Department of Mechanical and Aerospace Engineering

Electrification Planning of Rural Village in Maluku Province of Indonesia Using Renewable Energy Generation

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Copyright Declaration

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Abstract

Indonesia reached 98.1% electrification ratio in 2017, and non-renewable energy resources such as crude oil, coal, and natural gas dominated their final energy supply. The country aimed to reach 100% electrification ratio in the future, and at the same time, they have started adding renewable energy into its energy mix. Therefore, this project is aimed to examine the possibilities of maximising the utilisation of clean energy access to bring electricity to the rural villages in Indonesia.

By focusing on a rural village in Maluku Province of Indonesia as the case study with their solar and wind energy resources available, two electrification loads scenario were generated alongside with three different combinations of energy systems modelled for each load. These electrification loads scenario were classified as basic electrification (with the electricity demand of 70.8 kWh/day) and modern electrification (677 kWh/day), and the energy systems for each were modelled using the Hybrid Optimisation of Multiple Energy Resources (HOMER) as the selected software. This project examined the energy systems based on their energy performance and economical aspects to find the most suitable and techno-economic solution for the electrification plan.

The results found that the hybrid energy system is the most optimal solution regarding the energy performance of which maximised the utilisation of renewable energy technologies (with renewable fraction of 91.8% for both scenarios) and fully compensated the electricity demand. Moreover, the cost of energy (COE) of hybrid energy system for each scenario is $0.625 (basic) and $0.434 (modern) respectively. Overall, this project concludes that rural village electrification using hybrid energy systems is considered as a suitable option for a case study village in Maluku Province of Indonesia.

Acknowledgement

It seems essential to start my dissertation with expressing my gratitude to those who have accompanied me throughout my days in University of Strathclyde.

I would first like to express tremendous gratitude to Allah SWT, ‘The Creator’ of my thought, from whom I had strength, foresight, motivation and health.

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INTRODUCTION

1.1 Background

Indonesia has the fourth-largest population in the world after China, India, and the United States, with a total population of more than 250 million spread over more than 17,000 islands (IRENA, 2017). Located in the continent of Asia, Indonesia covers a total area of 1,904,569 km^2 of land and water combined, making it the 15^{th} largest nation in the world. As the population and energy demands grow, the government is tasked with providing accessible and affordable energy across the country to every citizen.

Indonesia represents a good case: according to The World Bank, the percentage of the population having access to electricity reached 98.1% in 2017. However, to reach an electrification ratio of 100%, there are still more than a thousand villages in remote and rural areas that need to be electrified, which is technically and economically challenging (PwC Indonesia, 2017). The challenges to electrification in several areas are partially caused by geographical difficulties, which present a burden to the National Electricity Company in Indonesia (PLN) for distributing the electricity through their network. At the same time, electrification challenges are also caused by the country's energy dependency on fossil fuels, which has resulted in the depletion of resources. In this case, hybrid energy systems are being considered as a solution, which would largely solve these issues (Blechinger et al., 2016).

Compared to conventional energy, the higher initial cost of renewable energy generation is often viewed as an obstacle in the decision-making process. On the other hand, renewable energy has many advantages, such as being clean, environmentally friendly, sustainable, and having generally low maintenance costs (once established). For example, in 2017 the average cost to install solar panels was from above $2000/kw for large-scale systems, to below $3700/kw for residential systems. In comparison, a natural gas plant might have a lower cost of approximately $1000/kw (UCSUSA, 2017). Introducing renewable energy generation to fulfil electricity demand is arguably challenging in developing countries such as Indonesia. Moreover, non-renewable energy resources such as crude oil, coal, and natural gas currently dominate the final energy supply system in Indonesia. However, the country has started adding renewable energy to its energy mix, and has set a target of 23% renewable energy use by 2025 (IRENA, 2017).

1.2 Aim and Objectives

The aim of is project is to maximise the utilisation of possible clean energy sources, to bring electricity to rural villages in Indonesia. Different combinations of hybrid energy systems will be modelled for this project, to find the most suitable technological and economical solution for the electrification plan.

The focus of this work is a rural village in the Maluku province of Indonesia, which is used as a case study, and the objectives are as follows:

- Create a possible energy demand forecast for typical rural villages that do not have electricity supplied by the grid.
- Investigate the renewable energy potential of the site.
- Use suitable modelling software to simulate the possible energy demand and supply systems.
- Evaluate and offer possible solutions, with recommendations for the most cost-effective energy systems for rural villages.

1.3 Scope of the Project

Within scope:

- Indonesia current energy situation.
- The domestic electricity demand of the case study.
- Renewable energy potentials and storage options.
- Costs.

Out of the scope:

- Energy policy, as it might be changed due to political aspects.

1.4 Methodology

An overview of the project methodology is presented in Figure 1.1.

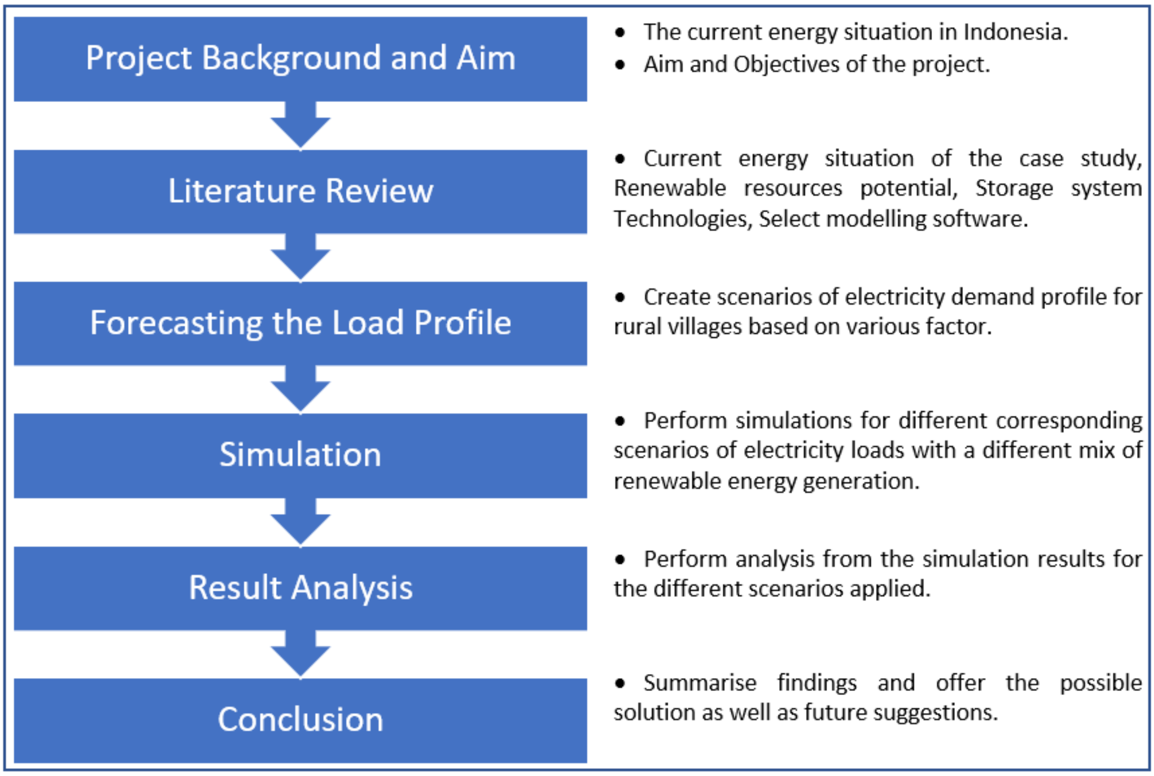


Figure 0.1 Schematic overview of methodology

The methodology of this project specifically consists some steps that need to be taken towards achieving the aims and objectives. These steps are as follows:

- Review the current energy situation in Indonesia, then search for an area that does not have 100% electrification ratio coverage, and does not have access to the grid.
- Investigate the renewable energy potential at the location, mainly focusing on wind and solar potential, as well as storage options for a combined hybrid energy system.
- Select suitable modelling software at the community-scale, as the project aim is to plan electrification for rural villages.
- Create demand assumption scenarios based on various factor in the domestic sector. Moreover, import the demand profile to the selected software and choose the technical components before the simulation process.
- Simulate the data to create a model, and examine the optimal solution for each load scenario.

2. LITERATURE REVIEW

It is essential to form a context with a theoretical background to support the aims of this project dissertation. This section contains an explanation about renewable energy systems, followed by descriptions of both hybrid energy systems and storage system technologies. Furthermore, the current energy situation of the case study will be presented, alongside the potential for using renewable energy. In addition, this section presents a review of the modelling software that will be used in this project.

2.1 Renewable Energy Description

Most of the energy sources used in the world are non-renewable. In 2016, Shell reported that 80% of the total world energy supply comes from fossil fuels, followed by 10% from biofuels, 5% from nuclear reactors, and 5% from renewable energy resources such as wind, solar, hydro, and geothermal. Because non-renewable resources dominate the energy supply, they have a significant impact on the environment by releasing greenhouse gas emissions. Increasing global warming, unexpected weather events, and reducing rainfall are world phenomena that have been caused by the energy activity of previous years (Dahal, Juhola and Niemelä, 2018).

If the world is to aim towards a sustainable future, it is necessary to switch from conventional energy sources and develop more renewable energy sources, which will reduce pollution and lead to a cleaner and healthier environment (Mohammadi and Mehrpooya, 2016). Renewable energy can be replaced rapidly by natural processes, and can be collected from renewable resources such as wind, solar, hydro, and geothermal heat. One of the advantages of these energy sources is that their CO2 emissions have a minimal contribution to the atmosphere compared to fossil fuels. Furthermore, the application of renewable energy will significantly contribute to the improvement of energy security, as renewable energy sources are now considered a competitive alternative for the world’s energy supplies (Das et al., 2018).

In the Association of Southeast Asian Nations (ASEAN), Indonesia is the largest country in terms of energy consumption. Moreover, it has exhibited an average yearly increase in Total Final Energy Consumption (TFEC) of 2.6% between 2002 and 2012 (IEA, 2014). IRENA, in their publications of renewable energy prospects in Indonesia 2017, states that Indonesia's electricity consumption will increase 300% by 2030, due to economic growth. Therefore, Indonesia is expanding the electrification in remote areas and islands, and the government is aiming towards 100% electricity access by 2026 (IRENA, 2017).

2.2 Hybrid Energy Systems

A hybrid energy system combines two or more renewable energy generating methods and non-renewable power generation into one system. Typically, conventional power generation (such as a diesel generator) is used, which is combined with two renewable energy generation methods to form a hybrid energy system (Olatomiwa et al., 2016). The idea of including conventional power generation is to prevent a lack of energy supply at peak demand, given that renewable energy generation relies on the weather.

These combined energy systems can significantly decrease the requirement for fossil fuels, especially if the selection of renewable energy sources is correctly based on the topographical area. This means that if the utilisation of renewable energy sources can be maximised, the dependence on conventional power generation will be reduced. Therefore, particularly for nations that rely on the utilisation of fossil fuels, the application of hybrid energy systems will lead to more sustainable power generation for the country (Ismail, Moghavvemi and Mahlia, 2013).

One of the most commonly used forms of renewable energy in hybrid systems is wind energy. Wind power can be harnessed by using a using a wind turbine to generate electricity. Basically, wind turbines work in the opposite way of a fan. Whereas a fan uses electricity to generate airflow, wind turbines use the wind to generate electricity. They work by transforming the kinetic energy from the spinning blades into electrical energy. Furthermore, the electricity generated by wind turbines can be used on-site or distributed to the grid (Nelson, 2014).

The other well-known form of renewable energy in hybrid systems is solar. Solar energy is derived from the sun's electromagnetic radiation, which is absorbed by the atmosphere in the form of light and heat. Sunlight can be captured by photovoltaic (PV) cells, or solar panels. Electrons are then knocked loose from their atoms, and they generate the electricity when the electrons flow through the cell. To put it simply, the application of a PV reaction converts solar radiation from sunlight into electrical energy (Shahsavari and Akbari, 2018).

2.3 Storage System Technologies

A concern about renewable energy technologies is that they are weather dependant. This means the availability of resources is intermittent, and depends on the weather or climate. For example, the availability of sunlight is more during summer than in winter, and wind speeds tend to be higher in winter compared to summer. Moreover, renewable resources are not only seasonally variable; daily (or even hourly) variations can affect the ability of renewable technologies to capture the energy. Therefore, power back-up storage is an essential inclusion in the system to achieve self-sufficiency, whereby the energy is stored for when the demand exceeds the supply, and allows the system to supply electricity during peak demand. There are numerous storage system technologies currently available, and among the most promising are pumped hydro, flywheels, and lithium-ion batteries.

