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Design and Techno-Economic Analysis of a Hydrogen-Based Micro Hydro-Solar Hybrid Energy System for Sustainable Energy Access: A Case Study in Sri Aman, Sarawak

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***Abstract*—Several rural areas in Sarawak do not have access to electricity. In Sarawak, most investigations prioritize conventional sources despite the emergence of technology such as fuel cells. Furthermore, diversified investigations on stand-alone hybrid renewable energy systems in Sarawak are lacking. This study aims to fill this gap by investigating the feasibility of a stand-alone hybrid renewable energy system for rural applications in Sarawak, with a specific focus on the potential benefits of incorporating hydrogen. Different configurations, namely A: Photovoltaic, hydrogen, micro-hydro, B: hydrogen, micro-hydro, C: micro-hydro, D: photovoltaic, and micro-hydro was explored, each with its results, and comparisons were performed between them. By analyzing the system under various load patterns and conducting a sensitivity analysis, the researchers found that scenario A was the most cost-effective and reliable option for a longhouse in Sri Aman, with a net present cost of $148,687, cost of energy of $0.19/kWh, and initial capital of $107,207. Simultaneously, scenario A has the highest annual generating capacity of up to 116521kWh annually. Sensitivity analysis revealed that the electrolyzer could impact the cost of the system. The electrolyzer is the third and second most expensive in scenarios A and B. This research demonstrates the potential of alternative energy sources to improve access to electricity in rural areas. It highlights the importance of continued exploration into emerging technologies to ensure everyone can access safe and reliable electricity.**

***Index Terms*—HOMER pro, hybrid renewable energy system, hydrogen, longhouse, micro-hydro, rural electrification, sarawak, solar, techno-economic**

NOMENCLATURE

AC: Alternating Current
PV: Photovoltaic
COE: Cost of Energy
USD: United State Dollars
DC: Direct Current
NPC: Net Present Cost
EFB: Empty Fruit Bunch
FC: Fuel Cell
O&M: Operation and Maintenance
GCV: Gross Calorific Value
HRES: Hybrid Renewable Energy System

I. INTRODUCTION

Electricity is one of the enablers for the development of communities and human society. With that, there have been advancements, such as using renewable energy sources for rural electrification. In Malaysia, authorities have set several initiatives, such as Petronas Power Sdn Bhd, to ensure rural communities obtain a safe and reliable electricity supply [1]. In the Malaysian state of Sarawak, rural electrification initiatives have been ramped up due to geographical restrictions, which causes grid extensions to be unfavorable. The local electrical utility company targets full state electrification by 2025 [2]. They launched several stand-alone renewable systems, mainly solar and mini-hydro energy, to help electrify rural communities. They have also recently signed an agreement to investigate the possibility of using Fuel Cells (FC) for rural electrification [3]. Rural electrification is also discussed in countries such as India and China.

Despite numerous publications and talks on rural electrification in Sarawak, some gaps hamper the effectiveness of these initiatives. Firstly, most publications focus on conventional sources, mainly solar, wind, hydro, and biomass [4], notwithstanding the emergence of technologies such as FC. Next, a stand-

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alone hybrid renewable energy system (HRES) has yet to be significant in Sarawak. Furthermore, some areas in Sarawak have yet to be electrified.

This study aims to design and optimize a stand-alone HRES in Sarawak for rural applications. This HRES will contain several sources to support its load, a longhouse based in Sri Aman. The components of this HRES will be sized before input into the HOMER Pro software. After simulating HOEMR Pro, a techno-economic analysis will be executed on the HRES to determine its overall feasibility. This study will also investigate the potential of hydrogen for rural electrification purposes by adding a hydrogen system to the HRES. Several load patterns will be assumed for the HRES, leading to more realistic assumptions on consumption patterns of the load. The variety of load patterns will also be considered when setting up the simulation in HOMER Pro.

As research on hydrogen energy for rural electrification has yet to be significant, it is hoped that this work can help attract attention to integrating hydrogen energy into rural electrification solutions. On top of this, this work focuses on rural electrification in Sarawak; hence this work hopes to encourage the development of stand-alone HRES in Sarawak.

II. PREVIOUS RURAL ELECTRIFICATION STUDIES

This section will focus on past rural electrification studies to give some insights into the nature of rural electrification and the general analysis of the respective system. The areas covered in Sarawak include Tatau [5], Kapit, Limbang, Sri Aman [6], Lundu [7], and Samarahan [8]. Areas outside of Sarawak that are covered include India [9], China [10], and Iran [11].

Generally, solar energy is a common pick for rural electrification, as most of the examined works, such as [5, 7, 11], utilize solar. The necessary technology to implement a stand-alone solar energy system has matured, and most of the successful rural electrification projects in Malaysia were reported to be using solar energy [5], hence a strong indication of its maturity as a solution. Despite this, it still has a relatively high cost compared to other solutions. John *et al.* [5] found that a stand-alone solar energy system is the most expensive between wind, biomass, and mini-hydro systems. Regardless, they still justified that Malaysia's consistent availability of energy and high solar irradiance can make up for its high cost. Furthermore, their cost analysis covers the manufacturing of the necessary components, hence the need for the materials for those components.

The hydro-powered system is popular in Sarawak due to its geographical advantage. Due to that, a hydro-powered system can generate large amounts of power, as seen in [6], where their HRES combinations that have hydro generate more energy than those without it. They also found that the hydro system has the highest annual power production compared to their other systems. This can be the cause for the high generating capacity of hydro-supported HRES.

Another interesting result from [6] is that the biomass-powered system generates the same amount of power across all three areas. This is attributed to the generators operating at maximum capacity across all the areas and the limited capacity of Empty Fruit Bunch (EFB). This may indicate the limits a biomass system may have for rural electrification. The study in India by [9] has also limited their biomass system to cooking fuel, hence may give further implications on how limited biomass systems are used for rural electrification.

The wind energy system was part of the investigation by [7] for a Photovoltaic (PV)-wind HRES. Their investigation revealed that wind is very pricey, as seen in Fig. 1. This can be attributed to the poor advancements of wind energy in Malaysia, leading to its high costs compared to solar, which has become cheaper after several decades of development.

