malaysia, there are a small but significant number of communities living in areas that are difficult to access and far from the national grid. Due to technical issues, grid extension to those communities is too costly and not economically feasible. Many of these communities are in areas only accessible by boat travel. The state government is aiming toward 100% electrification across the state by 2025, and as a result, various projects have been initiated by the government to increase electricity coverage in rural areas, such as Sarawak Alternative Rural Electrification Scheme (SARES) and the Rural Power Supply Scheme (RPSS) [3]. Despite considerable progress made by these schemes, as of 2018, 9% of the rural population still does not have an electricity supply which translates to an estimated number of 20,000 households [4]. Access to electricity is essential for the socio-economic development of the state. It will give access to the construction of more social infrastructures, such as clinics and schools, which will improve the overall quality of life (QOL) [5]. Therefore, installing off-grid RESs will be very beneficial to such communities. Due to Malaysia's location in the equatorial zone, it receives an abundance of sunlight all year round. Malaysia receives an average global horizontal irradiation of 4.5 $kWh/m^2/day$ [6]. Sarawak's geography is also characterized by having many rivers which have the potential of being used for hydroelectric power, such as micro hydropower turbines. As an example, the Rajang River currently houses Malaysia's largest and tallest hydroelectric project, the Bakun Hydro-Electric Dam Project (2400MW). Thus, the combination of RESs such as photovoltaic (PV) and hydro is a suitable choice for the electrification of rural areas in Sarawak. The purpose of considering hydropower in the hybrid system as opposed to a pure PV-based system is to expectantly supply the off-grid network in cases where solar energy is not available, for example, during sundown and night-time.

However, one downside of having a standalone RES is that renewable sources are very dependent on environmental conditions, which directly affects the energy production levels of such systems. PV power levels depend on the average sun hours, while hydro systems such as micro hydropower turbines depend on the average rainfall levels and flow rate of rivers. Reliance on a single technology also leads to system over-sizing, increasing the initial set-up cost of the system [7]. One solution to this problem is to integrate the usage of RESs with conventional energy systems (CESs) such as diesel generators to produce a hybrid renewable energy system (HRES). This way, the energy system can be more reliable and consistent, which is a must for powering rural households to avoid supply interruptions. Energy storage systems (ESSs) can also be integrated with HRESs to further harness renewable sources when there is an oversupply; for example, when the load demand during a sunny day is low, the extrasolar energy can be used to charge batteries in ESSs instead of going to waste. ESSs can then be discharged when there is a drop in RESs power levels.

A drawback to using RES is that the initial investment required might be very high. However, due to policies for encouraging renewable energy growth, solar power is at its cheapest point historically. For example, the European Union (EU) has set a goal to supply 32% of its energy from RESs by 2030 [8]. For utility-scale solar power, the average cost of electricity generation is around USD45 per MWh, while a decade ago, it was USD300 per MWh, showing an 85% reduction in price [9]. It is also reported that the cost of building coal plants is higher than installing solar farms, with the average cost of coal plants being around USD100 per MWh.

There have been a lot of studies discussing the usage of hybrid PV/diesel and PV/diesel/battery systems in Malaysia, but very few researches have discussed the techno-economic feasibility of PV/hydro/diesel/battery systems, while hydropower is one of the most abundant renewable resources in Malaysia. Lau et al. [10] analyzed the usage of a hybrid PV/diesel system in Malaysia for a 40-house rural residential area with a 2 kW peak load per house. Their analysis of the PV/diesel system was done in comparison to the standalone diesel system and PV/diesel/battery. Standalone diesel systems had the lowest operation cost but had the most pollutant emissions. Hybrid PV/diesel/battery had a lower operating cost than excluding batteries in their system. Excess PV power was used to charge the batteries, significantly optimizing the hybrid system instead of being considered a loss. It was noted that the initial set-up cost of the PV system was very high, as high as USD5600 per kW. However, their study [10] was conducted in 2010, and PV technology prices have significantly reduced since that time.

A study by Rohit and Subhes [11] is referred to justify the inclusion of hydropower in a hybrid system. Their study was done in an Indian rural village where the load requirements were approximately 500 kWh per day. The optimal hybrid system configuration is analyzed to be a hybrid PV/hydro/biodiesel with an ESS (battery). The system architecture compromised a 20 kW PV array, 30 kW small hydropower station, 10 kW biodiesel generator, and 40 batteries rated at 6.94 kWh each. Hydropower has been seen to supply 76% of the total energy consumed, while 14% was supplied by PV and the remaining 10% by biodiesel. Hydropower could supply a large portion of the energy required as it could be online 24 hours a day, while PV depended on the sun hours of the day. The difference between a system with one renewable source and multiple renewable sources has also been analyzed in Ref [11]. The overall flow for the planning and design process of an HRES was then determined. Firstly, an analysis of studies that implemented hybrid PV/diesel/battery systems was performed. This HRES combination was the most common due to its relative simplicity of the low number of components and only one renewable energy generation source.

Chong et al. [12] have studied the techno-economic viability of a hybrid PV/diesel/battery system for a housing estate in Harbin, China. Load profiles were set up for the 4 seasons with different loads at varying hours of the day, and a peak power draw of 500 kW was present during winter and summer. Different combinations of the three HRESs were simulated, and it was concluded that the full combination of a hybrid PV/diesel/battery system with a load-following dispatch strategy was the most cost-optimal option. The standalone diesel generator system was the most expensive due to the high operating cost and the large amount of fuel consumed by running the generators 24 hours daily. Their study also considered different aspects such as sensitivity analysis and dispatch strategy and has detailed analysis for the calculations of input parameters for PV array and diesel generator.

Halabi et al. [13] have analyzed the performance of hybrid PV/diesel/battery systems in Sabah, Malaysia. Two different locations have been chosen as the case studies, including an island and a rural area where existing hybrid PV/diesel/battery systems have been implemented. Their study compared the existing system to a standalone diesel system and a 100% PV/battery renewables-only system. The final proposed system by Halabi et al. [13] was a PV/diesel/battery system that had a low capital and replacement cost and lower renewables penetration. The initial investment for the new system was lower than the existing system in Ref [13]. A conclusion was made that a standalone diesel system had the least economic benefit and highest negative environmental impact while it was vice-versa for a fully renewable PV/battery system. Including batteries in a RES is noted to be essential to store excess energy and reduce power loss. A system with 100% renewables penetration is economically impractical due to high PV and battery capital and replacement cost; however, these prices are expected to decrease over the years with the introduction of more environment-conscious policies around the world.

The techno-economic feasibility of different combinations of hybrid PV/diesel/battery systems for replacing existing fossil fuel generators in the outlying islands of Taiwan was investigated by Tsai et al. [14]. It was reported that PV/diesel system with 15% renewables penetration resulted in excess electricity of up to 2.6% a year being wasted, which was a significant amount [14]. But by employing ESS, the excess electricity was reduced to 0.5%, showing the importance of ESS such as batteries in the HRES. A system with 40% renewables penetration was the optimal choice considering the net present cost (NPC) and the cost of energy (COE). Higher renewables penetration would lead to higher NPC and COE, but those would result in reducing the fuel consumption and lower CO_2 emissions. Their study also considered the region's interest and inflation rates. These factors were commonly overlooked when performing economic analysis. Another similar study has been done by Rehman and Al-Hadhrami [15] to replace existing fossil fuel generators with a PV/diesel/battery system for a rural area in Saudi Arabia. The same outcome was observed where an increasing renewables fraction leads to lower diesel fuel consumption but higher COE and NPC. Their study concluded that a renewable penetration of 20% was the most optimum configuration.

Ashraf et al. [16] have completed their analysis of PV/diesel/battery combinations using an analysis method known as the Elephant Herding Optimisation (EHO) algorithm. They compared the results with those obtained by another proprietary derivative-free algorithm from a microgrid simulation software. Their system had implemented objective functions such as low annualized cost, unmet load probability, and CO_2 emissions. EHO algorithm successfully optimised a system that has the lowest CO_2 emissions and lowest capital cost. However, it had some limitations such as poor battery system optimisation which led to a large portion of wasted energy. Thus, the proprietary algorithm was a simple and effective way of performing HRES analysis.