2.3.1 Pumped Hydro

Pumped hydro is a type of hydroelectric energy storage that consists of two water reservoirs at different elevations. This configuration can generate power (discharge) as the water moves down through a turbine, and it draws power as it pumps water (charge) from the lower reservoir to the upper reservoir.

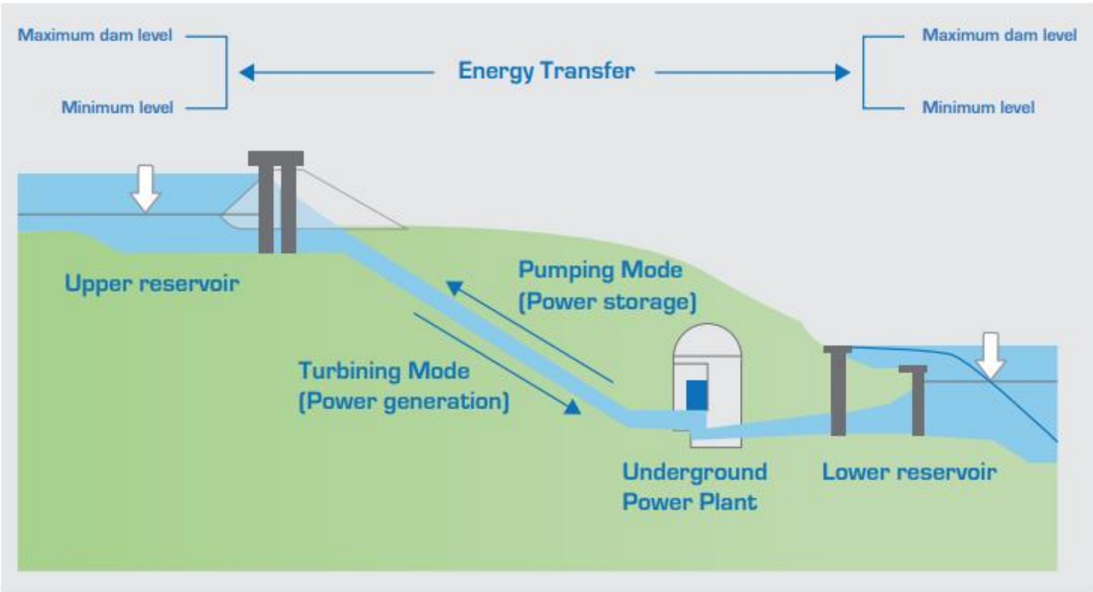


Figure 2.1: Pumped Hydro Storage Illustration (EASE, 2016)

This type of storage is one of the most popular storage system technologies, having a total installed capacity of 181 GW around the world (DoEUSA, 2018). However, there are conditions that must be satisfied to allow adoption of this technology; the chosen area must have both water availability and geographical height. Nevertheless, pumped hydro does not require high capital costs compared to other storage technologies.

2.3.2 Flywheel

Flywheel storage systems store electric energy input in the form of kinetic energy. Most configurations consist of a rotating mass, where the kinetic energy is stored with very low frictional losses. An integrated motor increases the speed of the flywheel to capture the energy. Then the energy is discharged using the same motor-generator by drawing down the kinetic energy.

This type of storage system has many advantages, such as low maintenance, a long lifecycle, and high-power capability. On the other hand, there is a significant disadvantage of this type of storage related to safety risks. If the flywheel is loaded with more energy than its components can accommodate this could result in a problem such as an explosion. Therefore, security walls are required as a safety component, thus increasing the weight and cost of the unit.

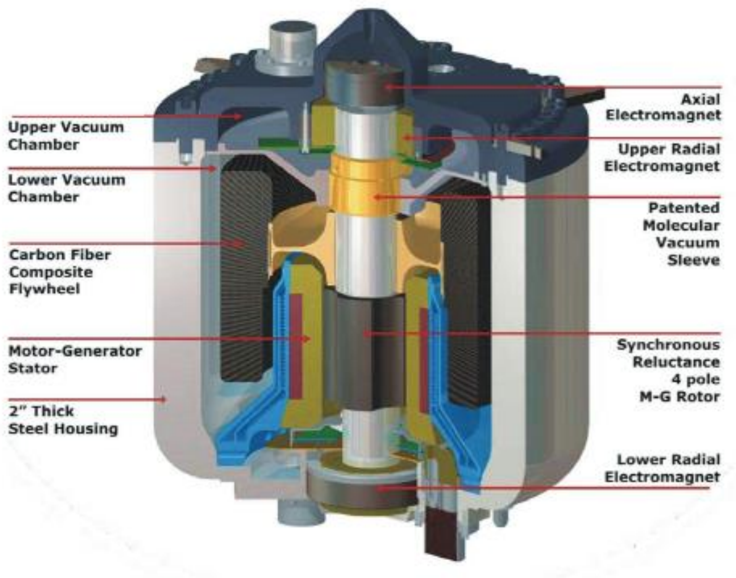


Figure 2.2: Flywheel storage illustration (POWERTHRU, 2016)

2.3.3 Lithium-ion Batteries

Lithium-ion (Li-ion) batteries are rechargeable, and contain a wide array of different chemistries that are transferred between the electrodes during charge and discharge reactions. This type of storage device is commonly used by electronic devices and electric vehicles. Moreover, Li-ion batteries have a high potential in renewable energy systems (Zheng et al., 2018).

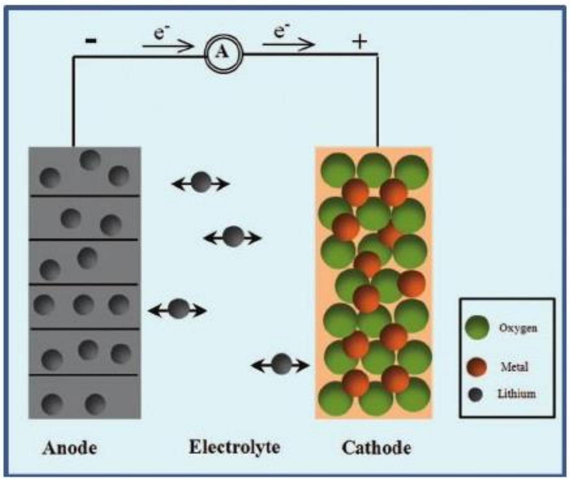


Figure 2.3: Lithium ion battery illustration (Barghamadi, Kapoor and Wen, 2013)

The advantages of Li-ion batteries are that they have a long life cycle, no memory effect, and a high energy density. However, they have the disadvantage of low power density (Zubi et al., 2018). In terms of price, Li-ion batteries are cheaper than other storage mediums for energy systems. Further, companies such as Tesla Inc. have already begun selling Li-ion power packs, which can be used for storing electricity generated by renewable energy technologies.

2.4 Maluku Province Supply and Demand

Maluku Province is one of 34 provinces in Indonesia, located in Eastern Indonesia. In 2018, the population of Maluku Province was approximately 1.75 million, spread over 11 cities and regencies (BPS-Statistics of Maluku Province, 2019). The Ministry of Energy and Mineral Resources of the Republic of Indonesia (2017) reported that electricity consumption had increased by approximately 13% between 2016 and 2017. This consumption was dominated by residential (64%), commercial (23%), public (12%), and industrial (1%) sectors (presented in Figure 3). The electrification ratio in Maluku was 87.1% in 2016, but the aim is to achieve 100% electrification ratio by 2024 (ADB, 2018). By the end of 2017, Maluku had 328 power plant units, with a total power of 219 MW (MEMR, 2017). Most of these power plants are powered by diesel (96.2%), followed by solar (2.9), and steam (0.9%).

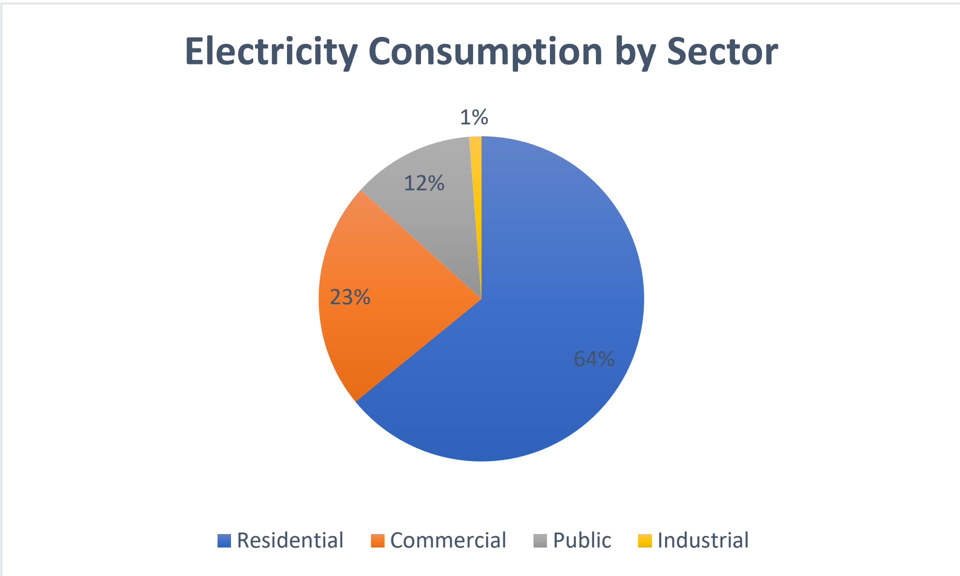


Figure 2.4: Electricity consumption by sector in Maluku province (MEMR, 2018)

2.5 Kai Island Current Energy Situation

The Kai Islands (also known as the Kei Islands) of Indonesia are a group of islands located in the Afrua Sea between Papua and Australia. This archipelago consists of two main islands, Kai Besar (Great Kai) and Kai Kecil (Little Kai) islands, and several other smaller islands, which cover a total land area of 1,438 km^2. Administratively, Kai Islands are part of the Southeast Maluku Regency in the Maluku Province of Indonesia.

Focusing This study focuses on Kai Besar Island (to be precise, the Kai Besar Utara Barat sub-district). This sub-district consists of 25 villages and has a total population of 9,570 (BPS-Statistics of Southeast Maluku Regency, 2018). Of these 25 villages, only 6 have electricity supplied by PLN (BPS-Statistics of Southeast Maluku Regency, 2018). This means that approximately 70% of the villages in the Kai Besar Utara Barat sub-district still do not have electricity supplied by the Government of Indonesia (GOI). Moreover, in these other villages that do not have access to the electricity grid, some people use diesel generators for lighting, and some others use kerosene lamps.

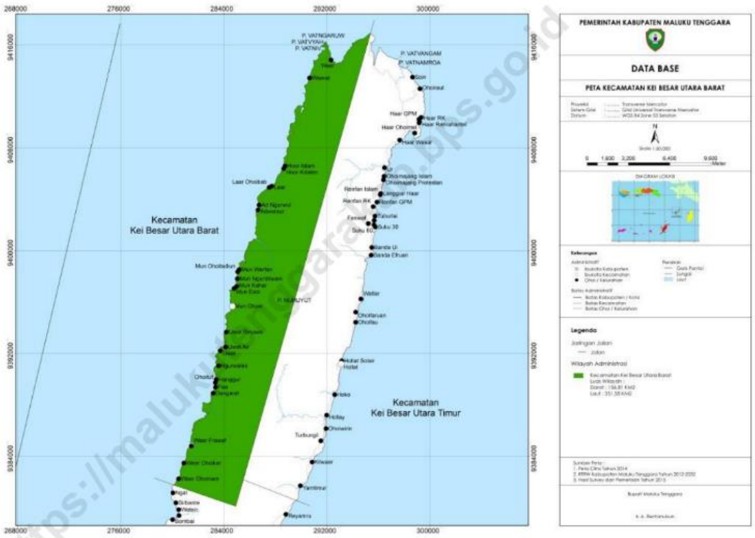


Figure 2.5: Kai Besar Utara Barat Subdistrict Map (BPS-Statistics of Southeast Maluku Regency, 2018)

This study models an Indonesian village with renewable energy resources in the Kai Besar Utara Barat sub-district, with Uwat Village being used as a case study for this project. This village is one of the 19 in Kai Besar Utara Barat sub-district that currently does not have electricity supplied by PLN. It is located at 05º 52' 49.32" S 132º 33' 00.18" E, and has a total population of 1,010 (BPS-Statistics of Southeast Maluku Regency, 2018).

2.6 Renewable Resources Potential

For this project, data are needed on the potential renewable resources for the site (such as wind and solar). Both wind and solar data are derived from the National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy Databases.