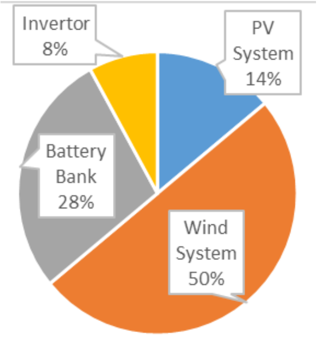


Fig. 1. Total distribution cost of PV-wind HRES.

The wind energy system is responsible for half of the overall cost distribution of the HRES, making it the most expensive system for the HRES. A sensitivity analysis found that the HRES is most sensitive to the wind energy system, meaning the wind energy system can drastically alter the overall costs of the HRES. This, along with the low wind speed in Sarawak, justifies that applying wind energy for rural electrification in Sarawak may not be viable compared to other countries such as China [10] and Iran [11]. Hence, wind energy will not be considered for this study.

Li *et al.* [10] designed and optimized a hybrid PV-wind-biogas system supported by 1kWh lithium batteries for a village in West China. A hydrogen production and storage system was also designed to cater to the hydrogen load. HOMER Pro was used for simulation purposes. The PV-wind-biogas-battery combination gave the lowest net present Cost (NPC) and the lowest amount of excess electricity, hence the most optimized design. The electrolyzer uses energy from the designed hybrid system for hydrogen production.

Rad *et al.* [11] also considered a hybrid PV-wind-biogas-FC system for an Iranian village for grid-connected and off-grid purposes. The off-grid mode is the focus here. HOMER Pro was used to obtain the ratings and economics of this HRES. The FC and electrolyzer ratings are significantly lower than the PV rating. Despite this, the hydrogen system increases the overall costs, especially the cost of energy (COE). However, it improves reliability by providing consistent energy during the downtime of other renewables, such as wind energy. The PV-biogas-battery configuration is ideal for low COE, NPC, operations, maintenance (O&M), and capital costs for off-grid purposes.

In this study, a performance comparison between natural gas reformer and an electrolyzer is performed to see which is more efficient for hydrogen production. The natural gas reformer option leads to lower costs, but delivering natural gas to rural areas is challenging, especially if it does not have grid connectivity. The results also show that despite its high cost, the proposed hydrogen system would contribute a small fraction of the overall generation.

Besides the discussed works, there are other initiatives for researching the possibilities of rural electrification in other areas. Regardless, a few common traits were observed.

Unconventional sources, namely FC, were investigated in other countries despite hydrogen technology yet being mature to be a conventional choice. In Sarawak, there has been the deployment of hydrogen vehicles and an integrated hydrogen production plant and refueling station [12] but using hydrogen for rural electrification is still under research [3]. Regardless, there were research initiatives on FC for works such as residential purposes in Malaysia [13] and Japan [14], the greenhouse in Turkey [15], and a community health clinic in South Africa [16].

Costs such as NPC, COE, O&M, and Capital are the financial focus. A sensitivity test should be performed to examine how sensitive the HRES is concerning the given parameters, such as cost [7] and load demand [10]. The parameters to design a HRES are generally the same, as seen in how solar irradiance is taken to size the solar energy system [5, 7, 9], flow rate to size the hydro system [5, 6], biomass resources to size the biomass energy system [5, 6, 9], and wind speed for the wind energy component [5–7]. These traits are also observed in the works at different locations, such as in Pakistan [17, 18], and Ghana [19], as well as in other parts of Sarawak, such as Bario [20].

The common software used is HOMER Pro. According to [21], it is commonly used to evaluate stand-alone HRES for rural electrification, and based on the examined sources, this software is a common choice. MATLAB is another common tool in sizing the HRES, but the procedure for this project does not require such a level of complexity. Hence MATLAB is not considered.

Overall, the literature review showed a variety of coverage on rural electrification. PV and hydropower systems are the more common choices for rural electrification, especially in Sarawak. Investigations on hydrogen-based technologies for rural electrification in Sarawak have not been identified. Hence, this work can lay the foundation for investigating hydrogen energy for rural electrification. On top of this, the identified rural electrification studies only utilized one load pattern, which does not accurately display other scenarios, such as festive seasons. This work will assume several realistic load patterns, which will be used to analyze the potential of the proposed stand-alone HRES.

This work will still have some limitations that are similar to or different from the other works discussed in the literature review. Realistic assumptions will be heavily used to obtain the necessary data for sizing the HRES. Information such as load patterns and the efficiency of the components will be assumed accordingly. On top of this, this work will rely on HOMER Pro to obtain the optimized designs. This may make the design slightly less optimal over works that used optimization algorithms to improve their respective designs. Finally, this work will focus on techno-economic strategy to analyze the results obtained from HOMER Pro. Hence, the analysis will not cover other matters, such as the control strategies of the proposed HRES.

III. STRUCTURE OF NETWORK

A. *Solar Energy*

Solar energy is defined as the energy from the sun that can be harnessed via the use of PV cells which could be used to create PV panels. As the sun's energy source, energy is readily available, provided the panels obtain the necessary sunlight. Regardless, it is normally complemented with another renewable source or a battery energy storage system (BESS) due to its dependence on the sun.

It is worth emphasizing the output of the PV panels is Direct Current (DC). With that, an inverter is connected after the panels to change the electrical current from DC to Alternating Current (AC). Simultaneously, a BESS would be connected to a DC/DC converter and the inverter. This way, both sources can help contribute to the load as AC.

One of the most crucial parameters to PV system design is sun hours. Sun hours are the general duration of sufficient sunlight for the PV system to generate electrical power. The daily peak sun hours can be used to design the capacity of the PV array by using equation 1 as given in [22].

$$P_{\text{array}} = \frac{W_{\text{demand (DC)}}}{PSH \times \eta_{\text{batt}} \times \text{DF}_{\text{PV}}} \tag{1}$$

where PSH is the daily peak sun hours during the critical design month, n_{batt} is the efficiency of the battery, and DF_{PV} is the de-rating factor of the PV array. DF_{PV} can be taken as 80%, with reference from [23]. $W_{\text{demand (DC)}}$ is the equivalent average DC load daily demand during the critical Month. This can be calculated using equation 2 as given in [22].

$$W_{\text{demand (DC)}} = W_{\text{DC}} + \frac{W_{\text{AC}}}{\eta_{\text{inv}}} \tag{2}$$

where W_{DC} is the average DC load daily consumption, W_{AC} is the average AC load daily consumption, and n_{inv} is the efficiency of the inverter.