Another study by Salameh et al. [17] has analyzed different tracking systems for PV arrays in a hybrid PV/diesel/battery system. Their systems contained several scenarios, including fixed structures, a continuous horizontal axis (elevation), a continuous vertical axis (azimuth), and dual-axis solar trackers. Their objectives were to obtain a system with the lowest COE and highest renewable fraction. Dual-axis solar tracker is noted to produce the best results with zero unmet load and a reasonable excess power percentage. The power output of the dual-axis solar tracker was 15.5% higher than that of the system with a fixed structure, showing the importance of the tracking systems when designing a PV system. Furthermore, by installing the dual-axis trackers, a reduction of 69.7% of CO_2 emissions was recorded as more solar energy was harnessed. Odou et al. [18] analyzed the effectiveness of a hybrid PV/hydro/diesel/battery system to power a remote area in Africa. The area of interest compromised of 50 households and several social and commercial infrastructures such as schools, clinics, and water pumping systems. Load profile was splinted into three categories, including household, community, and commercial load, each having its own hourly load demands. Their hybrid PV/diesel/battery system was reported to be more economically feasible compared to a grid extension project considered over the project's lifetime. The hybrid system also had a shorter payback period and up to 97% less CO_2 emissions compared to a standalone diesel system making it the best choice for rural electrification. Hydropower potential at their location was good; however, the hydro site was too far from the village, incurring additional costs from grid extension and making it less economically feasible. Thus, the effectiveness of certain renewable sources not only depends on their availability but also their distance to the required load.

Hoseinzadeh et al. [19] have analyzed the implementation of PV arrays, wind turbines, and batteries to supply an existing run-of-river plant due to the region of interest being water-scarce during hot seasons. The average power consumption modeled in the region was 665 kWh/day. During hot seasons, with just a standalone hydro plant, the power deficit could reach up to 125 kWh/day, which was 18.9% of the total required power. Power deficit would result in households not having electricity or facing frequent blackouts. Their study noted that for available hydropower of 61 kW, 20 kW of PV arrays and a 7.5 kW wind turbine should be added. Batteries were also employed to store the excess solar energy produced during the day and to be discharged during high loads or at night. Wind and hydro were both complementary to PV as those renewable sources were available at night. However, their study implemented a system with a renewable penetration of 100%, which was not recommended as renewable power is very source dependent.

The effectiveness of a hybrid PV/wind/battery system for an energy-poor rural village in India was studied by Krishan and Suhag [20]. In their system, a maximum power point tracker (MPPT) was implemented for the PV arrays and wind turbines. MPPT helped to maximize power extraction of sources with variable power such as PV and wind. Similarly, it was observed that the hybrid PV/wind/battery system performed the best compared to PV/battery and wind/battery showing the importance of having complementary renewable sources. However, the NPC of the system was quite high ($228,353), considering the system was only powering a community of 54 people consuming an average of 168.23 kWh/day with a peak of 36.5 kW. Oladigbolu et al. [21] have proposed a hybrid PV/hydro/wind/diesel/battery system to power a remote village located in Nigeria. The remote village was grid-connected, albeit only having 4 hours of electricity daily. The village had a total of 250 households and 20 healthcare centers. Load profile was divided into the two respective categories, including residential and healthcare, with varying hourly load demands. Their study made comparisons to a hybrid PV/wind/diesel/battery system and noted that the amount of disseminated CO_2 by this system was four times of a PV/hydro/wind/diesel/battery system [21]. The RES without hydro also had a higher operating cost, while most of the cost was spent on diesel fuel. However, the proposed system had generated 9.4% excess electricity, which should be minimized to allow for more efficient usage of the power system. The study noted that the proposed system had a high investment cost of $250,000, which was not economically suitable for implementation in a rural village. Thus, the system should be downsized to reduce costs. A large-scale analysis was performed by Baseer et al. [22] on an industrial city with an average load of 11,160 kWh/day while the peak load was 685 kW. They compared PV/diesel/battery, PV/wind/diesel/battery, PV/wind/battery, and wind/diesel/battery systems to identify the system with the lowest COE and NPC. PV/wind/diesel/battery was the most suitable system, followed by the wind/diesel/battery system. The inclusion of diesel generators helped to reduce the COE and NPC of the system. The capital cost of a 100% renewable energy-based system (PV/wind/battery) was 30% higher than non-renewable energy-based configurations in their study. Similar to several studies [14, 15, 20], a more environmentally friendly system can be obtained at the expense of higher initial investment, NPC, and COE. Their finding was also supported by another study done by Aziz et al. [23], which analyzed PV/hydro/diesel/battery systems. They concluded that the full hybrid PV/hydro/diesel/battery system was the best performing system. PV/battery and PV/hydro/battery systems would have a lower emission production but higher NPC and COE.

In a much smaller scale study, Haratian et al. [24] proposed a hybrid PV/wind/battery system to power a renewable energy laboratory in Iran. The average load requirement was noted to be around 4kWh/day. However, due to the region's low average wind speed of 3-4 m/s, installing the wind turbines in the system served to increase the COE and NPC by 20% and 10 %, respectively. The region's solar irradiation is around 5 $kWh/m^2/day$ which closely resembles the one in Sarawak. The most economical solution was modeled to be a PV/battery system with 1.2 kW PV arrays and 6 units of 3 kWh batteries. Even without the installation of wind turbines, there was no electricity shortage and the power generation could be done at a lower cost. This showed the importance of selecting the correct renewable sources according to region-specific characteristics such as wind speed and solar irradiation.

Elkadeem et al. [25] have provided a framework to ensure the optimal planning and design of HRESs and implemented said procedures to determine the feasibility of a hybrid PV/wind/diesel/battery system in Sudan. The introduced framework was divided into five categories. Firstly, the motivations such as environmental policies and financial incentives behind choosing HRES as a power system were determined. Next, a preliminary study was conducted to find which combination of renewable sources was suitable for that case study. Different factors such as load demand, meteorological data, and existing systems were considered, and the most appropriate configuration of HRES was found. After that, microgrid simulation software was utilized to provide a techno-economic and optimization analysis of the proposed HRES. Different variables, including the sizing of each renewable power component to obtain an optimal solution in terms of NPC and COE, could be investigated at this stage. After having an optimized system, technical, economic, and environmental assessment was done to evaluate the benefits of the proposed system. Lastly, a sensitivity analysis was performed to investigate the sensitivity of the proposed system against uncertain parameters such as variation in fuel price and interest rate. Using this framework, the authors in Ref. [25] successfully found a combination of HRES appropriate for the load scenario, providing excess energy of 9.65% and reducing harmful emissions by 95% compared to standalone diesel generator operation. Other authors such as Chauhan and Saini [26] also did the same study, including load and resource assessment, modeling of systems, problem formulation, demand management, and optimization in a case study in India. A summary of the related studies is tabulated in Table 1 (Appendix).

The purpose of this study is to design the best configuration of PV/hydro/diesel/battery components for a small rural town located in the Marudi division of Sarawak called Long Moh. Several objectives have been set to be achieved in this study. Firstly, the average load profile of the rural community in Sarawak is determined by the investigation. The available conventional and non-conventional sources of energy, such as solar irradiation, river flow, and diesel fuel cost, are obtained from national sources and meteorological references. Having that information, a suitable size for the proposed PV array, hydroelectric station, diesel generator, and battery bank is then determined. The best possible combination of these sources in terms of environmental effects, economic, and technical performance are analyzed. The aim is to find a combination of HRESs that provides an acceptable capital cost, replacement cost, and cost of operation and maintenance.

2. Site description

2.1 Study area

The case study location is a rural longhouse settlement named 'Long Moh' in the Marudi district of the state of Sarawak, Malaysia. It is located at coordinates 3.0576° N, 115.0766° E, and approximately 550 km east-northeast of the state's capital city Kuching. The main source of income comes from agriculture, such as fruits, vegetables, and meat, where the goods are taken to bigger villages nearby to sell. The exact population data of Long Moh is unavailable as it is a rural area; however, a longhouse settlement can be estimated to have 70 households [27]. According to a census conducted by the Department of Statistics Malaysia, the average household size in Sarawak is 4.4; thus, it can be estimated that Long Moh has a population of 308 people [28]. The location can be seen in the map of Sarawak given in Figure 1 [29].