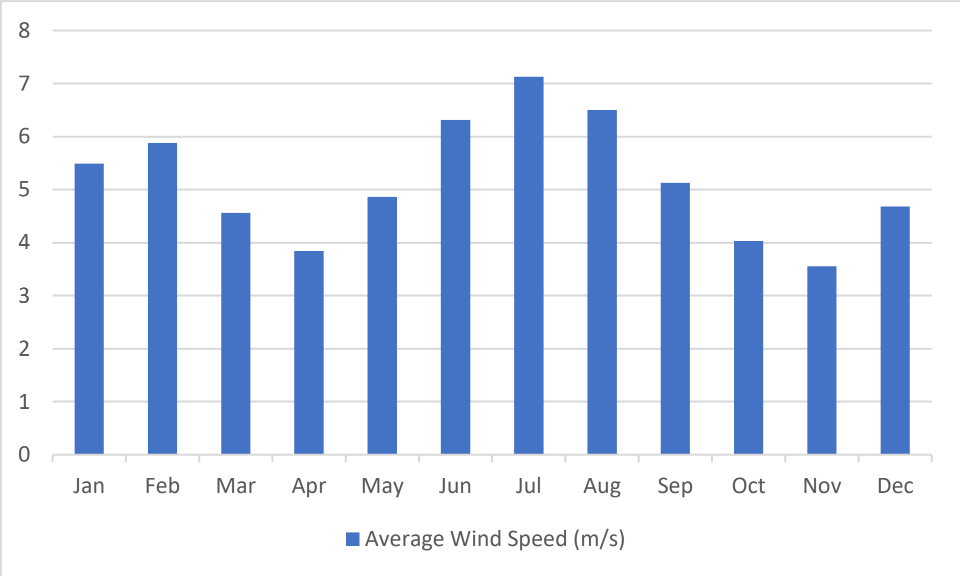


Figure 2.6: Monthly Averaged Wind Speed Data for The Site (NASA,2006)

Generally, wind resource data is needed to model a system for wind turbines, and this is usually presented as wind speed. The NASA Langley Research Center (2006) provides monthly averaged wind speed values at 50 m above the Earth's surface over a 10-year period (July 1983–June 1993). Throughout these years, the total average wind speed was 5.16 m/s for the site. Figure 5 presents the monthly averaged wind speed, with the minimum and maximum wind speeds of 3.5 m/s and 7.1 m/s occurring in November and July, respectively.

For the solar resource data, this is indicated by the amount of solar global horizontal irradiance (Solar GHI), which is measured in kWh/m^2. In Hybrid Optimisation of Multiple Energy Resources (HOMER), solar data is recognised in three forms: hourly and monthly average solar radiation, and the monthly average clearness index, which ranges between 0 and 1.

The NASA Langley Research Center (2006) has provided monthly averaged solar resource data over 22 years from 1983 to 2005 for the site. The site has a total average solar irradiation of 5.4 kWh/m^2/day throughout those 22 years. Figure 6 presents the monthly average solar irradiation and the clearness index. Of these average figures, the minimum is 4.8 kWh/m^2/day, which occurred in June, and the maximum is 6.3 kWh/m^2/day, which occurred in October. Moreover, the clearness index has a total average of 0.54.

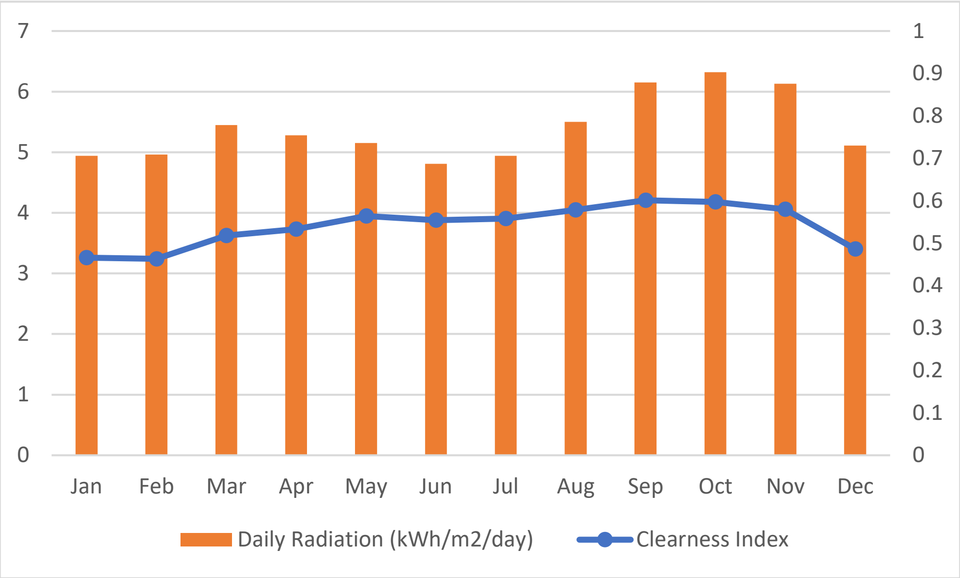


Figure 2.7: Monthly averaged solar resource data for the site (NASA,2006)

2.7 Software

After looking into two different energy modelling pieces of software (Energy Plan and HOMER), both of which can model supply and demand configurations for an off-grid solution at a community scale, HOMER was selected to model the energy systems for this project. Regarding the decision-making process for the choice of suitable software, several criteria were examined, which are summarised in Table 2.1.

Table 2.1: Modelling Software Summary of Comparison (Lyden, Pepper, and Tuohy, 2018)

	Energy Plan	Homer
Cost	Free	Free trial up to 21 days, Students £10-£31 per month
User Friendly	High	High
Scale Of The Model	National/regional	Community Scale
Summary	Suitable for modelling national and regional scale of energy systems with high techno-economic analysis. Regardless, this modelling tool is not so adaptable on a community scale.	Suitable for modelling supply-demand with renewable energy generation as well as energy storage with high techno-economic analysis for the hybrid energy systems.

HOMER is a piece of modelling software that can model energy supply and demand and compare power generation technologies, including renewables. It was developed by the US National Renewable Energy Laboratory (NREL) in 1933 to facilitate renewable energy industrial needs (HOMER Energy, 2010).

This software can model 10 kinds of micro power system components. This includes 3 components that can generate electricity from intermittent, renewable energy resources (solar PV, wind turbine, and hydro turbine); 3 that are dispatch-capable energy sources (grid, generators, and boilers); 2 types of delivery and conversion components (converters and electrolysers); and lastly, 2 types of energy storage (batteries and hydrogen storage tanks). In addition, HOMER evaluates financial and technical aspects of each possible combination of its components (scenario), which will make the decision-making process easier for the energy modeller.

2.8 Summary

Based on this review, the following conclusions can be drawn:

- The Indonesian government is expanding electrification in remote areas and islands. At the same time, they have started to add renewable energy into their energy mix, aiming towards sustainable future energy supplies.
- Uwat village is one of the villages in remote areas in Indonesia that currently does not have electricity supplied from the grid. Therefore, hybrid energy systems can be a solution for electrification planning in the village.
- The initial idea for the hybrid energy system combination is to maximise the utilisation of renewable energy resources that are available at the site of the case study. A diesel generator will be added to the combination to prevent unmet electricity demand from the renewable generation supply.
- As for the renewable generation in hybrid energy systems, a combination of solar PVs and wind turbines will be suitable for the site, as the site renewable potential shows the availability of both of these resources.
- Energy storage technologies will be added to store energy produced during periods of high supply, and to supply it when the demand is high. This will also minimise the utilisation of energy supplied by conventional power generation.
- After reviewing the two pieces of modelling software, HOMER will be used for modelling hybrid energy systems supply and demand in this project.

3. ELECTRICITY DEMAND FORECAST

The electricity load profile must be forecast, to enable planning of electrification for the case study. The first step of creating an electricity demand forecast is to define the size of a generic village. This project refers to village statistical data from BPS-Statistics of Southeast Maluku Regency (2018), to establish a typical generic village that consists of 1,010 inhabitants in 199 households with an average household size of 5 people.

In this project, electrification planning is only for household electricity demand, because the industrial sector does not develop rapidly in most rural areas. This project considers two categories of electricity demand for households: Scenario 1 is a basic electrification scenario, and Scenario 2 is a modern electrification scenario in Indonesia. Scenario 1 only focuses on small-sized household electricity use, providing lighting for both indoor and outdoor use, as well as a phone charger, for which the electricity will only be available for 12 h each day. On the other hand, electricity is available for 24 h in Scenario 2, as it is prepared for a medium-sized modern household with typical electrical appliance needs. Both assumptions of electricity demand scenarios are summarised in Table 3.1.

Table 3.1: Summary of Loads Scenario

	Basic electrification	Modern electrification
Overview	Basic electrification scheme for rural villages including lighting and charger	Typical average electrification scheme from the city for rural villages including lighting, charger, fan, tv, and refrigerator
Power Availability	Electricity is available for 12 hours from 18:00-06:00	Electricity is available for 24 hours
Load Profiles	Household: 0.36 kWh/day	Household: 3.4 kWh/day
	Total Village: 70.8 kWh/day	Total Village: 677.4 kWh/day

Another assumption regarding these load profiles is that the profile is constant, meaning there is no peak load or seasonal variation throughout the year. Moreover, all assumptions regarding the list of appliances, quantity, power consumption, usage duration, and total power consumption for Scenarios 1 and 2 are presented in Table 3.2 and Table 3.3.

Table 3.2: Assumptions for Basic Electrification Scenario

No.	Electrical Appliances	Quantity	Power Consumption (W)	Usage Duration per Day	Total Power Consumption (W)
1	Lightbulb Indoor	2	14	18:00-00:00	168
2	Lightbulb Outdoor	1	14	18:00-06:00	168
3	Phone Charger	1	10	18:00-20:00	20
				Total	356

Table 3.3: Assumptions for Modern Electrification Scenario

No.	Electrical Appliances	Quantity	Power Consumption (W)	Usage Duration per Day	Total Power Consumption (W)
1	Lightbulb Indoor	4	14	18:00-00:00	336
2	Lightbulb Outdoor	1	14	18:00-06:00	168
3	Phone Charger	1	10	18:00-20:00	20
4	Fan	1	55	12:00-15:00 & 20:00-23.00	330
5	TV	1	30	18:00-23:00	150
6	Refrigerator	1	100	00:00-00:00	2400
				Total	3404

The electrical appliances used in these assumptions are chosen based on the efficiency of each component.

4. FUTURE ENERGY SYSTEM SIMULATIONS

To model the future energy system for the case study, it is necessary to input the necessary data to the HOMER modelling software. As the initial idea of this project is to bring electricity to rural villages using renewable energy generation, these data needed by the software include renewable energy resources potential, electricity load profile, energy generation components, and storage technology. From Chapters 2 and 3, case study renewable energy resources potential were evaluated, and two electricity load profiles were created. Therefore, this chapter will explain the components and parameters that need to be configured to model the future energy system options for the case study, followed by its modelling scenarios.

4.1 Components and Parameters

The components for future energy system options in this project are as follows:

- PV panels
- Wind Turbines
- Diesel Generator
- Storage (Li-ion)
- Converter

4.1.1 PV Panels

A generic flat plate PV is selected for the PV component. With a lifetime of 25 years, the initial capital and replacement cost of the PV is set to 1,210 $/kW, and the operation and maintenance cost is set to 10 $/kW (IRENA, 2019). Table 4.1 summarises some characteristics of the selected PV.

Table 4.1: PV Panel Characteristics

	Value
Rated Capacity (kW)	1
Operating Temperature (0C)	45-48
Efficiency (%)	13
Derating Factor	80

4.1.2 Wind Turbines

A Bergey BWC XL-1 with an AC electrical bus is selected as the wind turbine component. With a lifetime of 20 years, the initial capital and replacement cost of a BWC XL-1 turbine is set to 1,500 $/kW, and the operation and maintenance cost is set to 20 $/kW (IRENA, 2019). This wind turbine was selected because the cut-in speed is less than other types of turbine, so it is suitable due to the low wind speed at the site. Figure 4.1 presents the power curve of the wind turbine.