B. *Hydropower Energy*

Hydropower relies on the motion of water to generate electricity accordingly. Hydropower plants can be divided according to their power output [24]. Micro-hydro would be the focus as its power output is generally within the suitable range for rural electrification projects. When designing a micro-hydro power plant, equation 3 is expressed as mentioned in [25].

$$P_t = \rho \times g \times H_n \times Q \times \eta_t \tag{3}$$

where P_t is the turbine power, Q is the flow rate, η_t is its efficiency, H_n is the net head, and ρ is the density of water.

C. Biomass Energy

Combustion of biomass, such as EFB, can be performed to power the generator. This is like using diesel generators but is less favored due to environmental reasons. The biomass potential depends on the type of bioresource available within the area. The recent works utilize animal manure or EFB as they are consistently produced. On the other hand, raw rice straw may not be ideal as it has high moisture content and low Gross Calorific Value (GCV) [26]. Hence, a site survey is needed to investigate the available biomass and obtain other information, such as climate and topography [27].

D. Hydrogen Energy

FC technology uses the chemical energy obtained from the oxidation of hydrogen, generating free-moving electrons, which will constitute electrical energy when connected to a circuit. Realistically, this action can only generate roughly 0.6 V to 0.8 V [28]. Multiple cells are combined to form a stack, increasing voltage and power output.

The usage of hydrogen energy for rural electrification was found to be possible after Schöne did a review on hydrogen and its capability towards universal access to energy [29]. It was found that hydrogen can be used as a backup energy supply for small-scale off-grid villages. Hence, this may imply the possibility of integrating hydrogen into off-grid HRES.

As seen in the work of [11], it is possible to implement FC in rural electrification projects. Reference [30] has also addressed this method, and Equations 4 and 5 are used to size the FC system.

$$P_{\mathrm{FC}} = P_{\mathrm{tank-FC}} \eta_{\mathrm{FC}} \tag{4}$$

where $\mathrm{P}_{\mathrm{tank-FC}}$ would be the output power from the hydrogen storage tank to the FC system and η_{FC} is the efficiency of the FC system.

$$P_{\mathrm{elec-tank}} = P_{\mathrm{ren-elec}} \eta_{\mathrm{elec}} \tag{5}$$

where $P_{\mathrm{elec-tank}}$ is the output power from the electrolyzer to the hydrogen tank, $P_{\mathrm{ren-elec}}$ is the power from the HRES to the electrolyzer, and η_{elec} is the efficiency of the electrolyzer.

E. Battery Energy Storage System

BESS is often used to complement the HRES as a backup when the HRES cannot meet power demands. It is commonly seen in PV-related systems as they are more susceptible to periods of insufficient power generation. Regardless, BESS can always be relied on for days of autonomy, the number of days the consumer can rely on it due to HRES being inoperable.

Energy storage can be further divided into two types, mainly electrochemical and hydrogen. Hydrogen storage has been discussed; hence this section only covers the electrochemical variant. This type of energy storage can be further divided into batteries, such as lithium ions. Reference [22] discussed sizing BESS for a stand-alone PV system, as seen in Eq. (6). This equation can be used to understand the expected capacity of the BESS for the proposed stand-alone HRES.

$$C_{\mathrm{req}} = \frac{\frac{W_{\mathrm{demand(DC)}}}{V_{\mathrm{DC}}} \times N_{\mathrm{storage}}}{\mathrm{DOD} \times \mathrm{DF}_{\mathrm{batt}}} \tag{6}$$

where N_{storage} is the days of autonomy per Month, DOD is the battery depth-of-discharge limit, $\mathrm{DF}_{\mathrm{batt}}$ is the de-rating factor for the battery, and V_{DC} is the system DC bus voltage.

F. Cost Analysis

Every system needs financial analysis, and a stand-alone HRES is no different. The analysis of past works shows a general trend of NPC, COE, and capital costs as the focus.

1) Net present cost

NPC is the current overall value of installation and operating costs of the system over its lifetime. This value is then subtracted from the present revenues the system earns over its lifetime. HOMER Pro will calculate the NPC of the system and prioritize it when optimizing results. Simply put, NPC can be seen as the overall cumulative cash flow of the system [31]. The formula for NPC is mentioned in Eq. (7), as given in [32].

$$\mathrm{NPC} = -\mathrm{CF}_0 + \frac{\mathrm{CF}_1}{(1+i)^1} + \frac{\mathrm{CF}_2}{(1+i)^2} + \cdots + \frac{\mathrm{CF}_n}{(1+i)^n} \tag{7}$$

where CF_t is the cash flow in the period t, i is the discount rate, and n is the project's life.

2) Cost of electricity

COE is the cost needed to generate usable electricity from the system. HOMER Pro can be used to calculate the COE of a system, but it prioritizes NPC when ranking and optimizing the system. Pandiyan [5] has emphasized that COE is a major factor in examining the economic output of an HRES. Hence, it is equally crucial to consider COE in considering the feasibility of an HRES.

Reference [11] presented an equation for COE, which is similar to the one used by HOMER Pro to obtain the COE value calculated by Eq. (8).

$$\mathrm{COE} = \frac{C_{\mathrm{ann}.t}}{E_{\mathrm{served}}} \tag{8}$$

where $C_{\mathrm{ann}.t}$ is the total annualized cost of the system and E_{served} is the annual energy demand.

G. Geographical Resources

The location for this project is a longhouse in Sri Aman, dominantly inhabited by Ibans. Some geographical information can be obtained from HOMER Pro, while others need further inspection. The solar information is identified, as shown in Fig. 2.

Based on Fig. 2, there are some changes in the daily solar radiation and clearness index throughout the year. Both variables are at their lowest in January at 4.28 kWh/m^2/day and 0.432, respectively. The daily solar radiation peaks at 4.89 kWh/m^2/day, and the clearness index peaks at 0.517 in June. This means that the PSH will be 4.89 h for the location. The average values for these variables are 4.7017 kWh/m^2/day and 0.4703.

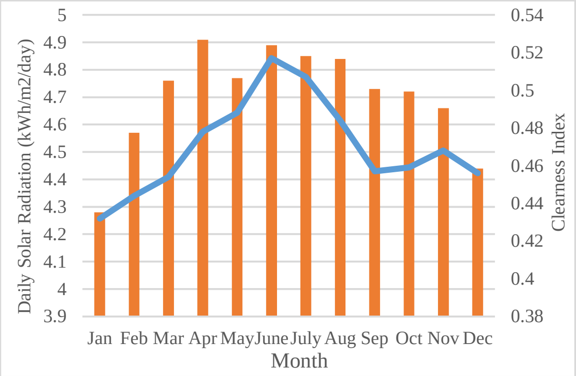


Fig. 2. Clearness index and daily radiation throughout the year.