Figure 1. Long Moh area in Sarawak state

Long Moh is currently not completely connected to the national grid; however, the government has plans in the future to do so. For now, the residents get power sparingly from portable diesel generators. The village is located next to the Baram River, which is the proposed river for a 1200 MW hydropower station. However, strong protests from locals were made because flooding of the dam would have resulted in the displacement of over 20000 locals. Thus, the project has since been halted indefinitely [30]. A micro-hydro station is one of the suitable renewable energy sources for Long Moh due to the strong hydropower potential of the Baram River.

2.2 Solar data and temperature

The average solar radiation data and clearness index for the year 2019 is obtained from NASA's POWER Data Access Viewer [31]. Temperature data for Long Moh is illustrated in Figure 2. The recorded temperature had an annual high of 23.06℃, a low of 21.9℃, and an average of 22.4℃. Solar radiation data is the average amount of solar radiation that is incident on a horizontal surface on Earth and has a unit of $kWh/m^2/day$. The Clearness index is a dimensionless measure of the clearness of the atmosphere, i.e., the amount of solar radiation that passes through the atmosphere to reach the surface of the Earth. Solar radiation ranges from 4.43 to 6.02 $kWh/m^2/day$ with a yearly average of 5.12 $kWh/m^2/day$. The Clearness index ranges from 0.47 to 0.58 with a yearly average of 0.51. Solar radiation data was also obtained from NASA as presented in Figure 3.

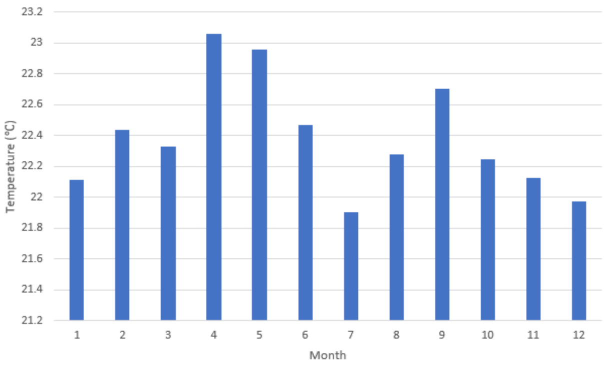


Figure 2. Temperature data for Long Moh in the year 2019

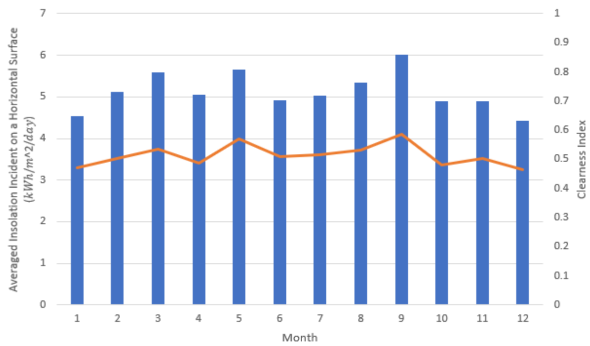


Figure 3. Solar radiation data for Long Moh in the year 2019

2.3 Hydrological data

A research team, in collaboration with a Sabah-based Non-governmental organization (NGO), LEAP (Land, Empowerment, Animals, People), provided an analysis of the streamflow for Long San, which is a village downstream of Long Moh [32]. The streamflow in Long Moh is assumed to be the same as in Long San as the two villages are located not too far from each other along the same river. Streamflow data is shown in Figure 4. The flow rate has a monthly average of as high as 98 L/s and as low as 31 L/s, with an annual average of 65 L/s.

2.4 Diesel Fuel Price

In 2020, diesel fuel price was 1.74 Malaysian Ringgit (RM) per liter which equals \$0.42. The fuel price in rural areas was the same as in the cities due to programs launched by the Ministry of Domestic Trade and Consumer Affairs to bring down retail prices of essential goods, including diesel fuel, in the rural regions in Sarawak [33].

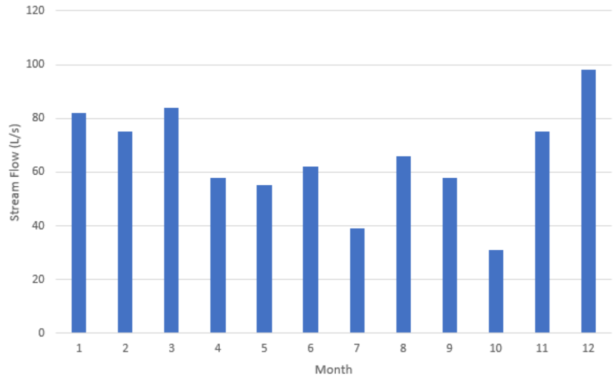


Figure 4. Baram River Stream Flow Data

2.5 Load demand assessment

As estimated earlier, the village of Long Moh contained a population of 308 with 70 households. The village also has other infrastructures such as a primary school, community church, and village store. Thus, the four main contributors to load demand will be households, schools, churches, and store loads. A breakdown of the individual load demand is listed in Table 2 (Appendix) and Figure 5. A normal weekday is assumed for the load profile, where they're in a power spike (21.48 kW) at 6 AM. At 7 AM, parents work, and children attend school until the afternoon, resulting in a low household load during that period. Household load then picks up in the evening when the family is home, and another spike (36.45 kW) occurs at 8 PM. The household load then settles at 17.06 kW. The community church only has gatherings on Sunday for 3 hours, while the village store is open 12 hours a day. This load is expected to be accurate for the whole year as Malaysia does not have a winter season where the heating will cause the power draw to increase. A day-to-day variability and timestep variability of 2% is added to the load profile in the simulation software to make the load profile more realistic. The day-to-day variability shifts the load profile upwards or downwards randomly while maintaining its shape, while timestep variability changes the shape of the load profile while keeping the size constant.

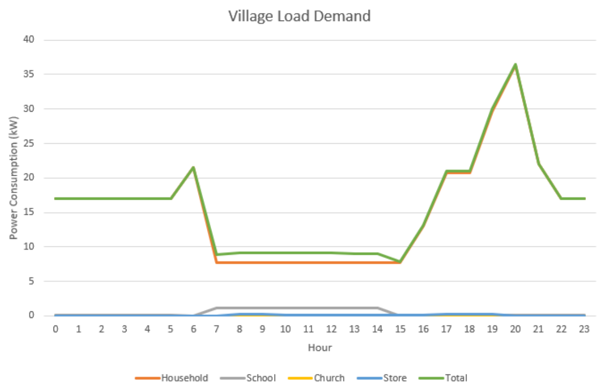


Figure 5. Load Demand Assessment for Long Moh

3. Methodology

The following framework was established to successfully evaluate the appropriate HRESs configuration. Firstly, a suitable location for HRES implementation was determined. The required data such as solar radiation, temperature, and river flow were obtained from meteorological sources. These data have been fed into microgrid simulation tools to analyze the generated power by PV arrays and hydropower turbines. Next, an hourly load profile was assessed based on the site's population and estimated load demand. Available infrastructures at the site also must be taken into consideration when the load profile is generated.

A flowchart presents the implemented optimization procedure in this study (Figure 6) [29].

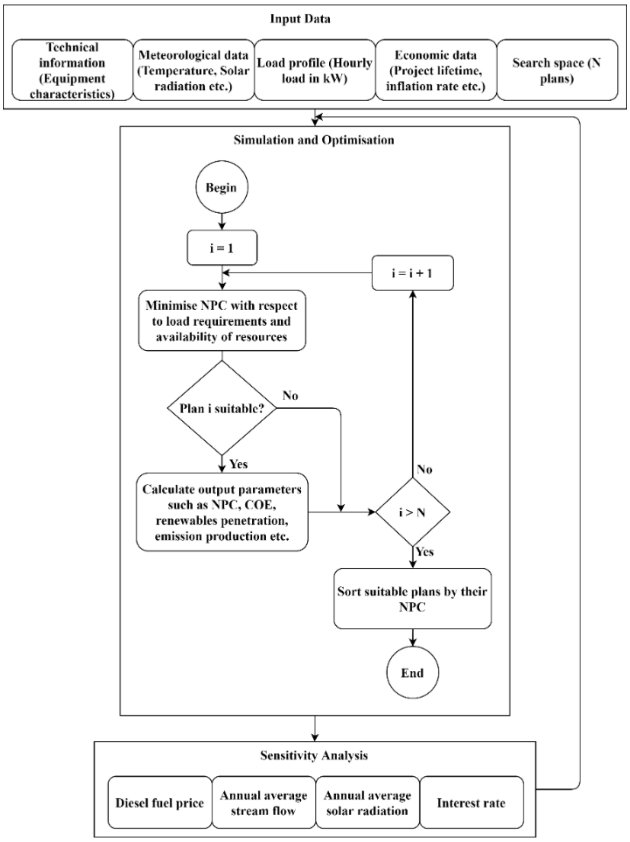


Figure 6. Flowchart showing optimization procedure

As seen from the 'Input data' section, the technical specification and cost of each renewable generation component in the proposed HRES is input into a simulation software together with the load profile and meteorological data of the case study. Economic data referred to parameters such as project lifetime and expected inflation rate. Simulation and optimization are performed by running iterations through a search space where the minimum and maximum number and size of system components are specified. After obtaining an optimized system, a sensitivity analysis is performed to gauge how variations in input variables such as diesel fuel cost, stream flow rate, and interest rate affect the overall performance of the system. This step is important if there is uncertainty in any of the input variables. For example, diesel fuel price is not a constant variable and will fluctuate according to global demand. Thus, a sensitivity analysis of diesel fuel prices for a range of values helps the designer to analyze the effect of fuel price fluctuations on the economic performance of the system.