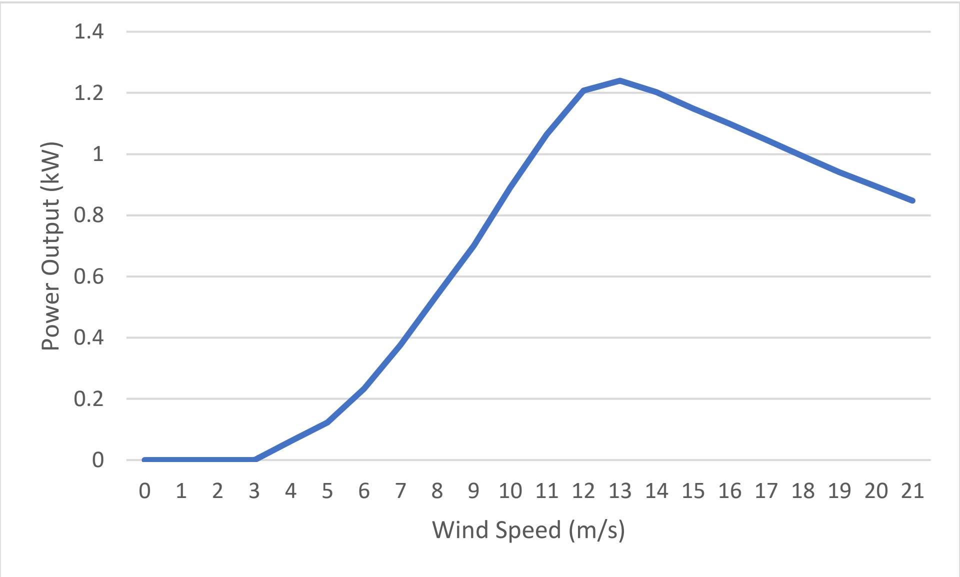


Figure 4.1: Bergey BWC XL-1 Power Curve

4.1.3 Diesel Generator

An auto-sized genset is used for this project. With a lifetime of 15,000 hours and a minimum load ratio of 25%, the initial capital and replacement cost for this diesel generator is set to 500 $/kW, and the operation and maintenance cost is set to 0.03 $/hour (LAZARD, 2017). It should be mentioned that the fuel price is set to 1.5$/L, which is twice the current price of diesel fuel in Indonesia. The fuel price is set higher than the original price due to limitations of the HOMER software. When the diesel generator is combined with renewable energy systems, the software prioritises the use of a diesel generator due to its low running costs compared to discharging the power from the battery, even though the battery is fully charged. Hence, to overcome this problem, the fuel price is set as stated above, so the software will prioritise discharging the power from the battery when the renewable generation cannot generate enough power to meet the demand.

4.1.4 Converter

To define the size of the converter, a generic system converter is selected in the HOMER software. The initial capital and replacement cost is set to 300 $/kW, and the lifetime of this converter is 15 years, with an efficiency of 95%.

4.1.5 Lithium-Ion Battery

This type of battery is selected due to its lower cost compared to other types of storage system technologies. Its lifetime is set to 15 years, with the initial capital and replacement cost set to 550 $/kWh. The operation and maintenance cost for this type of battery is set to 10 $/year.

Table 4.2: Lithium-ion Characteristics

	Value
Nominal Voltage (V)	6
Nominal Capacity (kWh)	1
Nominal Capacity (Ah)	167
Round trip efficiency (%)	90
Maximum state current (A)	167
Maximum Discharge Current (A)	500

4.1.6 Economic Input Parameters

The project lifetime is set to 20 years for all future electrification scenarios. The nominal discount rate is set at 12%, as the investors would calculate this in the case of investment in Indonesia (IRENA, 2019). Moreover, the expected inflation rate for this project is set to 2.25%, which is assumed from the average inflation target set by the Bank Indonesia in 2019 (BI, 2019). The real discount rate for this project is calculated at 9.54%.

4.2 Energy System Modelling Scenarios

To suggest the most suitable and economical energy system for the case study, three different energy system configurations are modelled for each load profile. The first configuration uses only conventional power generation (diesel generator). This was not offered as a solution for the electrification planning, but only as the base electrification model to be compared with the next two configurations. The second configuration is only equipped with renewable energy generation (PVs and/or wind turbines + batteries). Finally, the third configuration combines conventional power generation and renewable energy generation to create a hybrid energy system for the electrification option. The configurations of each modelling scenario for the load profiles are summarised in Table 4.3.

Table 4.3: Summary of Each Modelling Scenario

	Conventional	Fully Renewable	Hybrid
Configurations	Diesel Generator	PV and/or Wind Turbine + Lithium-Ion Battery + Converter	Diesel Generator + PV and/or Wind Turbine + Lithium-Ion Battery + Converter
Summary	Base model which uses a conventional power generation for the energy supply	Renewable model which uses only renewable energy technology to generate the electricity and considered as the most environmentally friendly energy system	Hybrid energy system which combines conventional power generation and renewable energy technology that could create balanced and clean energy access for the electrification planning.

4.3 Summary

From this chapter, the following conclusions can be drawn:

- Combinations of the energy system for the second and third configurations were investigated by using all the parameters set in the HOMER software, as stated in Section 4.1.
- Each combination was selected as the most techno-economic energy system.

The results and a discussion of each combination will be presented and discussed in the following chapter.

5. RESULTS AND DISCUSSION

This section presents the results and a discussion of the simulations in HOMER. As mentioned in the previous chapters, two demand scenarios were created for this project and three different combinations of energy system were analysed for each demand scenario. Initially, the idea of creating three different electrification options was to find the most suitable energy systems based on their financial evaluation and energy performance throughout the 20 years of their lifetime. These three options were also selected to fulfil each of the following three criteria: conventional energy systems, fully-renewable energy systems, or a combination of both conventional and renewable energy systems (hybrid energy systems). Amongst other configurations simulated for each criteria, these three electrification options will be subsequently presented and then compared, to obtain the most suitable from their techno-economical aspects.

The financial evaluations taken into consideration were Net Present Cost (NPC) of the investment and the Cost of Electricity (COE). NPC is the difference between the present value of installation and operation and the present value of all the incomes during the lifetime of the hybrid energy system. The COE is the average cost per kWh of useful electricity generated by the hybrid energy system, which is basically the difference between the total annualised cost of the overall system and the total electricity supplied to the load.

The energy performance of the hybrid energy system was investigated using two factors: renewable fraction and excess electricity. Renewable fraction is the fraction of the energy delivered to the demand that comes from renewable energy resources. Excess electricity is the additional (or surplus) electricity produced by the combination of the system that cannot be used to cover the current demand or charge the batteries. However, the excess electricity can be used to accommodate future increases in demand.

5.1 Basic Electrification Scenario

5.1.1 Conventional Energy System for Basic Electrification

To plan electrification using renewable energy generation, it was necessary to model the conventional energy system for the case study. After all parameters were set in the HOMER software, the optimisation results for this conventional energy system is a system that consists of an auto-sizing diesel generator of 20 kW. The total NPC of this system (over 20 years of its lifetime) is calculated at $214,602 with a COE of $0.944 per kWh. Initially, the capital for this energy system is $10,000 and it consumes 12,148 l of diesel per year to produce the electricity. Table 5.1 presents the results of a financial evaluation to determine the energy system needs over its lifetime, followed by the energy performance, which is presented in Table 5.2.

Table 5.1: Financial Evaluation Results of Conventional Energy System (Basic)

	Value
Capital	$10,000
Replacement	$21,577
O&M	$23,102
Fuel	$160,182
Salvage	$-259
Total	$214,602

Table 5.2: Energy Performance Results of Conventional Energy System (Basic)

Characteristics	Value
Diesel Generator electricity production (kWh/year)	30,730 (100%)
Excess Electricity (kWh/year)	4,872 (15.9%)
Unmet Electric Load (kWh/year)	0
Renewable Fraction (%)	0

According to the energy performance results, this system produces a total of 30,370 kWh/year to cover the demand. There was no unmet electricity load left from this energy system, because a diesel generator can produce a stable energy supply (regardless of conditions). However, it has an excess electricity load of approximately 16% per year. To elucidate further, Figure 5.1 illustrates the characteristics of this energy system.

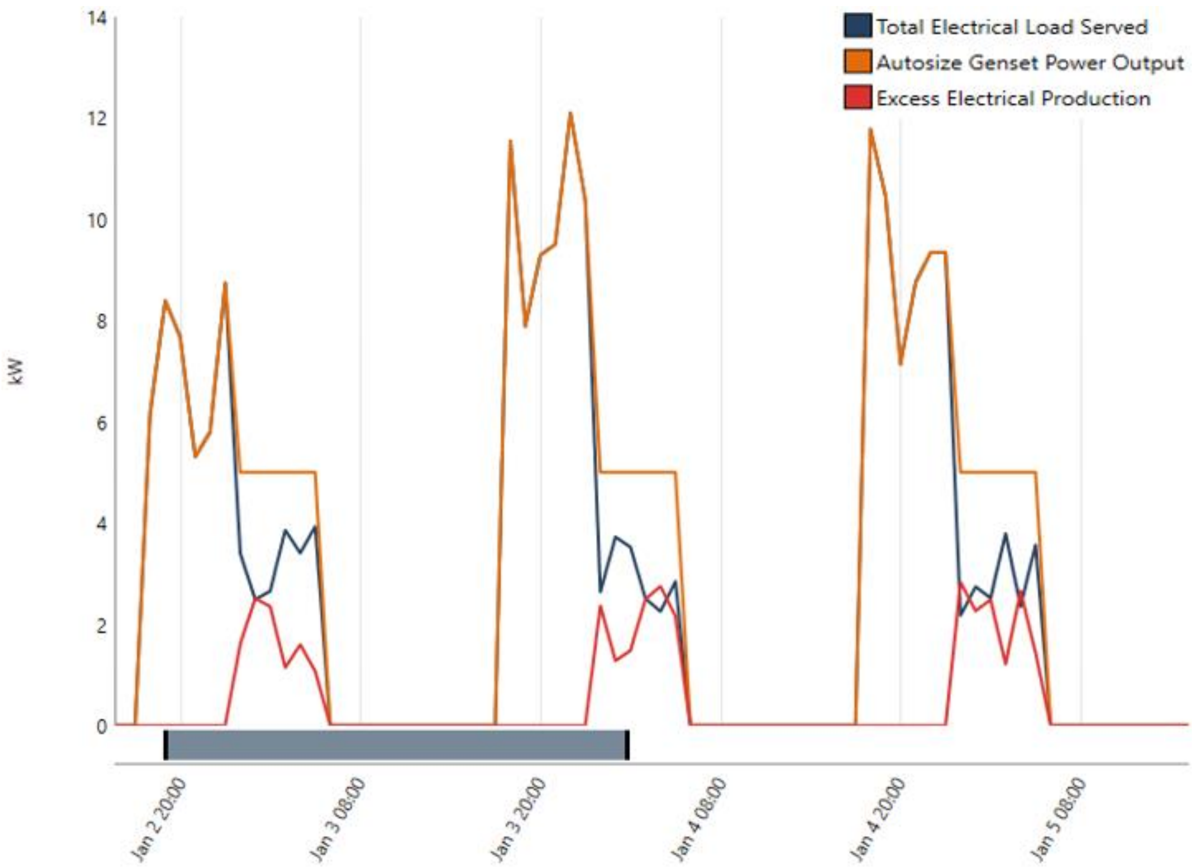


Figure 5.1: Conventional Energy System Power Characteristics (Basic)

It can be seen from Figure 5.1 that the diesel generator generates electricity from 06:00 to 18:00 to cover the demand for Scenario 1, as the electricity is only needed for 12 h. The diesel generator is set to run with a minimum load ratio of 25%. Consequently, during electricity production from 00:00 to 06:00, the diesel generator produces excess electricity due to the demand being below its minimum load ratio.

5.1.2 Fully Renewable Energy System for Basic Electrification

This scenario only uses a renewable energy generation combination to create the energy system. By optimising the software, the most techno-economic combination of this system is as follows: PVs (39 kW), wind turbines (11 kW), Li-ion batteries (143 kW), and converters (19 kW). The initial capital is calculated at $147,707, the total NPC for its lifetime is $176,514, and the COE is $0.777 per kWh. The financial investigation results for this system are presented in Table 5.3, followed by the energy performance results in Table 5.4.

Table 5.3: Financial Evaluation Results of Fully Renewable Energy System (Basic)

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Bergey BWC XL.1	16,500.00	0.00	1,933.94	0.00	0.00	18,433.94
1kWh Li-Ion	78,650.00	20,062.18	12,570.61	0.00	-8,482.29	102,800.50
Generic PV	46,900.93	0.00	3,407.35	0.00	-1,517.46	48,790.82
System Converter	5,656.67	1,1442.66	0.00	0.00	-609.96	6,488.37
System	147,706.60	21,505.84	17,911.90	0.00	-10,609.71	**176,513.62**

Table 5.4: Energy Performance Results of Fully Renewable Energy System (Basic)

Characteristics	Value
PVs Electricity Production (kWh/year)	61,245 (82.4%)
Wind Turbines Electricity Production (kWh/year)	13,070 (17.6%)
Total Electricity Production (kWh/year)	74,315 (100%)
Excess Electricity (kWh/year)	44,740 (60.2%)
Unmet Electric Load (kWh/year)	21.5 (0.08%)
Renewable Fraction (%)	100

According to the energy performance results from HOMER, total electricity production from this system is 74,315 kWh/year. It can be observed that PVs contribute the majority of production, with a total electricity production of 61,245 kWh/year (approximately 82.4%), while wind turbines generate 13,070 kWh/year (approximately 17.6%). The electricity demand for this scenario is 25,837 kWh/year; thus, from the total electricity production of this system it is observed that it produces an excess of 44,740 kWh/year, or approximately 60% more than the demand. Regarding unmet electricity, the performance of this energy system is good enough to compensate the demand, with a total unmet electrical load of 0.08%. For a detailed discussion of these results, Figures 5.2 and 5.3 present the characteristics of the energy performance during the dry hot season and the rainy monsoon season in the case study, respectively.