Sungai Engkari is a stream strategically located near Rumah Bada Longhouse. Its flow rate needs to be identified before sizing the micro-hydro system. Regarding a study by [33], the flow rate is assumed to be 60ℓ/s. This assumption can be made as the contour of Nanga Talong is roughly similar to that in Long Moh, Marudi. Hence, the flow rate is assumed to be roughly identical.

According to reference [34], the agricultural products produced are hill paddy and cash crops. Hill paddy is used as their primary consumption, while cash crops are sold as their primary income. Cash crops are not ideal as the general production amount is far too little as a biomass resource. As for the hill paddy, naturally, there will be raw rice straw. As reference [26] reported, it has high moisture content and low GCV. Hence it would need to undergo torrefaction before being used as an effective biomass resource. The torrefaction process would make the operation of the proposed HRES to be more complex. Even if the rice straw were to be used directly, the high moisture content might reduce combustion temperatures in the boilers, affecting the biomass system's overall efficiency [35]. Hence, biomass will not be part of the overall HRES design.

H. Load Profile

In Rumah Bada Longhouse, there is a total of 30 households. All households are assumed to have the same electrical appliances and exhibit similar consumption patterns. It is also assumed that all houses will have a similar structure of 2 bedrooms, one kitchen, one living room, and one toilet, and all households constitute two parents and two children. Several scenarios are assumed where different consumption patterns can be formed to ensure more realistic results. They can be combined, as seen in Fig. 3.

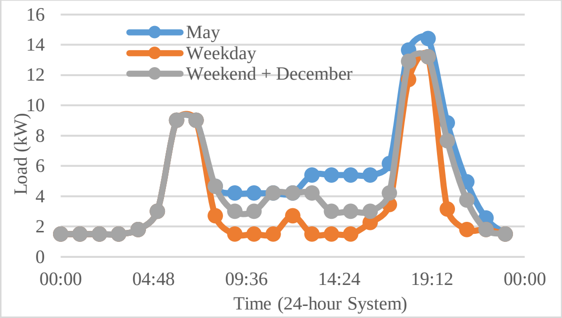


Fig. 3. Consumption patterns for all scenarios.

1) Load consumption on weekdays

The assumed usage and power consumption are listed in Table I. It needs to be emphasized that this is for typical weekdays and not for circumstances such as the festive season.

TABLE I: LOAD PROFILE FOR ONE HOUSE DURING WEEKDAYS

Appliance	Power Rating (W)	Duration (h/day)	Number of Appliances	Energy per Appliance (Wh/day)	Energy (Wh/day)
Television	50	2	1	100	100
Light Bulbs	10	4	5	80	400
Fans	40	7	4	280	1120
Rice Cooker	500	0.5	1	250	250
Radio	25	3	1	75	75
Refrigerator	50	24	1	1200	1200

Based on the assumptions, one house would consume up to 3.145 kWh of energy daily. This would total up to 94.35 kWh used by the longhouse on a typical weekday. The load demand would be higher in the morning, between 05:00 and 08:00. In the evening, between 17:00 and 21:00. This is due to the assumption of meals preparation being performed at that duration as well as the entire family being present in their respective homes, hence accumulatively higher energy demand.

2) Load consumption in weekends and December

Energy consumption during weekends and in December would be assumed to be higher than on typical weekdays. This is due to the assumption that the families would be in their respective homes most of the time, hence resulting in higher energy consumption. In Malaysia, December is typically the end-of-year holiday break for the children, hence the overall assumption.

Each household would consume 4.84 kWh worth of energy; hence the longhouse would need 145.2 kWh to support this consumption. Similar to the weekday consumption pattern, demands would peak in the morning and evening. This is due to meal preparations for the family. Around lunchtime, energy consumption will be slightly higher.

3) Load consumption in May

As the population is dominantly comprised of Iban, another assumption made is that May would be entirely used to prepare for the Gawai festival, held in June. This would result in much higher energy consumption than the other two scenarios. Overall, one household would demand 6.95 kWh worth of energy. This will lead to 208.5 kWh worth of energy demand for the longhouse.

There would also be two peaks, one in the morning and the other in the evening, for similar reasons. The difference between this pattern and the rest is that the energy demand in the afternoon is much higher. This assumes that most preparations are performed during this time, hence higher energy consumption. Furthermore, with relatives coming back for celebrations, the energy demand in the evening would be much higher compared to the other two scenarios.

4) Annual load growth considerations

The annual load growth should also be considered as part of an analysis to determine the long-term capabilities of the proposed stand-alone HRES. Concerning [36], the proposed growth rate for domestic users would be 5.9%. However, as the context of their study focused on a larger pool of consumers, this rate had to be lowered to fit the context of this study. Hence, the annual load growth rate for this study is 4.5%.

I. Sizing the System

The proposed design consists of a micro-hydro, PV, converter, BESS, and hydrogen system, as seen in Fig. 4. The hydrogen system consists of a fuel cell to generate electricity from hydrogen, an electrolyzer to produce hydrogen, and a hydrogen tank to store excess hydrogen. The sizing for each major system is subdivided as shown in Fig. 4. It can also be seen that the average load consumption would be 165.59 kWh per day, which in turn leads to an annual demand of 60440.35 kWh. The stand-alone HRES is set to have a lifetime of 25 years.

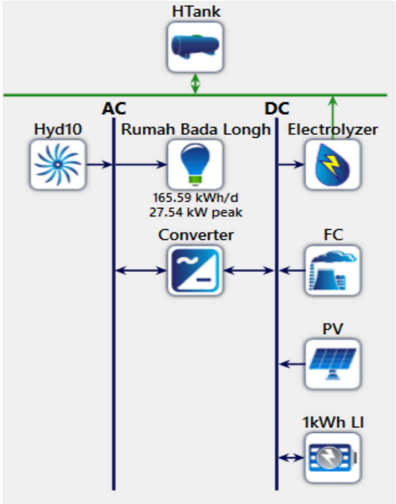


Fig. 4. Proposed HRES configuration.