4. Modeling of the hybrid RES

4.1 System Components

There are four main components in this hybrid system, namely, PV modules, micro-hydropower turbines, batteries, and diesel generators (DG). A bi-directional converter is also required to convert the DC power provided by PV modules/batteries to AC power for loads and AC power from diesel generators/hydropower to DC power for battery charging. A simple schematic of the overall system components connection is given in Figure 7.

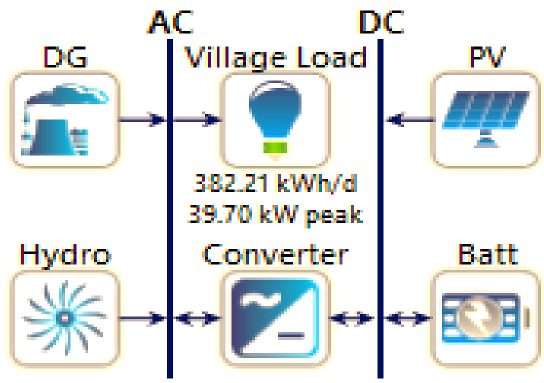


Figure 7. Schematic of the system

4.2 Dispatch Strategy

A control strategy which is called the dispatch strategy is applied to diesel generators and battery bank operation when enough renewable energy is not available to power the load. Three types of dispatch strategies, including Cycle Charging (CC), Load Following (LF), and Combined Dispatch (CD), are used. In CC strategy, whenever a diesel generator is required to be online to serve a load, it runs at full capacity, and the excess power generated would be used to charge the batteries. In the LF strategy, when a generator is required, it only runs to produce enough power to supply the required load. CD strategy intelligently moves between CC and LF strategies depending on the current netload. For low net loads, CC is used, while for high net loads, LF is used.

4.3 PV modules

LONGi Solar Hi-MO4m Monofacial Modules (LR4-72HPH-440M) were selected for this study. The specifications of this PV module under standard testing conditions of 1000 W/m^2 irradiance and cell temperature of 25°C are as follows: maximum power ($0.44kW_p$) is 440 W, open circuit voltage is 48.9 V, short circuit current is 11.46 A, maximum power voltage is 41.1 V, maximum power current is 10.71 A, and module efficiency is 20.2%. This PV module comes with a 25-year linear output power warranty; thus, 25 years is selected as the lifetime of the modules, and no replacement is needed throughout the project's lifetime. The 440 W_p the module has a market price of $230-$250; thus, the cost of the PV system is estimated to be $530/k$W_p$ [34]. A tracking system is also required to ensure the modules are always facing the sun. Tracking systems can be obtained for $100/k$W_p$, while other soft costs including installation fee, shipping, import duties, and sales tax are estimated to account for 50% of the final cost [35], giving a total capital cost of $\$1260/kW_p$. Derating factor is set to 99.45%/year which is obtained from the manufacturer's datasheet which states the module will degrade < 2% in the first year and 0.55% from years 2-25. Dust accumulations on the panels might contribute to the derating factor, however, the residents should perform periodic cleaning of the modules to prevent dust accumulation. Periodic cleaning contributes to the annual O&M costs which is set to $\$10/kW_p$/year. The power output of PV modules is calculated using Eq. 1 [36]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) [1 + \alpha_P (T_c - T_{c,STC})] \quad (1)$$

where Y_{PV} is the PV module's output power under standard test conditions (STC) (kW), f_{PV} is the PV derating factor (%), $\bar{G}_T$ is the solar radiation incident on the PV array in the current time step (kW/m^2), $\bar{G}_{T,STC}$ is the incident radiation at STC (1 kW/m^2), α_P is the temperature coefficient of power (%/°C), T_c is the PV cell temperature in the current time step (°C) and $T_{c,STC}$ is the PV cell temperature under STC (25°C). PV cell temperature and ambient temperature are different. During the day, cell temperature can exceed the ambient temperature by 30°C or more, while during the night, the cell temperature is the same as ambient temperature. Thus, the temperature can be calculated as follows [36]:

$$T_c = T_a + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{G_T}{G_{T,NOCT}}\right) (1 - \frac{\eta_{mp}}{\tau\alpha}) \quad (2)$$

where T_a is the ambient temperature (°C), $T_{c,NOCT}$ is the nominal operating cell temperature (°C), G_T is the solar radiation incident on the PV module (kW/m^2), $G_{T,NOCT}$ is the solar radiation at which nominal operating cell temperature is defined (0.8 kW/m^2), η_{mp} is the PV module's efficiency at its maximum power point (%), τ is the solar transmittance of any covering over the PV module, and α is the solar absorption factor of the PV module (%).

4.4 Hydropower

The micro hydropower turbine under consideration has the following specifications [32]:

The design flow rate is 60 L/s, minimum flow ratio is 25%, maximum flow ratio is 150%, pipe head loss is set at zero percent, and turbine efficiency is 60%. In addition, the available net head is assumed to be 25 m, which is the net head available at a dam in Long San, another village downstream of Long Moh. The cost of micro-hydropower is $1300/kW, which is obtained from previous micro-hydropower projects conducted by NGOs such as CREATE Borneo. The lifetime is 30 years, while replacement costs are $1300/kW. O&M costs are negligible and assumed to be zero. Power generated from the micro-hydro turbine can be calculated using [36]:

$$P_{hyd} = \frac{\eta_{hyd} \cdot \rho_{water} \cdot g \cdot h_{net} \cdot \dot{Q}_{turbine}}{1000W/kW} \quad (3)$$

where η_{hyd} is the hydro turbine efficiency (%), ρ_{water} is the density of water (1000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), h_{net} is the effective head (m) and $\dot{Q}_{turbine}$ is the water flow rate through the hydro turbine. For the hydro turbine flow rate, it must be more than the minimum flow rate specified; otherwise, it will be zero. Likewise, the flow rate cannot exceed the specified maximum flow rate, and if it does, it will be capped at that value. Nominal hydropower represents the size of the hydro system given streamflow equal to the design flow rate specified. The nominal hydropower for this turbine is 8.83 kW.

4.5 Diesel Generator

Diesel generators of a few sizes are considered, namely 12 kW, 33 kW, and 50 kW. The selected diesel generators are from the 50 Hz, 230V Premium Generator series. Diesel fuel consumption of the generators is 2.4 L/h for the 12-kW model, 6.18 L/h for the 33-kW model, and 12.7 L/h for the 50-kW model. The three generators cost $6000, $8700, and $12500, respectively, including transportation costs. It has an estimated lifetime of 15000 hours and a replacement cost of 50% of the capital costs. Replacement cost is lower than capital cost as only parts of the diesel generator need overhauling, and the generator is not swapped with a new unit. The O&M cost is set at 3% of the capital cost, and the minimum load ratio is set at 30%. Other important parameters of diesel fuel for emissions calculation are carbon monoxide (6.5 g/L of fuel,) proportion of fuel sulfur converted to PM 2.2%, unburned hydrocarbons (0.72 g/L of fuel), particulate matter (0.49 g/L of fuel), and nitrogen oxides (58 g/L of fuel) [12].