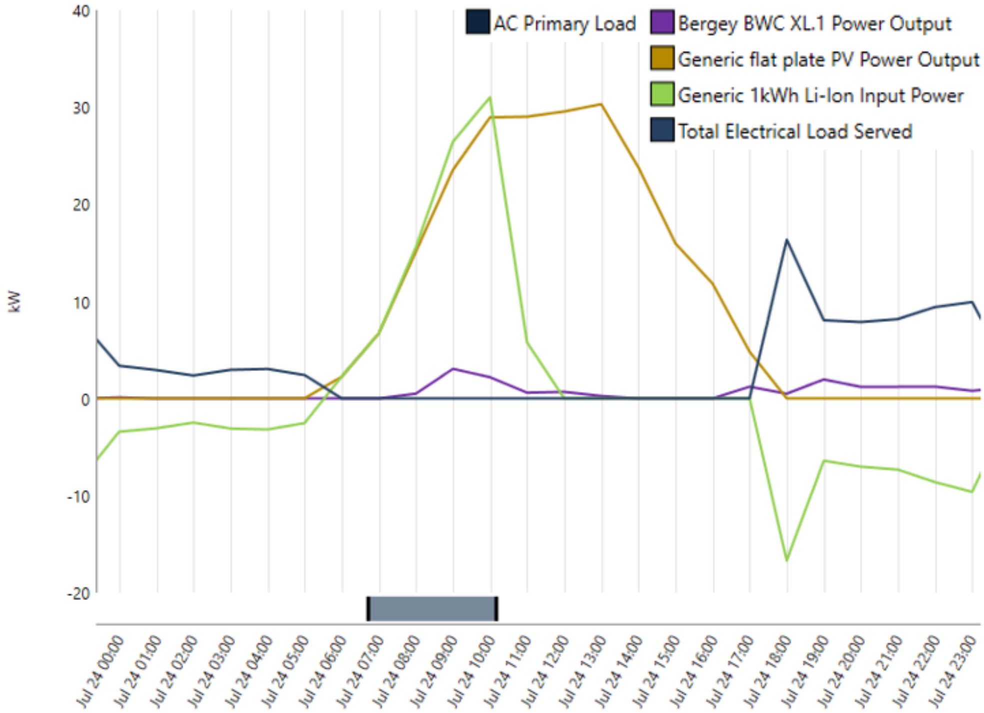


Figure 5.2: Fully Renewable Power Characteristics in Dry Hot Season (Basic)

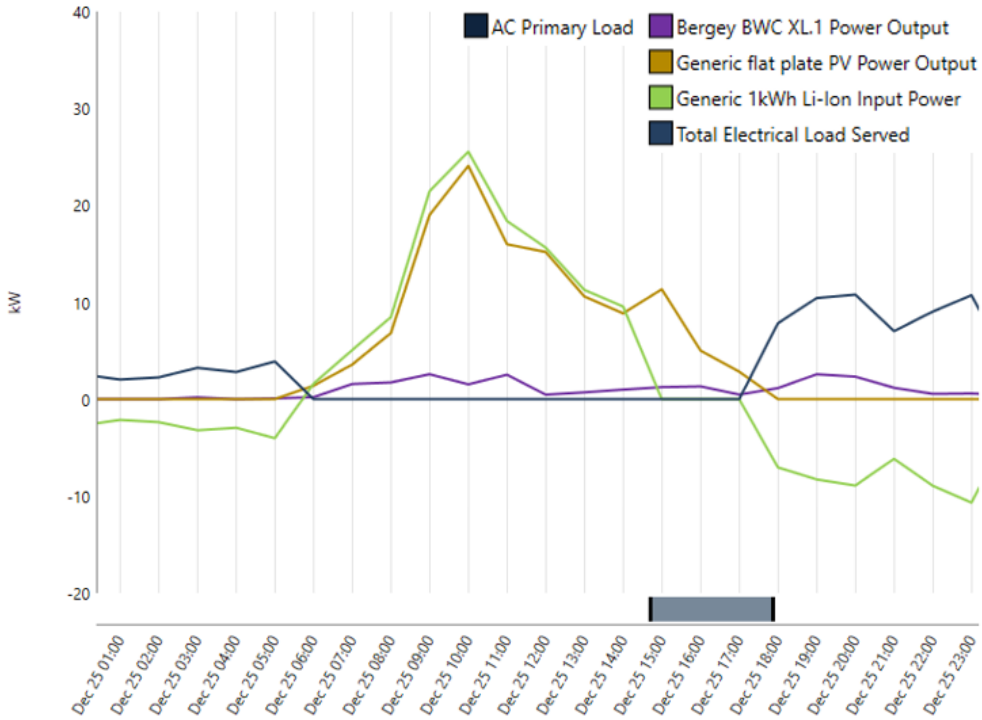


Figure 5.3: Fully Renewable Power Characteristics in Rainy Monsoon Season (Basic)

As is evident from Figure 5.2, in the dry hot season, PVs can produce power output from 05:00 to 18:00 and reach a peak of approximately 30 kW between 10:00 and 14:00. Wind turbines produce their power output from approximately 08:00, then stop at 14:00 and start again at 16:00 until approximately 23:00. The total power output from PVs and wind turbines from

06:00 to 18:00 are stored in the batteries, because there is no electricity demand during this time. In the evening, when the demand needs more electricity, the batteries discharge their power and combine with the power output from the wind turbines to cover the demand.

During the rainy monsoon season, PV production shows a reduction compared to the hot dry season. Conversely, wind turbine performance in this season shows an increase in power output. In terms of excess electricity, it is observed that the total production from renewable generation in the rainy monsoon season is lower than in the hot dry season. Hence, the excess electricity generated in the rainy monsoon season is lower than in the dry hot season.

5.1.3 Hybrid Energy System for Basic Electrification

This electrification scenario combines both conventional and renewable energy technologies. The initial idea of the hybrid energy system scenario is to maximise the implementation of available renewable resources, then add a diesel generator to balance the output to meet demand; hence, it is expected that there will be no demand shortfall. The most suitable combinations for the criteria above consist of a 20 kW diesel generator, 17 kW of PVs, 8 kW of wind turbines, 104 kW of Li-ion batteries, and a converter of 14.3 kW, with a total renewable fraction of 91.8%. From the economic investigation, this system has total NPC of $142,017 over its lifetime of 20 years, with a COE price of $0.625 per kWh. The initial capital of this energy system is $104,086, which is the cheapest compared to the two other previous scenarios. Table 5.5 summarises the results of the financial investigation, followed by Table 5.6, which presents the performance results of this energy system.

Table 5.5: Financial Evaluation Results of Hybrid Energy System (Basic)

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	10,000.00	0.00	2,072.83	12,335.16	-770.04	23,657.96
Bergey BWC XL.1	12,000.00	0.00	1,406.50	0.00	0.00	13,406.50
1kWh Li-Ion	57,200.00	16,926.40	9,142.26	0.00	-4,664.38	78,604.29
Generic PV	20,582.60	0.00	1,495.32	0.00	-665.94	21,411.99
SystemConverter	4,303.13	1,097.65	0.00	0.00	-464.09	4,936.69
System	104,085.73	18,024.05	14,116.92	12,335.16	-6,564.44	**142,017.42**

Table 5.6 Energy Performance Results for Hybrid energy System (Basic)

Characteristics	Value
Diesel Generator Electricity Production (kWh/year)	2,109 (5.5%)
PVs Electricity Production (kWh/year)	26,878 (69.8%)
Wind Turbines Electricity Production (kWh/year)	9,506 (24.7%)
Total Electricity Production (kWh/year)	38,942 (100%)
Excess Electricity (kWh/year)	8,941 (23.2%)
Unmet Electric Load (kWh/year)	0
Renewable Fraction (%)	91.8

A According to the performance results, the hybrid energy system has a total electricity production of 38,942 kWh/year, of which 94.5% comes from renewable energy generation. PVs generate the highest electricity production in this system with a total of 26,878 kWh/year, followed by the wind turbines with 9,506 kWh/year, and 2,109 kWh/ year production from the diesel generator. Regarding the excess electricity, this system generates a total of 8,941 (approximately 23%) excess electricity that could not be stored by the batteries. However, compared to the renewable energy system scenario, this excess electricity is lower by approximately 80%. Further, there is no unmet electric load with this energy system, which

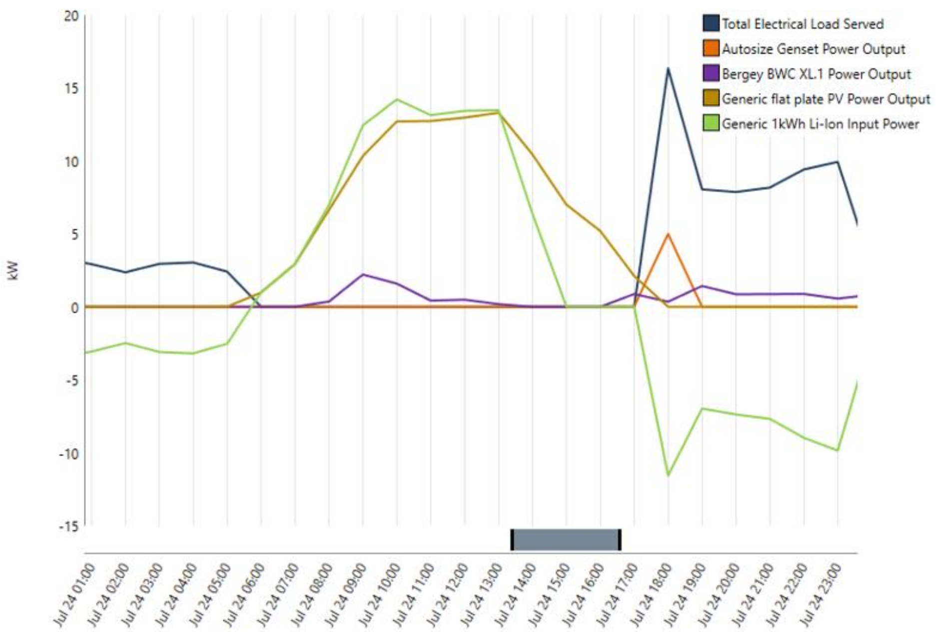


Figure 5.4: Hybrid Energy System Power Characteristics in Dry Hot Season (Basic)

means all loads are covered by the system. Figures 5.4 and 5.5 show the characteristic of the hybrid energy system in the hot dry and rainy monsoon seasons, respectively.

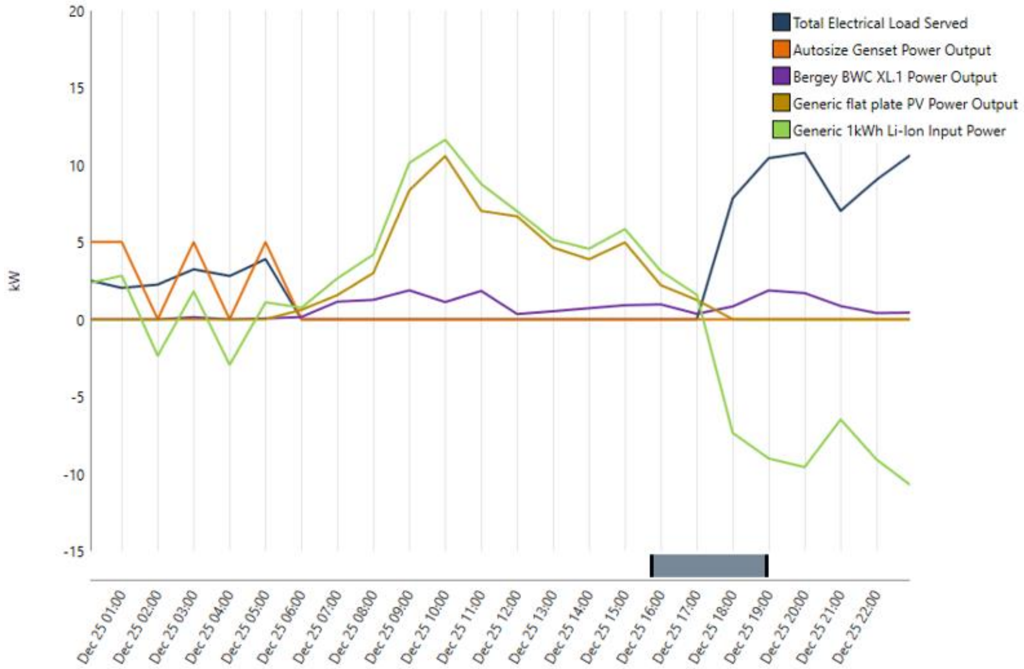


Figure 5.5: Hybrid Energy System Power Characteristics in Rainy Monsoon Season (Basic)

As presented in Figures 5.4 and 5.5, typical days in the hot dry and rainy monsoon seasons are selected to show the power generation characteristics in this scenario. Similar to the previous scenario, PV electricity production at noon (combined with the production from wind turbines) are used to charge the batteries, because there is no electricity demand at this time. Then, the batteries discharge their power to cover the demand, which starts at 17:00. The generator is also activated at approximately 17:00, because the energy from the batteries at that time is insufficient to cover demand. In the rainy monsoon season, the performance of PVs (which is the major contributor to productivity) is slightly decreased due to the weather. Consequently, electricity stored by the batteries is not enough to cover the whole demand. Therefore, the diesel generator is turn on and off to cover the demand (together with the battery and wind turbine production) in the evening.