1) PV system

With the de-rating factor taken as 80% and W_{AC} be 94.35 kWh, the remainder of the parameters can be assumed about other relevant materials. Regarding [27], inverter efficiency can be assumed to be 98%. Hence, using Eq. (2), DC load consumption can be calculated as 96.2755 kWh. With the assumption of n_{batt} to be 86.5%, substituting the parameters to Equation (1) will result in the PV array generating 30.7 kW at a PSH of 4.89 h. Hence, 30.7 kW is the peak power of the PV system.

2) Micro-hydro system

With the flow rate of 60 ℓ/s, the net head and efficiency of the system would be needed. The efficiency of the micro-hydro system will be assumed as 85% concerning [21], while the net head will be 20 m, as per the assumption by [33]. This leads to an output power of approximately 10 kW.

3) Hydrogen system

The HRES would need to supply power to the electrolyzer. This enables the electrolyzer to perform the process of electrolysis, producing hydrogen gas as a valuable output. The mini-hydro system would be responsible for powering it to ensure consistent output. With that, $P_{\text{ren-elec}}$ would be 10kW. By referring to the published report [11], η_{elec} can be assumed to be 85.5%, roughly similar to that in the work of [10]. This will give a value of 8.55 kW for $P_{\text{elec-tank}}$. Assuming the power from the tank to the FC components is transferred at no losses, this value would then be multiplied by η_{FC} of 55%, regarding [21]. This will lead to a power output of 4.7025 kW from the FC system.

4) Battery Energy Storage System

Regarding the designed PV system, $W_{\text{demand,DC}}$ is 96.2755 kWh. Concerning [2], DOD would be taken as 70%. As for DF_{batt}, it is assumed to be 97% [37]. Due to the nature of the project, it is assumed that the VDC is 24 V [22]. The results can be observed in Table II with different numbers of days per Month for autonomy, N_{storage}, of up to 3 days.

TABLE II: SIZE OF BESS WITH VARYING. N_{STORAGE}

$N_{storage}$ (days/month)	C_{req} (kAh)
1	5.9079
2	11.8158
3	17.7238

With economic and system complexity considerations, it is best to have one day of autonomy for the HRES. With the hydrogen system acting as a backup due to the hydrogen tank, one day of autonomy from the BESS would be more economical while maintaining technical stability. Hence, the BESS would be rated at 141.7901 kWh.

J. Financial Considerations

Besides the technical inputs, financial inputs are needed to accurately model the HRES. With that, several sources were utilized to obtain estimated figures for each component's capital, replacement cost, and O&M cost. They are listed as shown in Table III. It is worth noting that the values obtained were in United States Dollars (USD).

TABLE III: FINANCIAL INPUTS

Components	Capital Cost	Replacement Cost	O&M Cost
PV Panel	\$ 900/kWp	\$ 850/kWp	\$ 10/kWp/year
Fuel Cell	\$ 2000/kW	\$ 1860/kW	\$ 0.05/hour
Electrolyzer	\$ 1500/kW	\$ 1500/kW	\$ 10/year
Converter	\$ 300/kW	\$ 300/kW	\$ 3/kW/year
Hydro Turbine	\$ 1300/kW	\$ 1300/kW	\$ 0/year
Hydrogen Tank	\$ 600/kg	\$ 600/kg	\$ 10/year
Battery	\$ 500/kWh	\$ 500/kWh	\$ 5/kWh/year

IV. TECHNICAL ANALYSIS

The results obtained can be tabulated as shown in Table IV. It is worth noting that several feasible scenarios are produced from the simulation; hence they are the only ones considered. Based on Table IV, there are four different logical scenarios. Scenario A generated the most electricity among the four designs, while Scenario C produced the least. This can be due to the complexity factors as Scenario A has several sources, whereas Scenario C only has one.

TABLE IV: SIMULATED TECHNICAL RESULTS

Scenario	Generating source			
	A	B	C	D
Excess electricity (%)	12.7	3.64	28.5	44.4
Electricity produced (kWh/yr)	116,522	90,144	87,654	11,2452
Electricity consumed (kWh/yr)	99,778	84,473	60,441	60,440
Autonomy from BESS (hrs)	8.35	8.35	8.35	8.35
Mean output of P (kW)	2.83	-	-	2.83
Rated capacity of PV (kW)	18.1	-	-	18.1
Mean output of mini-hydro (kW)	10	10	10	10
Average output of FC (kW)	1.57	0.981	-	-
Rated capacity for FC (kW)	4.7	4.7	-	-
Mean input for electrolyzer (kW)	4.49	2.74	-	-
Rated capacity for electrolyzer (kW)	8.55	8.55	-	-
Nominal capacity of BESS (kWh)	72	72	72	72

A: PV, hydrogen, micro-hydro; B: Hydrogen, micro-hydro
C: Micro-hydro; D: PV, micro-hydro

TABLE V: ANNUAL ENERGY OUTPUT FOR EACH SCENARIO

Scenario	PV (kWh/yr)	Micro-Hydro (kWh/yr)	FC (kWh/yr)
A	24,797	87,654	4,070
B	-	87,654	2,490
C	-	87,654	-
D	24,797	87,654	-

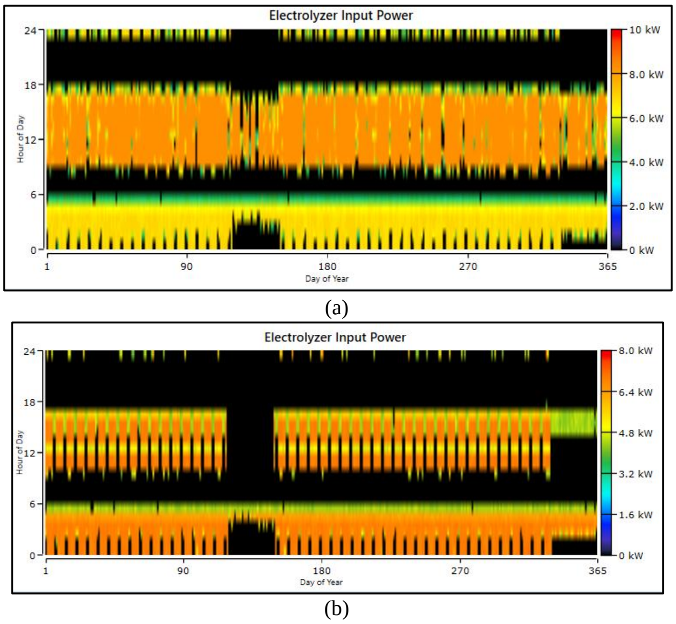
Regardless of the scenarios, all components have the same specifications. The PV system is rated at 18.1 kW, FC is rated at 4.7 kW, micro-hydro is rated at 10kW, and the BESS has a nominal capacity of 72 kW with 8.35 hours of autonomy. As the original computations are sized individually rather than collectively, HOMER Pro can select ideal power ratings, which accounts for deviations from the initial calculations. By calculating each system independently, an estimated range of values for the rating of the components can be obtained.