4.6 Batteries

A lead-acid battery of Surrette S480 Brand (6 V, 375Ah (20-hour)) is chosen for this study. The minimum state of charge is set at 40% and the efficiency at 80%. Four of these batteries are connected in series to form a DC bus voltage of 24 V. Each battery unit has a capital and replacement cost of $390, while the O&M cost of $50/year is assumed [12]. Battery quantities of 0-20 batteries with 4 battery intervals are considered.

4.7 Converter

A bidirectional converter is needed to convert AC to DC and vice versa. The converter is assumed to have the specifications as follows [14]:

Rectifier and inverter efficiency of 95%, capital and replacement cost of $900/kW, O&M cost of $1/kW/year, and a lifetime of 10 years. Converter sizes of 0-10kW with 1kW intervals are considered. A summary of the component's techno-economic parameters is given in Table 3 (Appendix).

4.8 Economic Modelling

For each plan in the search space, the aim is to minimize NPC required while being susceptible to constraints such as whether the system can satisfy the load demand. NPC is defined as the cost incurred by a system over its project lifetime, minus its revenue. Cost includes capital cost, fuel cost, operation and maintenance (O&M) cost, and replacement cost, while revenue is the salvage value which is simply the value remaining in a component at the end of the project lifetime. The salvage value is calculated as follows [36]:

$$S = C_{rep} \cdot \frac{R_{comp} - [R_{proj} - (R_{comp} \cdot INT\left(\frac{R_{proj}}{R_{comp}}\right))]}{R_{comp}} \quad (4)$$

where C_{rep} is the replacement cost ($), R_{comp} is the component lifetime (years), R_{proj} is the project lifetime (years), and INT() is a function that rounds down a real number to the nearest integer. Real interest rate is used in the calculation between one-time costs and annualized costs and is given by the formula [36]:

$$i = \frac{i' - f}{1 + f} \quad (5)$$

where i' is the nominal interest rate (%) (the rate at which borrowing occurs), and f is the expected inflation rate over the project lifetime (%). By implementing a real interest rate, inflation can effectively be factored out from the economic analysis. Another important parameter is the COE, which is defined as the average cost per kWh of useful electrical energy produced by the system. It is calculated by dividing the annualized cost of electricity production by the total electric load supplied. In this study, a nominal interest rate of 6% and an inflation rate of 2% is set [37].

5. Results and discussion

5.1 Overview

In this section, the optimized system, together with its techno-economic, environmental, and sensitivity analyses, are presented below. An overview of the most optimized systems in their respective categories is tabulated in Table 4 (Appendix). The systems are sorted according to their NPC in ascending order. Out of 3,492 computer simulations, only 1,836 were feasible, and the best five systems of each configuration are analyzed. The configurations are Hydro/DG/Battery, PV/Hydro/DG/Battery, Hydro/DG, PV/Hydro/DG, and standalone DG.

The most optimal system is the Hydro/DG/Battery system with a 33 kW DG, 4 batteries, 2 kW Converter, and LF dispatch strategy. It has an NPC of $213,694.90 and a COE of $0.08/kWh. It has the second-lowest operating cost (OC) of $9,495.56/year and the third lowest initial investment required (IC) of $23,537.70. This system has a renewable fraction (RF) of 45.72% with a diesel fuel consumption (FC) of 14,642.17L/year. Excess electricity of 11.67% is produced with a 0% unmet load. Compared to the third-best performing system, which is a Hydro/DG system, adding the battery helps to bring down all the recorded parameters significantly at the expense of a slightly higher IC. This shows the importance of an ESS in a renewable energy system.

By choosing the Hydro/DG/Battery system instead of the Hydro/DG system, a simple payback of 4.1 years can be achieved with a return on investment (ROI) of 25.1%, which is the yearly cost savings relative to the initial investment.

The worst performing system is the standalone DG system with a 50 kW DG implementing a CC dispatch strategy. It has an NPC of $346,222.60, COE of $0.12/kWh, and OC of $16,664.54, which are 62%, 62.1%, and 75.5% larger than the Hydro/DG/Battery system. However, it has the lowest IC required at $12,500, which is the cost of the 50-kW diesel generator. FC is also the highest at 30,743.16 L of fuel consumed a year, contributing to 75% of the OC annually. Figure 8 shows a comparison between the standalone DG system and the best performing Hydro/DG/Battery system. For the first year, the standalone DG system will have a lower cost overall; however, after 1.4 years, the cumulative cost for the Hydro/DG/Battery system becomes lower than that of the standalone DG system. An ROI of 62.1% is also reported.

The initially proposed system of PV/Hydro/DG/Battery has the lowest OC ($9,149.15/year), which is $346.41 less than the Hydro/DG/Battery system. However, it has a $10,822.90 higher NPC ($224,517.80) and a $13,510 higher IC ($37,037.70). The OC is not low enough to justify switching to the proposed system, as shown in Figure 9. Throughout the project lifetime simulation of 40 years, simple payback is not possible, and consequently, an ROI of 0% is recorded. Thus, economically, the proposed system is not the most optimal configuration in this scenario. However, this system has the highest RF of 52.8% and thus the lowest diesel FC of 12,863.63 L/year, making it the most environmentally friendly system.

5.2 Hybrid Hydro/DG/Battery system analysis

The best performing system has the following specifications:
8.83 kW of hydropower,
33 kW of DG,
4 units of batteries,
A 2-kW converter and using LF dispatch strategy. A breakdown of the costs involved in this system is given in Figure 10.