5.2 Modern Electrification Scenario

5.2.1 Conventional Energy System for Modern Electrification

As stated in the literature review, the case study currently does not have an electricity system supplied and installed. Therefore, the base model electricity system was modelled with an auto sizing generator as the supply to meet demand. This system is considered the standard system, and will be compared with the renewable and hybrid energy systems. The size of the diesel generator is set to 96 kW, with an initial capital of $48,000 for the generator itself. This energy system has a total NPC of $1.75M over its lifetime, and a COE price of $0.807/kWh. One of the reasons for the total NPC being expensive is because the diesel generator consumes 95,016 l of diesel per year. Table 5.7 summaries the total cost of this energy system, including capital, replacement, operation and maintenance, fuel, and salvage costs over the lifetime. Table 5.8 presents the energy performance results of this system.

Table 5.7: Financial Evaluation Results of Conventional Energy System (Modern)

	Value
Capital	$48,000
Replacement	$233,247.34
O&M	$221,777.24
Fuel	$1,252,875.74
Salvage	$-2,484.83
Total	1,753,415.49

Table 5.8: Energy Performance Results of Conventional Energy System (Modern)

Characteristics	Value
Diesel Generator electricity production (kWh/year)	268,748 (100%)
Excess Electricity (kWh/year)	21,499 (8%)
Unmet Electric Load (kWh/year)	0
Renewable Fraction (%)	0

According to the energy performance results, this system generates 268,748 kWh per year to cover the 24 h electricity demand. Moreover, there is no unmet load for the electricity generated by this system. However, there is a total excess of 21,499 kWh/year (approximately 8%). This is because the minimum electricity load is below the minimum load ratio of the diesel generator, which is set at 25% to prevent shortening of its lifetime. The characteristics of this energy system are presented in Figure 5.7.

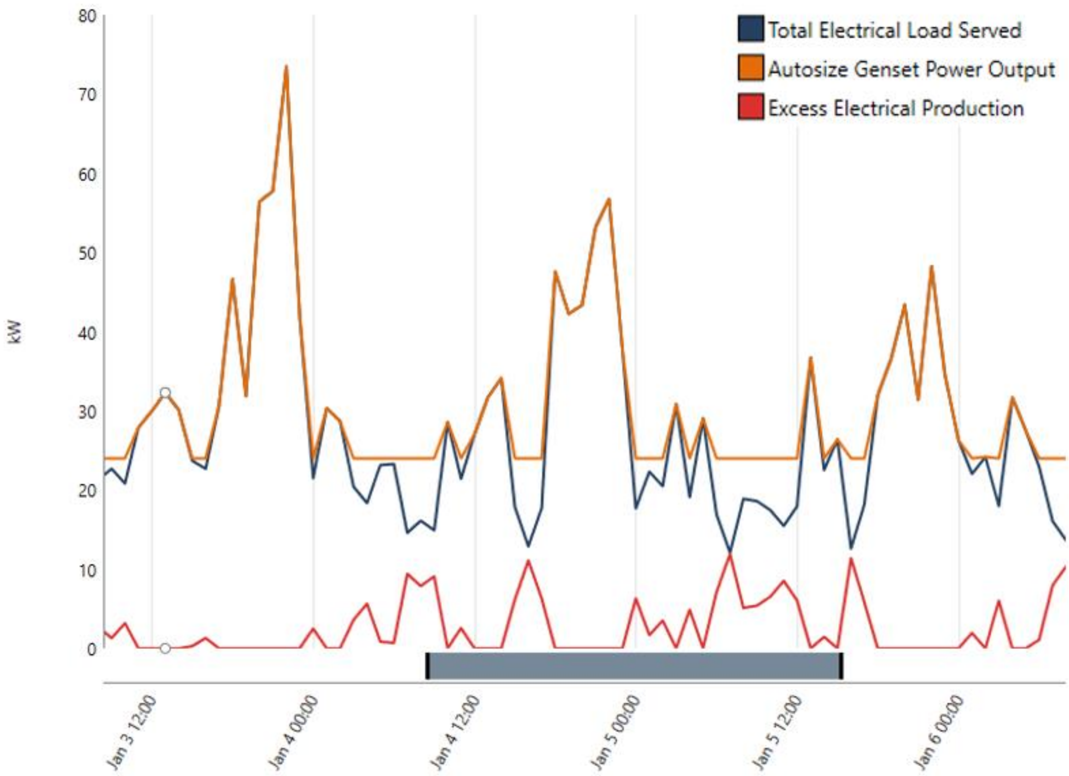


Figure 5.6: Conventional Energy System Power Characteristics (Modern)

As is evident from Figure 5.6, the diesel generator runs for 24 h to meet the demand. The diesel generator produces excess electricity frequently, due to the minimum load being below its minimum load ratio during the 24 h of demand.

5.2.2 Fully Renewable Energy System for Modern Electrification

This scenario is set to reach 100% of the renewable fraction by varying the capacity of PVs and wind turbines combined with Li-ion batteries and converters for the energy systems to meet demand. The most techno-economic combinations of this energy system consist of PVs (359 kW), wind turbines (100 kW), Li-ion batteries (944 kW), and converters (85.5 kW). The total NPC of this system is $1.33 million, and the COE price is $0.611, which is cheaper than the base model over its 20-year lifetime. However, the initial capital for this system is $1.13 million, which is almost 25 times more expensive than the initial capital for the base model. Regarding the overall cost for the system, Table 5.9 summarises the cost by component, followed by the energy performance results of this system, which is presented in Table 5.10.

Table 5.9 Financial Evaluation Results of Fully Renewable Energy System (Modern)

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Bergey BWC XL.1	150,000.00	0.00	17,581.28	0.00	0.00	167,581.28
1kWh Li-Ion	519,200.00	132,438.45	82,983.62	0.00	-55,995.01	678,627.06
Generic PV	434,628.42	0.00	31,575.71	0.00	-14,062.22	452,141.91
System Converter	25,661.78	6,545.85	0.00	0.00	-2,767.59	29,440.04
System	1,129,490.20	138,984.30	132,140.60	0.00	-72,824.82	**1,327,790.29**

Table 5.10: Energy Performance Results of Fully Renewable Energy System (Modern)

Characteristics	Value
PVs Electricity Production (kWh/year)	567,558 (82.7%)
Wind Turbines Electricity Production (kWh/year)	118,822 (17.3%)
Total Electricity Production (kWh/year)	686,379 (100%)
Excess Electricity (kWh/year)	416,765 (60.7%)
Unmet Electric Load (kWh/year)	92.9 (0.04%)
Renewable Fraction (%)	100

According to the simulation results, the electricity production (per year) from PVs and wind turbines are 567,558 and 118,882 kWh, respectively. Altogether, this system produces a total of 686,379 kWh/year. However, without adding the conventional power system (diesel generator), this renewable energy system could not meet 100% of the electricity load. It can be seen from Table 5.10 that this system covers the energy demand with high reliability, because the unmet electric load is 92.9 kWh/year (0.04%) from the whole demand per year, which is considered extremely low for a system with 100% renewable energy fraction. Moreover, it could be said that this renewable energy system is sufficiently optimised to compensate the electricity demand.

In terms of the excess electricity, it can be observed that it has a very high amount (approximately 60%), with a total of 416,765 kWh/year. This occurs because the system relies only on renewable energy sources. Consequently, electricity production is unstable and unpredictable, and the batteries are unable to store all the extra electricity produced. Figures 5.7 and 5.8 present the characteristics of this energy performance during the hot dry and rainy monsoon seasons, respectively, for further in-depth discussion.

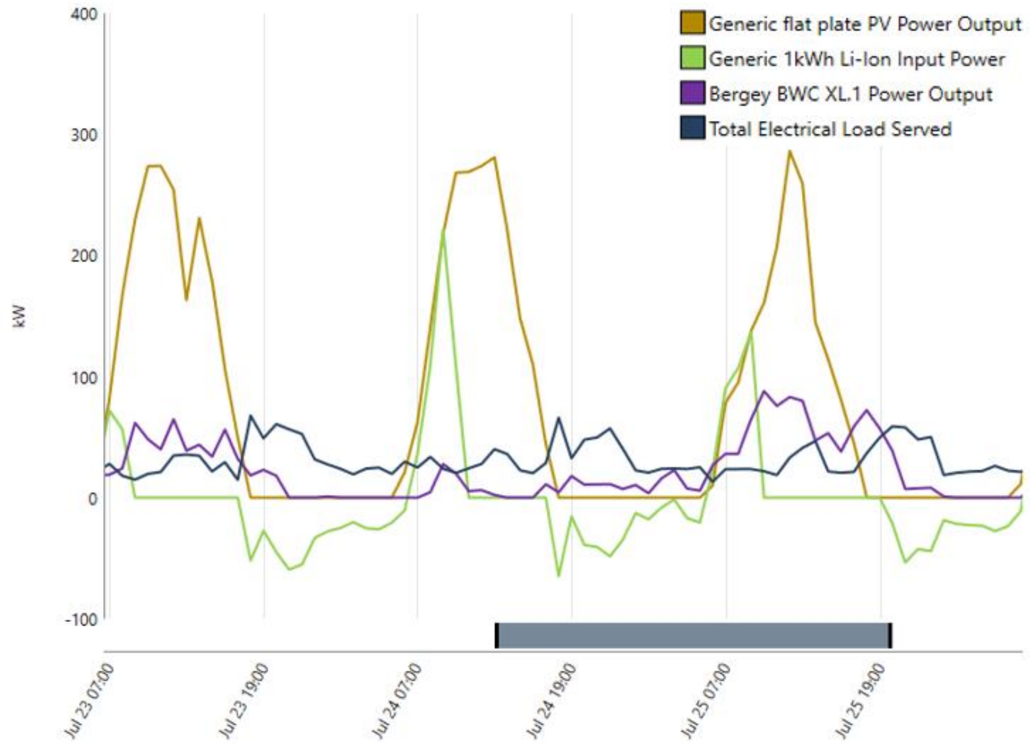


Figure 5.7: Fully Renewable Power Characteristics in Dry Hot Season (Modern)