From the perspective of excess Electricity, Scenario B has the lowest excess electricity at 3.64%, whereas Scenario D has the highest amount at 44.4%. When comparing Scenario D with Scenario A, Scenario A has a much lower excess electricity of 12.7%, which differs by having a functional hydrogen system. This implies that having the hydrogen system can minimize excess electricity, which is logical as the electrolyzer takes in and uses excess electricity. This can be seen in Table V upon comparing Scenario B and Scenario C.

Throughout the simulation, none of the results showed scenarios without the micro-hydro system. The micro-hydro system is also the largest contributor to the overall generation, up to 87,654 kWh annually. This finding is synonymous with the finding in [6]. The FC contributes little to the overall generation despite its high cost, which is synonymous with the results of [11].

Based on Table V, Scenario A, which had the most generating sources, generated the most annual energy, totaling up to 116,521 kWh annually. Assuming that the HRES can generate this amount consistently throughout its lifetime and that the load continues its increment annually, the HRES in Scenario A can sustain the load for up to 15 years, where the annual demand at that time would be 111,932.2 kWh. Starting from the 16-year mark until the 25-year mark, the energy demand will be higher than 116,521 kWh. This may bring certain issues in meeting the power demand. A possible improvement method would be a control strategy to manage power consumption, but this is out of the scope of this work and its analysis.

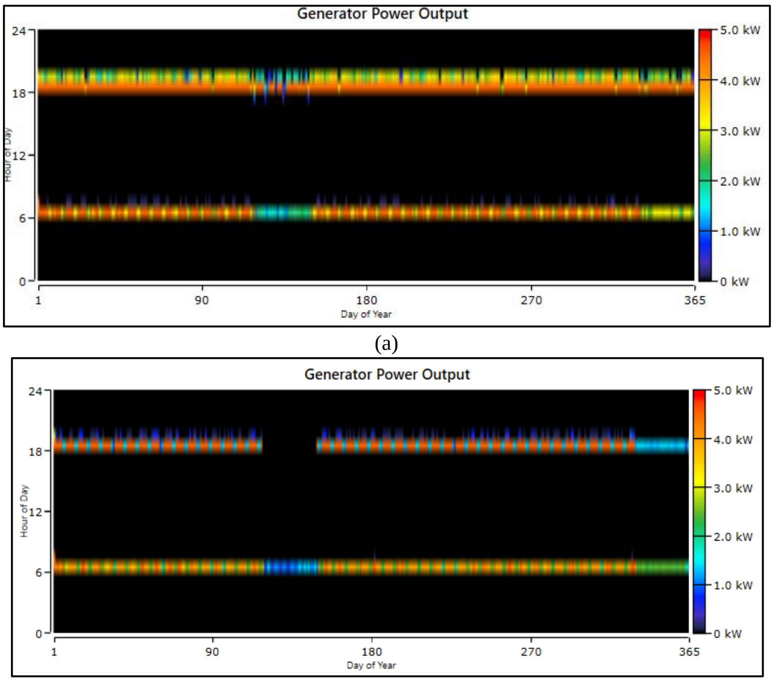
In-depth analysis of the hydrogen system can be performed on Scenario A and Scenario B, as seen in Fig. 5 and Fig. 6. As the electrolyzer takes in energy from the HRES, spectrograms of the input power for the electrolyzer and the output power for the FC can be observed.



(a)

(b)

Fig. 5. Spectrogram of input power for electrolyzer in (a) Scenario A and (b) Scenario B.



(a)

(b)

Fig. 6. Spectrogram for output power for FC in (a) Scenario A and (b) Scenario B.

Based on Fig. 5, the electrolyzer in Scenario A does not receive input power during the high energy demand period; hence the black region during those periods is present. Based on the assumed consumption pattern, the energy demand will be lower during the middle of the day; hence the electrolyzer will operate at its rating of 8.55 kW.

As for the electrolyzer in Scenario B, it has difficulties obtaining input power due to lower generating capacity, especially during May and December, when the energy demand is much higher than usual. Naturally, the electrolyzer takes in excess electrical energy to operate. Hence the lower excess Electricity in Scenario B may pose issues for the hydrogen system to function optimally. This is numerically shown in Table IV, as the mean input power for the electrolyzer is only 2.74 kW, which is much less than that for the electrolyzer in Scenario A.

An interesting finding from the simulation is that the FC in Scenario A does not generate power during its ‘Optimized’ state, as seen in Fig. 6. This may be due to the FC operating in a way that allows the electrolyzer to operate first to generate hydrogen to be stored in the hydrogen tank. As intended, the FC generates power during its ‘Forced On’ state. The FC in Scenario B had difficulties supporting the generating system in May and December. This is again attributed to the lower generating capacity of this design, which leads to lower excess electricity. Regardless, it can operate at its rated value of 4.7 kW.

V. ECONOMIC ANALYSIS

Besides technical results, the economic results of each scenario were obtained, as shown in Table VI.

From Table VI, Scenario C has the cheapest cost overall, while Scenario A is the most expensive. This can be attributed to the complexity of the designs, where Scenario C has fewer components than Scenario A. Scenarios A and B, which contain a hydrogen system, are more expensive than Scenarios C and D, which do not have a hydrogen system. This result aligns with the findings from [11], where adding hydrogen will make a system more expensive.

TABLE VI: SIMULATED ECONOMIC RESULTS

Scenario	**A**	**B**	**C**	**D**
NPC ($)	148,687	127,763	87,165	106,212
COE ($/kWh)	0.190	0.164	0.112	0.136
Operating Cost ($/year)	3,222	2,861	1,556	1,770
Initial capital ($)	107,031	90,783	67,053	83,330
O&M Cost ($/year)	1312	1118	410.53	591.40

The COE for these designs is much lower than those in the literature review. This may be due to low annualized costs, as seen in Fig. 7.