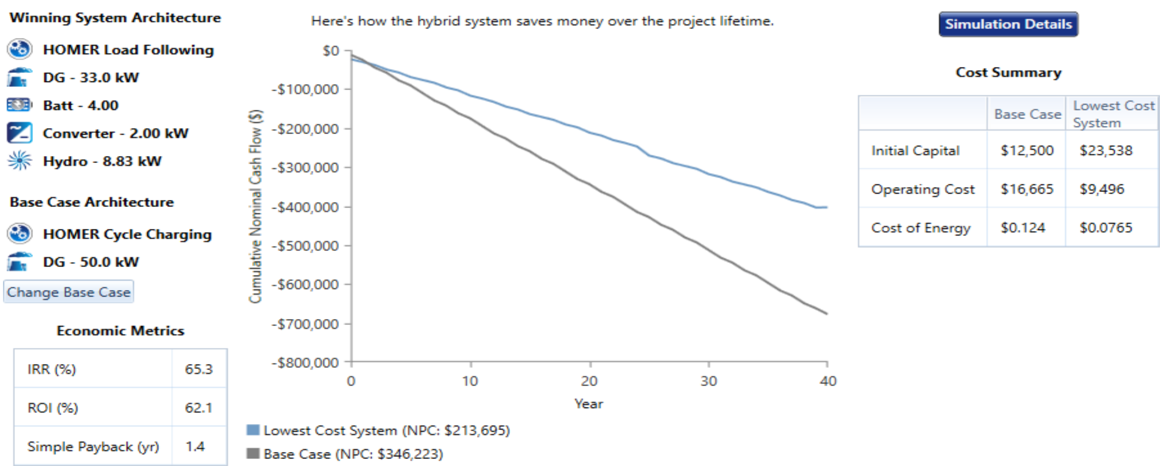


Figure 8. Hydro/DG/Batt vs DG

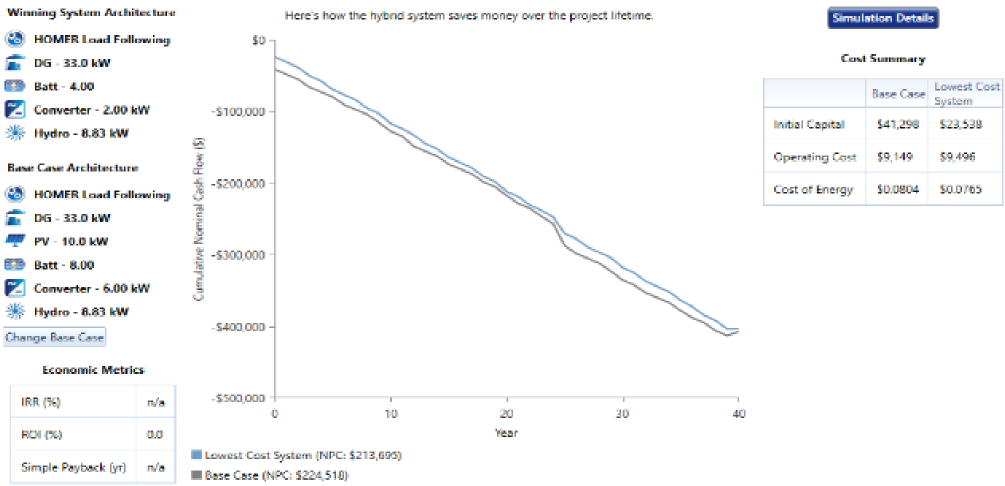
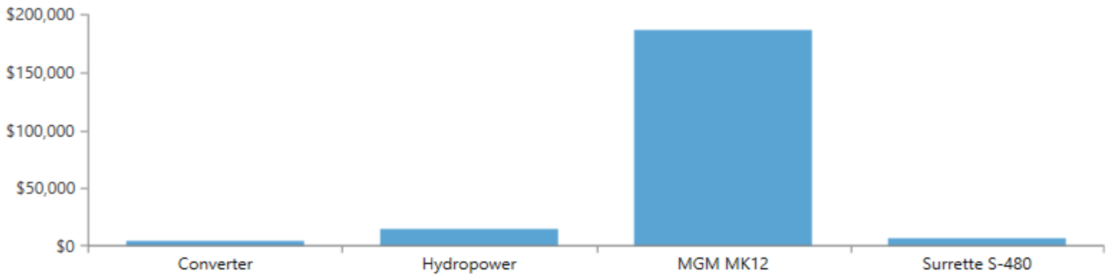


Figure 9. Hydro/DG/Batt vs PV/Hydro/DG/Batt



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Converter	$1,800.00	$2,626.89	$40.05	$0.00	$0.00	$4,466.94
Hydropower	$11,477.70	$4,387.45	$200.26	$0.00	-$985.57	$15,079.84
MGM MK12	$8,700.00	$34,446.75	$21,015.38	$123,153.56	-$503.02	$186,812.67
Surrette S-480	$1,560.00	$1,993.53	$4,005.18	$0.00	-$223.26	$7,335.45
System	$23,537.70	$43,454.62	$25,260.88	$123,153.56	-$1,711.84	$213,694.91

Figure 10. Cost Summary for Hydro/DG/Battery system (Cost type: Net Present)

Production	kWh/yr	%
MGM MK12	75,724	47.9
Hydro	82,392	52.1
Total	158,116	100

Consumption	kWh/yr	%
AC Primary Load	139,507	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	139,507	100

Quantity	kWh/yr	%
Excess Electricity	18,452	11.7
Unmet Electric Load	0	0
Capacity Shortage	28.5	0.0204

Quantity	Value	Units
Renewable Fraction	45.7	%
Max. Renew. Penetration	173	%

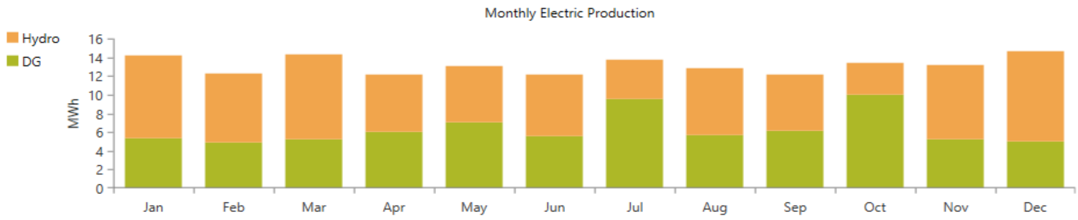


Figure 11. Electrical Analysis for Hydro/DG/Battery system

Diesel power has the highest contribution to the NPC of the system at 87.4% of the total NPC, and 65.9% of diesel power's total NPC is used by diesel fuel costs. Hydropower has the highest capital cost, but it has minimal O&M replacement cost due to the turbine having a lifetime of 30 years. Battery and converter costs are minimal due to their low quantities and sizes. From Figure 11, the fraction of energy generated by hydro is proportional to the streamflow, which is the highest in December and the lowest in October. Consequently, the energy generated by DG is inversely proportional to streamflow as DG compensates for the remaining load that hydropower is unable to supply. Overall, this system produced the lowest excess electricity of 11.7%, with a 0% unmet load. Some excess electricity is required as an operating reserve, which is set as 10% load in the current time step. Power draw is not constant and will fluctuate unpredictably. Without an operating reserve, the power draw will exceed the capacity of the power system leading to an increase in unmet electric load. Capacity shortage differs from the unmet load as capacity shortage considers both unmet load and unmet operating reserve. Figure 12 shows the power sources plot, which plots the total electrical load, DG power output, hydropower output, and battery input power daily for the whole year. DG is the main source of energy for this system which explains its 87.4% contribution to the NPC. In the months of July and October, when streamflow is the lowest, the DG operates continuously and does not switch off. Input power to the battery is approximately zero during these two months as the DG is operating at full capacity to supply the electrical load.

5.3 Environmental Analysis

DGs generate power from the combustion of diesel fuel, which releases pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), particulate matter (PM), and sulfur dioxide (SO_2) and nitrogen oxides (NOx). Pollutant emissions for the top 5 performing systems are presented in Table 5 (Appendix). Emissions are proportional to the amount of diesel fuel consumed by the system annually in g/L.

The system with the least amount of pollutants is the proposed PV/Hydro/DG/Battery system having the least emissions of CO_2 (33,874 kg/year), CO (83.6 kg/year), UHC (9.26 kg/year), PM (6.3 kg/year), SO_2 (82.5 kg/year), and NOx (746 kg/year) due to its high renewables penetration. In comparison to the worst environmentally friendly system (DG), emissions savings of 58.2% are recorded for all pollutants. The optimal Hydro/DG/Battery system has an emission saving of 52.4% compared to the standalone DG system. Emissions can be reduced further by switching to a more efficient DG that uses a higher grade of diesel fuel, such as Euro5 diesel.

5.4 Sensitivity Analysis

In this study, sensitivity variables selected are diesel fuel prices, annual average streamflow, annual average solar radiation, and interest rate. These variables have the most uncertainty and are expected to change throughout the projects' lifetime. The variables are modified to ±50% of their original values with 25% of increments, as shown in Table 6 (Appendix). The result of the sensitivity analysis of the optimal system (DG/Hydro/Batt) is presented in Figure 13. Even with considering a 50% increase in diesel fuel price from \$0.42 to \$0.63, Hydro/DG/Battery is still the most optimal choice in terms of NPC. Annual average solar radiation is increased to give PV modules a higher energy generation potential, but the constant power flow from hydro is still the winner in this analysis. NPC increases with diesel fuel price changes as expected which varies from a minimum of \$152,118.10 to a maximum of \$274,592.20 with ±50% fluctuations in the diesel fuel price. The system configuration remains the same as before when the diesel fuel price reaches \$0.525/L and above, and the power converter is increased from 2 kW to 3 kW. Next, the sensitivity variables are diesel fuel price and annual average streamflow. The results obtained are illustrated in Figure 14.