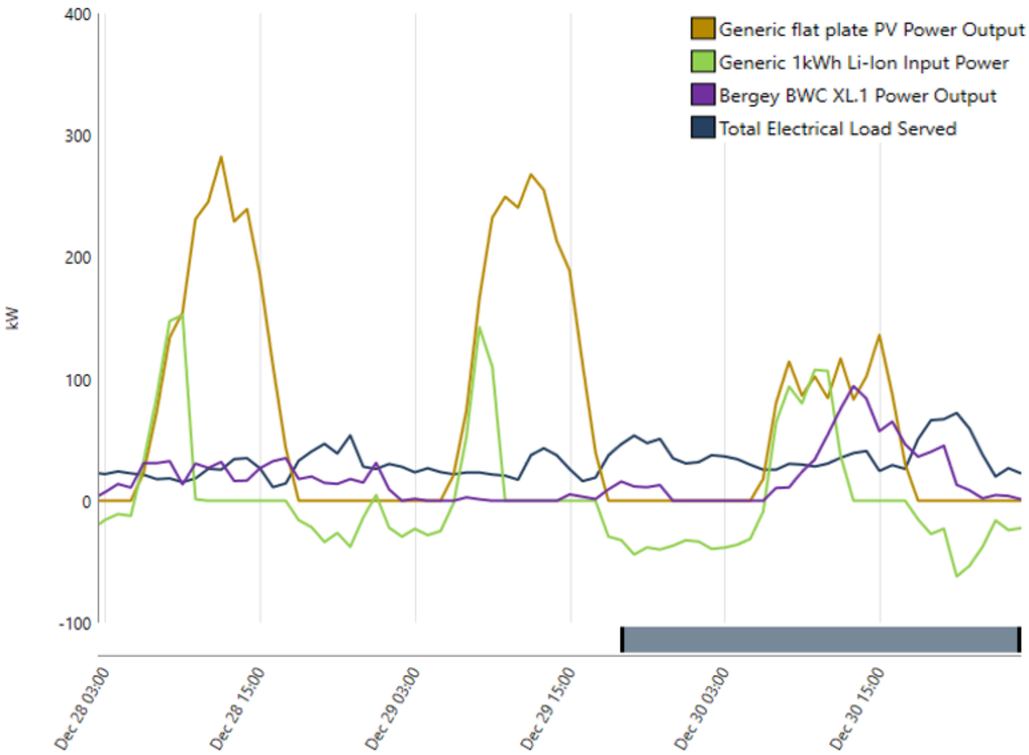


Figure 5.8: Fully Renewable Power Characteristics in Rainy Monsoon Season (Modern)

According to Figures 5.7 and 5.8, typical days in the dry hot and rainy monsoon seasons are selected from this renewable system scenario to show the pattern of electricity production. In the dry hot season (Figure 5.7), PVs produce power from approximately 05:00 to 18:00, and reach a peak at 12:00 of slightly below 300 kW, which is almost ten times the demand at this time. Regarding wind turbines, the output period is wider at some times, but they are not as stable as the PVs. For example, on 23rd July wind turbines managed to produce approximately 25 kWh from 07:00 to 20:00, and on 25th July they produced more (almost 100 kW at 13:00). For batteries, they typically starts discharging their power in the evening from 17:00 to 06:00 the next day, due to the electricity production from wind turbines being insufficient to cover demand. The rainy monsoon season, as shown in Figure 5.8, has a similar pattern of electricity production to the hot dry season, but PVs produce less power (approximately 150 kWh), as shown on 30th December. Overall, batteries play an important role in this energy system, as they discharge each evening until the next morning to cover demand.

5.2.3 Hybrid Energy System for Modern Electrification

This scenario combines conventional power generation with renewable energy technologies. After the software simulated the combinations of this hybrid energy system, the most techno-economic combination was selected. From the technological perspective, this combination was selected because it achieves a renewable fraction of 91.8% using a combination of a diesel generator (96 kW), PVs (151 kW), wind turbines (77 kW), Li-ion batteries (593 kW), and converters (74.2 kW). From the economic investigation, this system was selected as it has a total NPC of $943,724 with a COE price of $0.434 per kWh over its lifetime of 20 years. The initial capital of this energy system is $695,101, which is the cheapest compared to the previous two scenarios. Table 5.11 summarises the cost, and Table 5.12 summarises the energy performance results of this system.

Table 5.11: Financial Evaluation Results of Hybrid Energy System (Modern)

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	48,000.00	7,927.27	19,266.26	99,323.98	-7,651.21	166,911.30
Bergey BWC XL.1	115,500.00	0.00	13,537.58	0.00	0.00	129,037.58
1kWh Li-Ion	326,150.00	86,497.83	52,128.48	0.00	-33,111.20	431,665.10
Generic PV	183,194.83	0.00	13,309.09	0.00	-5,927.19	190,576.72
SystemConverter	22,256.80	5,677.30	0.00	0.00	-2,400.36	25,533.73
System	695,101.63	100,147.40	98,241.41	99,323.98	-49,089.97	**943,724.45**

Table 5.12: Energy Performance Results of Hybrid Energy System (Modern)

Characteristics	Value
Diesel Generator Electricity Production (kWh/year)	20,288 (5.7%)
PVs Electricity Production (kWh/year)	239,224 (68.2%)
Wind Turbines Electricity Production (kWh/year)	91,493 (26.1%)
Total Electricity Production (kWh/year)	351,005 (100%)
Excess Electricity (kWh/year)	82,358 (23.5%)
Unmet Electric Load (kWh/year)	0
Renewable Fraction (%)	91.8

It is evident from Table 5.12 that this system has a total production of 351,005 kWh/year, of which 94.3% comes from renewable energy generation. PVs have the highest production by generating 239,224 kWh/year, followed by wind turbines with a total production of 91,493 kWh/year. Furthermore, the diesel generator contributes 20,288 kWh/year to supply when the renewable technologies were not able to cover demand, which resulted in zero unmet load. The excess electricity from this hybrid system is 82,358 kWh/year, approximately 80% less than the excess electricity from the renewable energy system described earlier. Overall, the financial and the energy performances suggest that this energy system represents the best balance of conventional and renewable energy generation as the energy supply for constantly covering the demand. For further discussion, Figures 5.9 and 5.10 illustrate the characteristics of this hybrid energy system in the hot dry and rainy monsoon seasons, respectively.

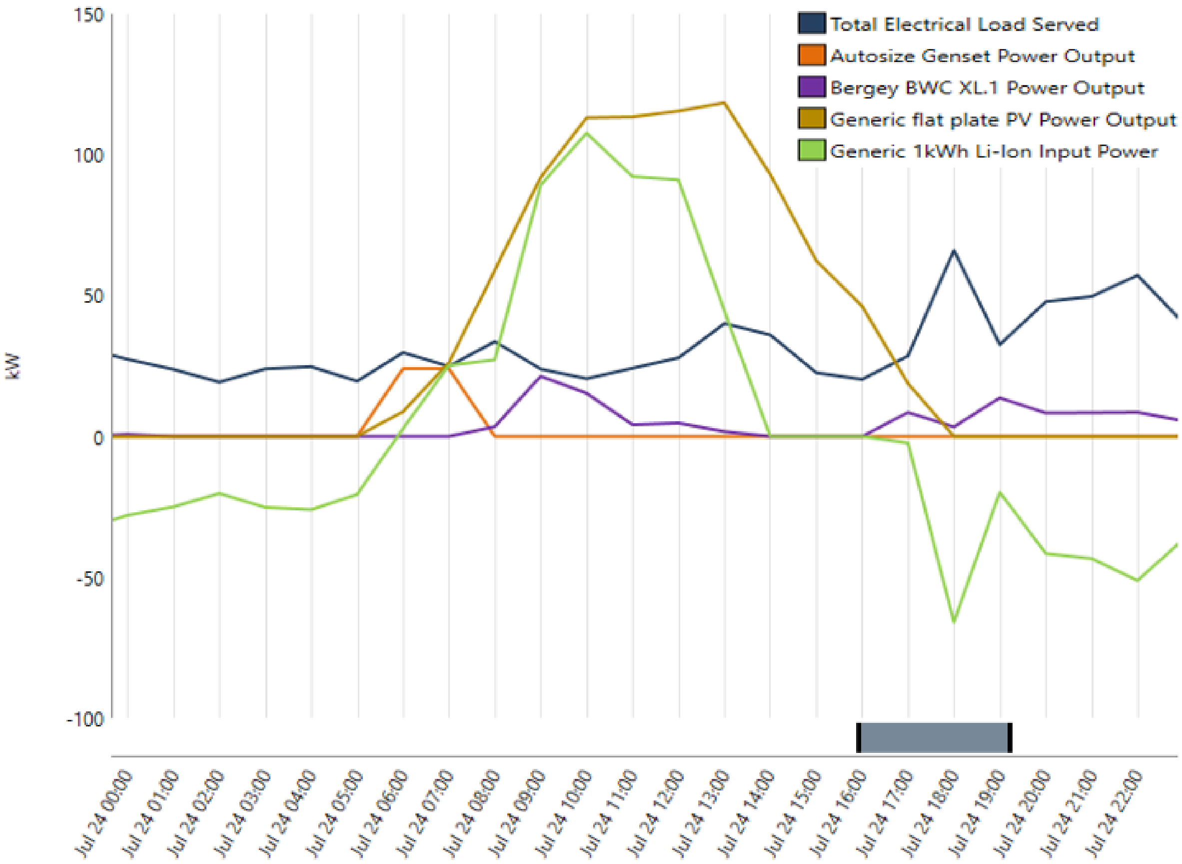


Figure 5.9: Hybrid Energy System Power Characteristics in Dry Hot Season (Modern)

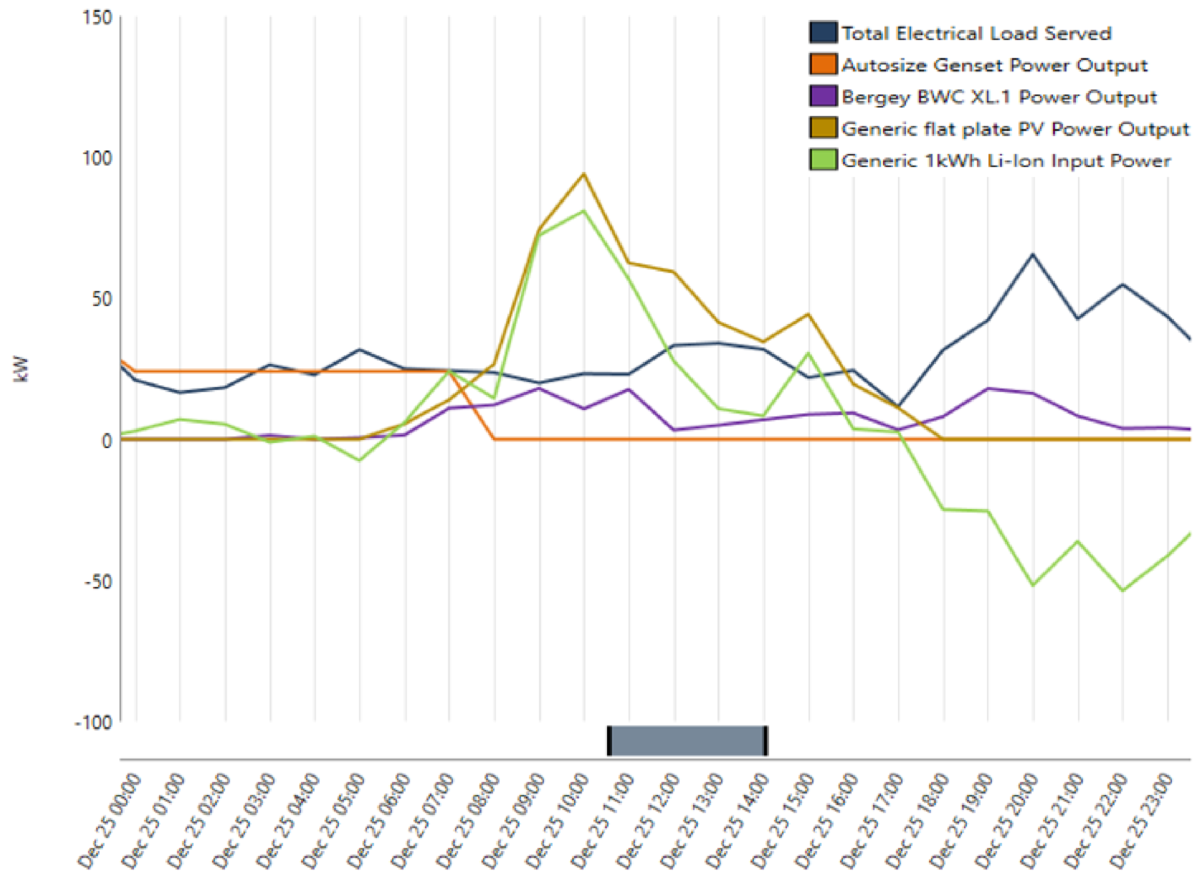


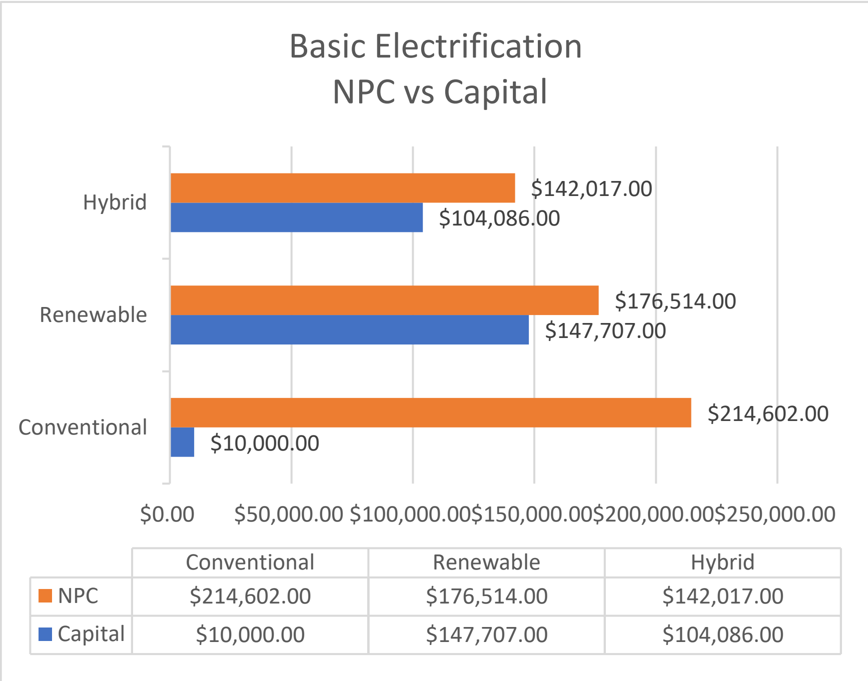
Figure 5.10: Hybrid Energy System Power Characteristics in Rainy Monsoon Season (Modern)

As illustrated in Figures 5.9 and 5.10, typical days in the hot dry and rainy monsoon seasons are selected to show the characteristics of the energy systems. In the hot dry season, combinations of renewable energy generation and batteries were able to cover the load in sequence, with support from the diesel generator at its minimum load ratio of 25% for no longer than 3 h in the morning. PVs could produce power from 05:00 to 18:00, while the wind turbines produced output from 07:00 to 14:00, continuing at 16:00 until 23:00. When the power output of the combined PVs and wind turbines exceeds demand, the batteries store electricity. Then the batteries discharge electricity to cover demand in the evening when renewable generation is unable to meet the load without the diesel generator being used.