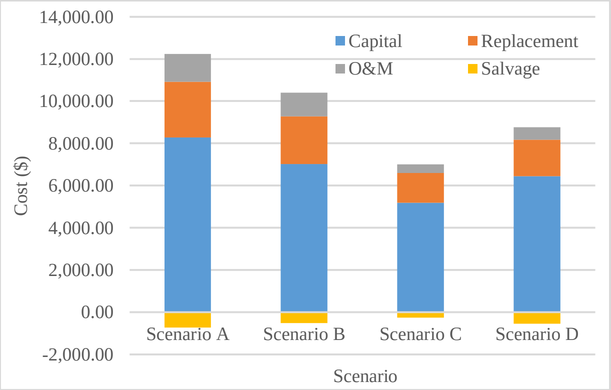


Fig. 7. Breakdown of annualized cost.

The annualized cost of these systems (Fig. 7) can be used mathematically to trace back their respective COE. The calculated COE values are close to the simulated values. This proves that the simulations are valid as the manual calculations tally with the simulations.

Upon further inspection, the breakdown of the NPC for each scenario can be observed. This breakdown is graphically shown in Fig. 8 for Scenario A. Based on Fig. 8, BESS takes up most of the overall NPC, similar to the other scenarios. This can be attributed to the high number of batteries required for this BESS. It is possible to decrease the number of batteries required, but this may risk the designs suffering potential faults. Hence, it is best to maintain this value as it is.

Sensitivity analysis can be performed to examine how the overall system would change based on certain variables. Due to the nature of hydrogen in rural electrification in Malaysia, sensitivity analyses on the hydrogen system were performed, namely the FC, electrolyzer, and hydrogen tank. Scenarios A and B are the focus of this section as they utilize hydrogen. 10% variation on the capital and replacement costs is implemented for the sensitivity analysis. The results for Scenario A are listed, as shown in Table VII, Table VIII, and Table IX. It is worth noting that the pattern from Scenario A is similar to that in Scenario B; hence only Scenario A is discussed.

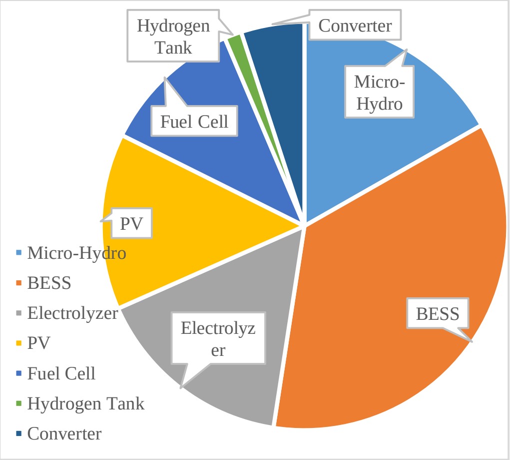


Fig. 8. NPC breakdown for scenario A.

TABLE VII: SENSITIVITY ANALYSIS ON FC FOR SCENARIO A

Variable Cost	**Multiplier**	**NPC ($)**	**Initial cost ($)**	**O&M Cost ($/yr)**	**COE ($/kWh)**
Capital Cost	0.9	147,800	106,128	3,224	0.189
	1.0	148,687	107,031	3,222	0.190
	1.1	149,628	107,972	3,222	0.192
Replacement Cost	0.9	148,795	107,068	3,228	0.190
	1.0	148,687	107,031	3,222	0.190
	1.1	148,633	107,031	3,218	0.190

TABLE VIII: SENSITIVITY ANALYSIS ON ELECTROLYZER FOR SCENARIO A

Variable Cost	**Multiplier**	**NPC ($)**	**Initial cost ($)**	**O&M Cost ($/yr)**	**COE ($/kWh)**
Capital Cost	0.9	147,458	105,786	3,224	0.189
	1.0	148,687	107,031	3,222	0.190
	1.1	149,970	108,314	3,222	0.192
Replacement Cost	0.9	147,762	107,068	3,148	0.189
	1.0	148,687	107,031	3,222	0.190
	1.1	149,666	107,031	3,298	0.192

TABLE IX: SENSITIVITY ANALYSIS ON HYDROGEN TANK FOR SCENARIO A

Variable Cost	**Multiplier**	**NPC ($)**	**Initial cost ($)**	**O&M Cost ($/yr)**	**COE ($/kWh)**
Capital Cost	0.9	148,537	106,881	3,222	0.190
	1.0	148,687	107,031	3,222	0.190
	1.1	148,837	107,181	3,222	0.190
Replacement Cost	0.9	148,666	107,031	3,221	0.190
	1.0	148,687	107,031	3,222	0.190
	1.1	148,708	107,031	3,224	0.190

Based on the results, NPC is the most volatile regarding price changes. As NPC relies on the present value of components, changing the cost of a component will affect its numerical value. Another observation is that changes in the replacement costs will affect the O&M cost significantly, and the same can be said for the initial cost and its relationship with capital costs.

The three components examined affect the overall costs differently. FC has the potential to decrease the COE of a design by having lower capital. The same can be said for the capital and replacement costs of the electrolyzer. However, changes in the cost of the hydrogen tank will not affect the overall Cost of Scenarios A and B as significantly as the other components. Hence, it can be concluded that both designs are least sensitive to changes in the cost of the hydrogen tank.

VI. OVERALL DISCUSSION

The micro-hydro, BESS, PV, and hydrogen systems have varying importance within the proposed HRES. The micro-hydro and BESS systems are in all four designs, and micro-hydro is the biggest contributor to electricity generation in all four designs, signifying their role as fundamental components for the HRES. Financially, BESS is the most expensive component in all four designs, but its large size is crucial to ensure the system's stability.

From a technical perspective, the PV system will contribute about a fifth of the overall energy generation, hence leading to higher excess electricity as seen in Scenarios A and D. However, this can be mitigated by installing a hydrogen system so that the electrolyzer can take in some of the excess electricity for its use. This is evident when Designs A and B have lower excess Electricity than Scenarios C and D. By using the excess electricity; the electrolyzer can produce hydrogen, which the FC can use to generate small amounts of electricity.