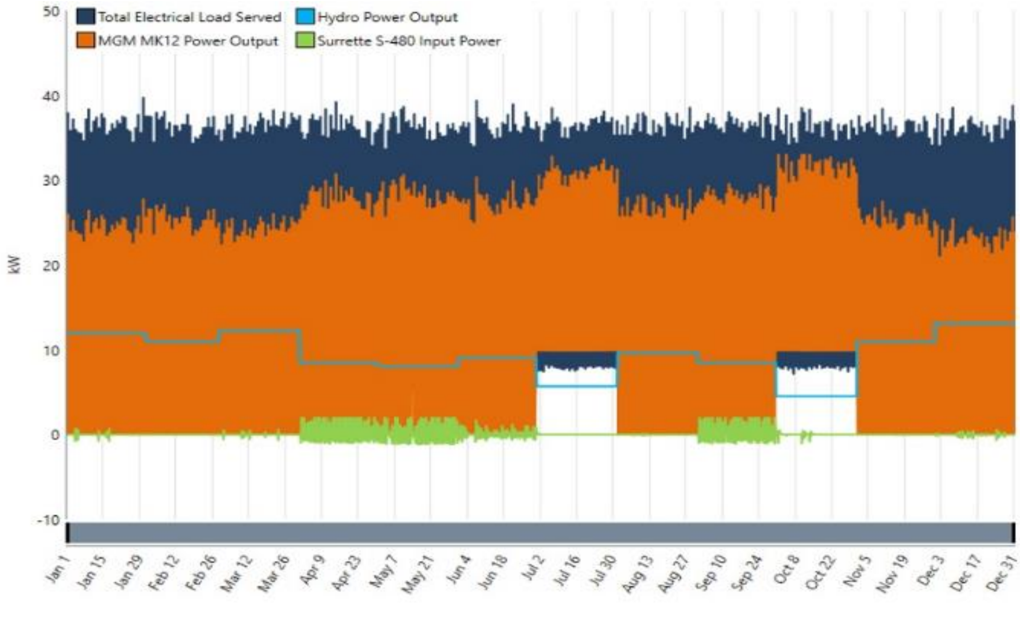


Figure 12. Power Sources plot for Hydro/DG/Battery system

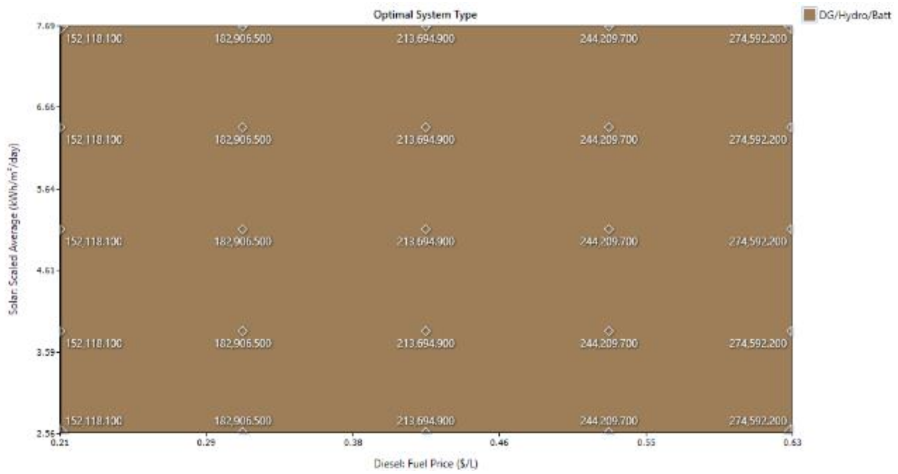


Figure 13. Sensitivity analysis of diesel fuel price vs annual average solar radiation with superimposed total NPC

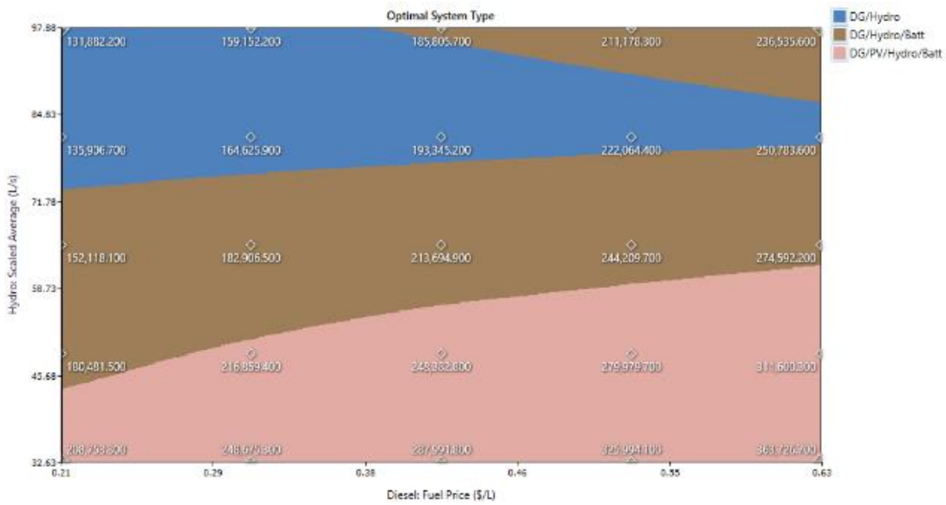


Figure 14. Sensitivity analysis of diesel fuel price vs annual average streamflow with superimposed total NPC

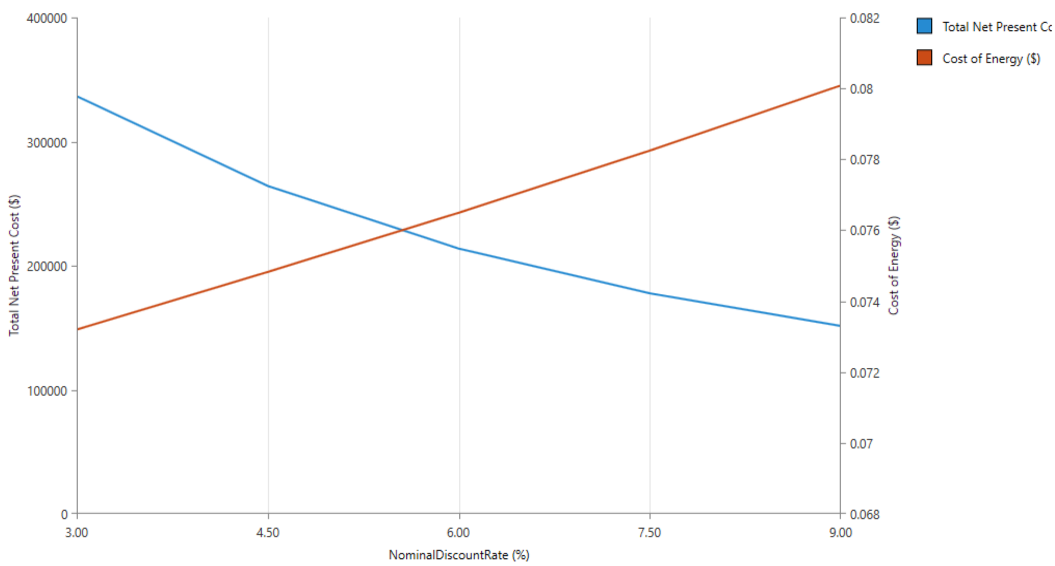


Figure 15. Graph of NPC and COE against interest rate

The system with the lowest NPC is a DG/Hydro system with 33 kW DG, 8.83 kW hydro, diesel fuel price of $0.21, and annual average streamflow of 97.9 L/s. The most optimal system varies between DG/Hydro, DG/Hydro/Battery, and DG/PV/Hydro/Battery.

The proposed DG/PV/Hydro/Battery system with 10 kW PV, 33 kW DG, 8.83 kW hydro, 8-12 batteries, and a 7-8 kW converter is the best choice when the scaled average of hydropower drops below 48.9 L/s. A minimum NPC of $131,882.20 is recorded with the highest streamflow and lowest diesel fuel price, while a maximum NPC of $363,726.70 is recorded with the highest diesel fuel price and lowest streamflow. The relation between the nominal discount rate, that is, the interest rate, the total NPC, and COE, are plotted in Figure 15. The nominal discount rates are set from 3% to 9% to realize the effect of changes in nominal discount rates on COE and NPC. Total NPC decreases with an increase in the nominal discount rate. This is because total NPC is the present value of all cash flows in the system. With an increase in interest rate, the present value of future cash flow decreases. On the other hand, COE increases slightly with an increase in interest rate. An increase in interest rate decreases the salvage value of components which results in a higher COE. The intersection between NPC and COE occurs at ~5.75% representing the point at which the system is most economical.