Installation of a hydrogen system would make technical sense to compensate for the excess electricity and contribute to the overall generation mix, but it is pricey. In Scenarios A and B, the electrolyzer is the third and second most expensive, respectively, and it can easily change the overall cost of a design, as seen from the sensitivity test. However, the technical advantages it brings are worth considering. The hydrogen system can decrease the excess electricity, but a certain amount of it may be needed to ensure it can operate optimally, as seen from Scenario B, where the electrolyzer suffers from little input power; hence the FC in Scenario B operates less optimally than in Scenario A.

From an economic perspective, Scenario C would be ideal as it is, overall, the cheapest design. HOMER Pro has also declared this design ideal based on its low NPC. However, it has the second highest excess electricity. Furthermore, relying on one generating system defeats the purpose of designing a stand-alone HRES, and it is not ideal, especially when the hydro system is under maintenance. Despite being the cheapest design, Scenario C is the least ideal design among the four designs as it has multiple technical aspects, such as a lack of alternative generating sources and high excess electricity.

From a technical perspective, scenario A would be the ideal choice as it has a high generating capacity, on top of generating the second lowest excess electricity. It has its caveat of being the most expensive design among the four designs, but this is justified by the fact that this design is the most complex, with all three sources involved. Furthermore, when comparing the economic results of this design with those in the literature review, it is much lower, hence relatively cheaper than the discussed designs in the literature review. With that, Scenario A would be ideal for Rumah Bada Longhouse as it is inexpensive, properly utilizes all the components within the system, and has sufficient generation capacity to supply both the longhouse and the electrolyzer.

VII. COMPARISON OF CHOSEN DESIGN WITH LITERATURE REVIEW

A comparison is made between the chosen design from this work, Design A, with several proposed designs from the literature review. This is done to understand the advantages and disadvantages of both this work and the proposed design compared to those from the literature review. The designs and their respective details can be tabulated in the Table X below.

TABLE X: COMPARISON OF SEVERAL DESIGNS FROM THE LITERATURE REVIEW

Design	Ref.	Location	Generating Capacity	Daily Demand (kWh)	COE ($/kWh)
PV, Wind, Biomass, BESS	[10]	Siba, Linze, China	PV: 278kW Wind: 10kW Biomass: 70kW	1,448.40	0.162
PV, Wind, Biomass, Hydrogen, BESS	[11]	Zavieh-Solfa, Chaldaron, Iran	PV: 75kW Wind: 4.2kW Biomass: 15kW FC: 10kW	361.00	0.246
PV, Diesel Generator, BESS	[20]	Bario, Sarawak, Malaysia	PV: 255kW Diesel: 600kW	2,898.32	0.160
PV, Micro Hydro, Hydrogen, BESS	Proposed Work	Sri Aman, Sarawak, Malaysia	PV: 18.1kWp Micro Hydro:10kW FC: 4.7kW	165.59	0.190

The design based on Siba, Linze, and China [10] utilizes wind and biomass, two sources that are not very advantageous in Sarawak. On top of this, hydrogen is not considered in the author’s proposed system. Compared to Design A, Design A utilizes a hydrogen system, showcasing a higher level of novelty over the design in reference [10] as it uses conventional sources.

The design by [11] showcased a hydrogen system for rural electrification and generally higher generating capacity than Design A. However, the Iranian design has the highest COE despite having the second lowest daily demand. [11] has a COE of $0.246/kWh, compared to Design A, which has a COE of $0.190/kWh.

Finally, compared to the work based on Bario [20], the Bario-based work utilized diesel generators as part of its main system. Design A purely uses sources that emit very minimal carbon, as opposed to using diesel as its source. This gives Design A an advantage in terms of long-term environmental impact.

By comparison, the work’s daily demand and generating capacity are lesser than the works in the literature review. On top of that, the proposed design has the second-highest COE, with a value of $0.190/kWh. However, there are some advantages that the proposed design has over the other tabulated works.

VIII. CONCLUSIONS AND POSSIBLE IMPROVEMENTS

A stand-alone HRES has been sized for Rumah Bada Longhouse, Sri Aman. Information such as solar radiation was easily obtained, but information such as flow rate was assumed based on reasonable comparisons. The consumption pattern of the longhouse was assumed, and various patterns were considered. HOMER Pro was then used to simulate the hybrid renewable energy system. Four different scenarios were discussed. Regardless, the individual systems all have similar specifications. HOMER Pro favored Scenario C as the cheapest, but it faces several technical issues. It has high excess electricity that can be compensated for by installing a hydrogen system. This is evident by observing Scenario B, hence excess electricity of 3.64%. The amount of excess electricity before considering the hydrogen system can affect its performance, as seen by comparing Scenarios A and B. Regardless, its addition will increase the overall cost of a scenario. The cost of energy for these designs was calculated, which aligns well with the simulated results. Observations on the net present cost found that the battery energy storage system takes up most of the overall net present cost for all four scenarios. Overall, scenario A is ideal for the longhouse as it fits technical requirements while maintaining economic advantages. It has a cost of energy of $0.190/kWh with the highest generating capacity of up to 116,521 kWh annually.

Further investigations on hydrogen for rural electrification are needed as the electrolyzer can drastically alter the overall cost, and its generation potential has yet to be further explored. On top of this, Scenario A, despite having the highest annual energy generating capacity, has issues sustaining the load after 15 years, assuming the growth rate is constantly increasing and that the system maintains its output. Additional research on the control strategy for energy consumption would be needed to further optimize the proposed system. Regardless, this work has shown the possibility of using hydrogen energy for rural electrification and its impact on a stand-alone hybrid renewable energy system. Not only that, stand-alone hybrid renewable energy systems are beneficial in the long term for rural communities and the environment. Hence, it is hoped that these initial results can act as the base for further research on hydrogen-based technology in rural electrification topics and encourages the potential development of hydrogen-based hybrid renewable energy systems in Sarawak to electrify rural areas.

CONFLICTS OF INTEREST

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

AUTHOR CONTRIBUTIONS

Conceptualization, Data Collection, and Interpretation, Writing – Original Draft Preparation, Writing – Editing, Millenium Wong; Supervision, Writing – Reviewing, Validation, Hadi Nabipour Afrouzi; Writing – Editing – Formatting – Reviewing, Ateeb Hassan; Writing – Reviewing, Elammaran Jayamani; Writing – Reviewing, Jalal Tavalaei; Writing – Reviewing, Jaka Sunarso; Writing – Reviewing, Kamyar Mehranzamir All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

Data will be available on request, and interested individuals can contact hafrouzi@swinburne.edu.my for further information.

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