6. Conclusion

This study presented an environmental and techno-economic analysis of an off-grid HRES for the electrification of a rural village in Marudi, Sarawak, Malaysia. The initially proposed system was a hybrid PV/Hydro/DG/Battery system; however, the most economical system based on the computer simulation is a hybrid Hydro/DG/Battery system. The final Hydro/DG/Battery system consists of an 8.83 kW hydro generator, 33 kW DG, 1 string of 4 units of 6V batteries, 2 kW converter with an LF dispatch strategy. This system has an NPC of $168,831.30, COE of $0.08/kWh, OC of $9223.59/year, IC of $23,537.70, and RF of 45.72%. Excess electricity of 11.7% is recorded, which is acceptable to meet the 10% operating reserve. Environmentally, this system produces 52.4% fewer emissions compared to the standalone DG system, which greatly helps in maintaining the green environment of the rural village. The emissions will affect the residents' health and produce unwanted environmental impacts such as smog. Economically, the hybrid Hydro/DG/Battery system has a simple payback of 1.4 years and an ROI of 62% when compared to the standalone DG system. However, the proposed PV/Hydro/DG/Battery system is the most environmentally friendly system with the lowest diesel fuel consumption of 12,863.63 L/year and the lowest pollutant emission production. It also has the lowest OC at $9,149.15, but the NPC is significantly higher than the optimal system (Hydro/DG/Battery) at $224,517.80, such that a simple payback is not possible when comparing the two systems. Sensitivity analysis was performed to see whether the optimal configuration changes with ±50% changes in diesel fuel price, annual average streamflow, and annual average solar radiation. The Hydro/DG/Battery system is the most optimal choice in the sensitivity analysis of diesel fuel price and average solar radiation. For the analysis of diesel fuel price and average streamflow, DG/Hydro/Battery system is only optimal when the average streamflow is more than 58.73 L/s. Average streamflow lower than 58.73 L/s would result in PV/DG/Hydro/Battery is the most optimal choice. NPC and COE values increase with an increase in diesel fuel price and a decrease in annual average streamflow. The interest rate is also varied to determine its economic impact on the system. It was observed that an increase in interest rate leads to an increase in NPC and a decrease in COE. According to the results above, a hybrid Hydro/DG/Battery system is the most optimal option with justifiable trade-offs for a slightly higher environmental impact. The initial investment required of $23,537.70 was reasonable considering that the village has a population of 308. Rural electrification is a priority; given the impact it brings on the socio-economic development of the country.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

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Appendix

Table 1. Summary of the techno-economic studies conducted for HRESs

Main HRES	Location	Daily Electrical Load (kWh/day)	System Components	NPC ($)	Ref.
PV/DG/Battery	Harbin, China	2300	500kW PV, 1250kW DG, 600 Surette S460 batteries	8,162,822	[12]
PV/DG/Battery	Pulau Banggi, Sabah, Malaysia	6632.86	800kW PV, 630kW DG, 2880 kWh batteries	9,345,510	[13]
PV/DG/Battery	Benin, Africa	679.77	150kW PV, 50kW DG, 98 H3250 batteries	555,492	[18]
PV/Hydro/Wind/DG/Battery	Imo, Nigeria	3853	50kW PV, 94.1kW Hydro, 1kW Wind, 150kW DG, 111kWh batteries	1,007,995	[21]
PV/Wind /DG/Battery	Compound 1, Al-Jubail, Saudi Arabia	11,160	580kW PV, 550kW Wind, 1800kW DG, 880 Surette 4KS25P batteries	9,620,000	[22]
PV/Hydro/DG/Battery	Sakran, Iraq	23.29	13kW PV, 14.7kW Hydro, 5kW DG, 8 Surette 6CS25P batteries	113.201	[23]

Table 2. Load Demand Assessment for Long Moh

Load Categories	Components	Power Draw (W)	Units	Hours Active (hours/day)	Daily power consumption (kWh/day)	Time
Household 2 bed 1 bath	Ceiling Fan	75	1	6	0.45	4pm-10pm
	Standing Fan	50	2	9	0.9	10pm-7am
	Fluorescent Lamp	32	4	5.75	0.736	3 units, 6am-7am, 7pm-10pm, 1 unit 7pm-6am
	LED TV + Set-Top Box	110	1	4	0.44	5pm-9pm
	Washing Machine	320	1	0.3	0.096	1 hour every 3 days
	Water Pump (0.5hp)	370	1	2	0.74	2 hours a day
	Fridge	80	1	24	1.92	24 hours
Household Total					5.282	
70 Households Total					**369.74**	
Primary School 100 students, 4 classrooms office, canteen	Ceiling Fan	75	6	8	3.6	7am-3pm
	Fluorescent Lamp	32	12	8.5	3.264	10 units 7am-3pm, 2 units 7pm-6am
	Water Pump (1hp)	750	1	4	3	2 hours a day
School Total					**9.864**	
Community Church	Ceiling Fan	75	4	0.43	0.129	3 hours a week
	Fluorescent Lamp	32	8	0.43	0.11008	3 hours a week
Church Total					**0.23908**	
Village Store	Standing Fan	50	2	12	1.2	8am-8pm
	Fluorescent Lamp	32	5	5	0.8	8am-10am, 5pm-8pm
	Water Pump (0.5hp)	370	1	1	0.37	1 hour a day
Store Total					**2.37**	
Village Total					**382.21308**	

Table 3. Summary of proposed components' specifications

Component	Parameter	Specification	Component	Parameter	Specification
PV	Power Sizing	0-40kW, 10kW intervals	Diesel Generator	Power Sizing	12,33,50kW
	Derating Factor	99.45%		Minimum Load Ratio	30%
	Temperature Coefficient	-0.35%/°C		Lifetime	15000 hours
	Nominal Operating Cell Temperature	45°C		Capital Cost	$6000,8700,12500
	Efficiency	20.20%		Replacement Cost	50% of capital cost
	Lifetime	25 years		O&M Cost	3% of capital cost
	Capital Cost	$1260/kW			
	Replacement Cost	$1260/kW			
	O&M cost	$10/kW/year			
Hydropower	Design Flow Rate	60L/s	Batteries	Nominal Voltage	6V
	Minimum Flow Ratio	25%		Capacity	375Ah/20hour
	Maximum Flow Ratio	150%		Lifetime	12 years
	Pipe Head Loss	0%		Capital Cost	$390
	Turbine Efficiency	60%		Replacement Cost	$390
	Net Head	25m		O&M Cost	$50/year
	Lifetime	30 years		Batteries per string	4
	Capital Cost	$1300/kW		String Size	0-5, 1 string intervals
	Replacement Cost	$1300/kW			
	O&M cost	$0/kW/year			
Converter	Power Sizing	0-10kW, 1kW intervals	Diesel Fuel	Cost	$0.42
	Efficiency	95%		Carbon Monoxide	6.5g/L
	Lifetime	10 years		Unburned Hydrocarbons	0.72g/L
	Capital Cost	$900/kW		Particulate Matter	0.49g/L
	Replacement Cost	$900/kW		Proportion of Fuel Sulphur converted to PM	2.20%
	O&M cost	$1/kW/year		Nitrogen Oxides	58g/L

Table 4. Results from computer analysis

System Configuration	PV (kW)	Hydro (kW)	DG (kW)	Batt (Unit)	Conv (kW)	NPC ($)	COE ($/kWh)	OC ($/yr)	IC ($)	RF (%)	FC (L/yr)	Excess (%)	Unmet (%)
Hydro/DG/Batt	-	8.83	33.00	4.00	2.00	213,694.90	0.08	9,495.56	23,537.70	45.72	14,642.17	11.67	0
PV/Hydro/DG/Batt	10.00	8.83	33.00	4.00	3.00	224,517.80	0.08	9,149.15	37,037.70	52.79	12,863.63	16.24	0
Hydro/DG	-	8.83	33.00	-	-	229,164.90	0.08	10,435.84	20,177.70	37.64	16,622.58	17.64	0.002
PV/Hydro/DG	10.00	8.83	33.00	-	2.00	239,287.90	0.09	10,222.27	34,577.70	41.42	15,652.74	23.70	0.002
DG	-	-	50.00	-	-	346,222.60	0.12	16,664.54	12,500.00	-	30,743.16	12.84	0

Table 5. Pollutant emissions from top 5 best performing systems

System Configuration	CO2 (kg/yr)	CO (kg/yr)	UHC (kg/yr)	PM (kg/yr)	SO2 (kg/yr)	NOx (kg/yr)
Hydro/DG/Batt	38,558.00	95.20	10.50	7.17	93.90	849.00
PV/Hydro/DG/Batt	33,874.00	83.60	9.260	6.30	82.50	746.00
Hydro/DG	43,773.00	108.00	12.00	8.15	107.00	964.00
PV/Hydro/DG	41,219.00	102.00	11.30	7.67	100.00	908.00
DG	80,957.00	200.00	22.10	15.10	197.00	1,783.00

Table 6. Sensitivity variables and their respective values

Sensitivity Variables	Values
Diesel fuel price ($)	0.21, 0.315, 0.42, 0.525, 0.63
Annual average stream flow (L/s)	32.63, 48.94, 65.25, 81.56, 97.88
Annual average solar radiation (kWh/m^2/day)	2.562, 3.843, 5.124, 6.405, 7.686
Interest rate (%)	3, 4.5, 6, 7.5, 9