A similar situation occurred during the rainy monsoon season, as illustrated in Figure 5.10. Typically, the batteries discharged their stored electricity when renewable generation was insufficient to cover demand. Then, the diesel generator was activated at its minimum load ratio when there was not enough power from the batteries to cover the load themselves. The power output from PVs in this season was less than in the hot dry season, but the power output from wind turbines increased. Wind turbines produced power from 06:00 to approximately

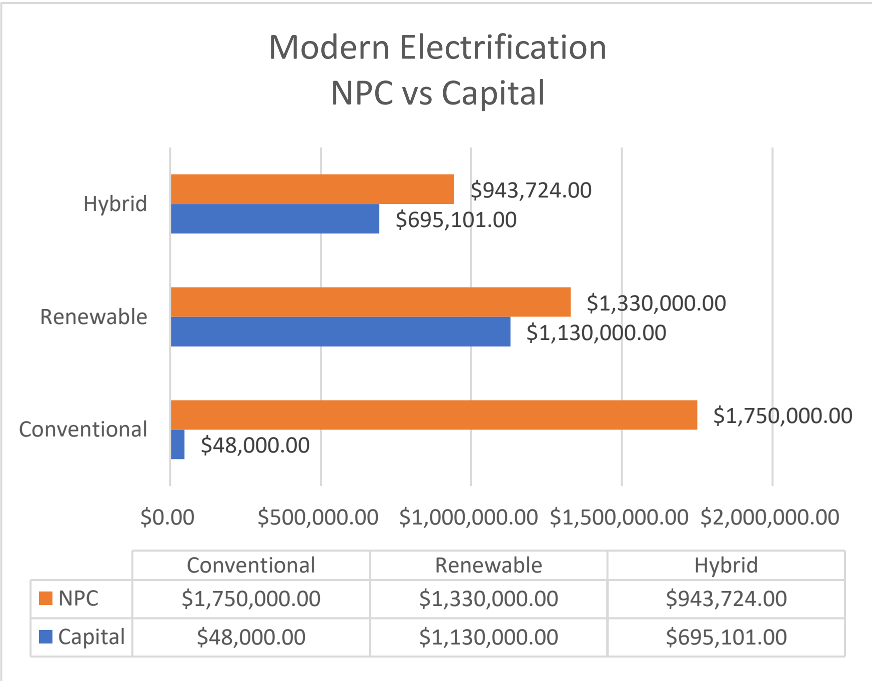
23:00 continuously. However, due to the decreasing power output from the PVs, the excess electricity stored by the batteries at noon was insufficient to cover the demand for the next morning. In this situation, the diesel generator was activated to generate electricity to cover this demand.

5.3 Energy Systems Comparison and Summary



	Conventional	Renewable	Hybrid
NPC	$214,602.00	$176,514.00	$142,017.00
Capital	$10,000.00	$147,707.00	$104,086.00

Figure 5.12: NPC vs Capital Energy Systems Comparison (Basic)



	Conventional	Renewable	Hybrid
NPC	$1,750,000.00	$1,330,000.00	$943,724.00
Capital	$48,000.00	$1,130,000.00	$695,101.00

Figure 5.11: NPC vs Capital Energy Systems Comparison (Modern)

Figures 5.11 and 5.12 summarise the financial investigation of the three electrification options for both basic and modern electrification plans for this project. First, it can be seen from the figures that the conventional energy systems have the cheapest initial capital. However, from the total NPC it is clear that these electrification options are not economically efficient for both basic and modern electrification plans through the calculations of implementing and running them throughout their 20-year lifetimes. Second, the renewable energy systems show significant differences in terms of capital cost compared to conventional energy systems. For the basic electrification plan, the capital cost itself is almost $150,000 (approximately 15 times more expensive than the conventional system), while the modern electrification plan is even higher, requiring almost 24 times the capital cost of the conventional systems. This means that implementing renewable energy technologies for energy systems is not cheap, and a significant financial layout is necessary for the initial capital. Nevertheless, it can be seen from the NPC that total costs (including capital, replacement, operation and maintenance, fuel, and salvage) throughout the 20 years) to implement and run this energy system is calculated at $176,000 for the basic, and $1,330,000 for modern electrification. It could be said that in the long-term, costs needed to run these energy systems are much cheaper compared to conventional systems.

Finally, for hybrid energy systems in both electrification scenarios, the initial capital and total NPC for these systems throughout the 20 years are between the conventional and renewable energy systems. Clearly, these systems are not cheap to implement, because they consist of renewable energy technology combinations. However, the costs can be reduced compared to all-renewable energy systems, due to this energy system being combined with conventional power generation.

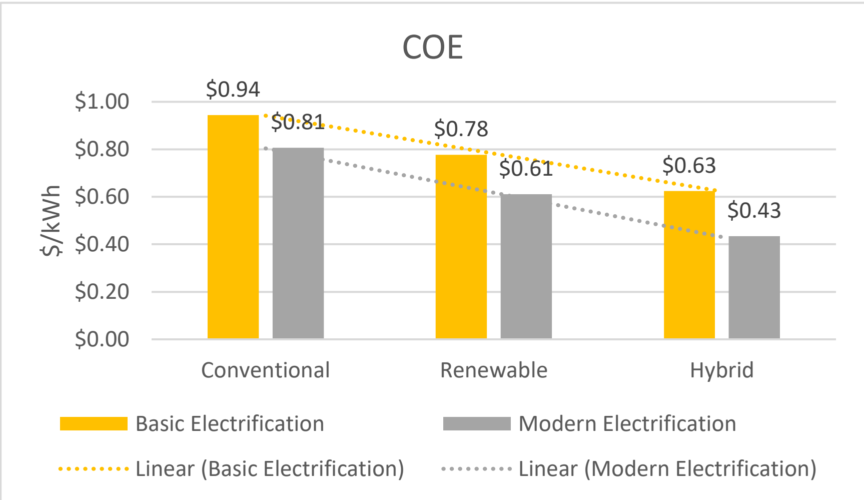


Figure 5.13: Comparison of COE

Figure 5.13 presents a comparison of the COEs of three electrification options. For basic electrification, the COE of conventional, renewable, and hybrid systems are $0.94, $0.78, and $0.63, respectively, while for modern electrification the COEs are $0.81, $0.61, and $0.43, respectively. From these simulation results, it could be said that the implementation of hybrid energy systems would reduce the cost of energy compared to conventional energy systems and would be even cheaper than the all-renewable energy systems. Consequently, amongst the three energy systems, hybrid energy systems are the most economical.

Regarding the energy performance of the electrification options for both basic and modern electrification, Tables 5.13 and 5.14 provide a summary.

Table 5.13: Energy Performance Results Summary (Basic)

	Unit	Conventional	Renewable	Hybrid
Renewable Fraction	%	0	100	91.8
Diesel Generator Electricity Production	kWh/year	30,730	0	2,109
PVs Electricity Production	kWh/year	0	61,245	26,878
Wind Turbines Electricity Production	kWh/year	0	13,070	9,506
Total Electricity Production	kWh/year	30,730	74,315	39,942
Excess Electricity	kWh/year	4,872	44,740	8,941
Unmet Electrical Load	kWh/year	0	21.5	0
CO^2 Emission	kg/year	31,799	0	2,453

Table 5.14: Energy Performance Results Summary (Modern)

	Unit	Conventional	Renewable	Hybrid
Renewable Fraction	%	0	100	91.8
Diesel Generator Electricity Production	kWh/year	268,748	0	20,288
PVs Electricity Production	kWh/year	0	567,558	239,224
Wind Turbines Electricity Production	kWh/year	0	118,822	91,493
Total Electricity Production	kWh/year	268,748	686,397	351,005
Excess Electricity	kWh/year	21,499	416,765	82,358
Unmet Electrical Load	kWh/year	0	92.9	0
CO^2 Emission	kg/year	248,715	0	19,717

According to the results, the main characteristic of conventional energy systems is their ability to produce energy efficiently to cover demand, with a small amount of excess electricity and no unmet demand. Nevertheless, this energy system produces significant CO^2 emissions compared to the other two options.

Renewable energy systems also considered has high reliability in order to cover the demand. However, they are not like conventional systems, this energy system still left the unmet electricity demand but its only below 1 percent from the total demand. Further, these systems produced a significant amount of excess electricity (approximately 60%) in both electrification scenarios. These systems produce zero CO2 emissions; hence, they are considered the most environmentally friendly.

Hybrid energy systems offer balanced energy performance compared to the other energy systems. They are able to compensate demand without any unmet load remaining, and produce less excess electricity compared to renewable energy systems. The renewable fraction of both hybrid energy systems (for basic and modern electrification) accounted for 91.8% of the total energy system. This means that the CO2 emissions from these systems are small, due to the maximisation of renewable energy generation.

Overall, because the initial idea of the electrification plan was to maximise the implementation of renewable energy resources for both basic and modern electrification scenarios, hybrid energy systems were selected as the most suitable techno-economic options for electrification planning.

5.4 Limitations and Uncertainties

Limitations and uncertainties are generally considered as a part of a project's development. Therefore, this project is subject to several limitations and uncertainties. One notable uncertainty of this project is related to the price of the components. The costs were estimated largely as averaged prices from some literature and publications which in reality, costs and other variables may vary specifically depends on the scale of development and other situations.

Another uncertainty happens when generating loads scenario which is arguably challenging considered that there are no current electricity consumption data from the government department publications. Therefore, the assumptions for the electricity demand were made by identifying a set of typical electricity appliances needs for basic small-sized house and modern medium-sized house electrifications.

Furthermore, regarding the software limitations, HOMER would prioritise the use of diesel generator due to its low fuel costs compared to discharging the power from the battery when the renewables could not cover the loads. Therefore, in this project, the fuel price is set twice as much from its actual cost to minimise the use period of the diesel generator in the hybrid energy systems.

5.5 Future Work

Regarding the limitations stated, as well as, the limited timeframe for this project, the results might not be completely accurate. Therefore, for further research, the following list should be taken into considerations for a better result:

- Accurate Parameters – As regards to all the assumptions made in this project, more accurate data would be necessary to get better results such as costs for components.
- Improved Renewable Energy Data Resources – Such as newer data for solar GHI and wind speed.
- Environmental and Social Impacts – For further improvement, environmental and social impacts conditions should be studied.
- Sensitivity Analysis – Sensitivity analysis should be carried out as well as with in depth economical investigations.

6. CONCLUSION

T The aim of this project was to maximise possible clean energy access to electrify rural villages in Indonesia, to reach an electrification ratio of 100% for the country in the future. By focussing on a case study in the Maluku Province in Indonesia, renewable energy potential has been investigated. It was found that both solar and wind resources were available at the case study site.

From all software available for energy modelling, Energy Plan and HOMER were investigated to find the most suitable energy modelling supply and demand for this project. HOMER was selected because it is user-friendly and adaptable for community-scale energy modelling, which could enable high level techno-economic analysis of the selected energy systems. However, to model the energy systems for the case study, electricity loads and all component parameters for the energy systems must be determined. Therefore, two electrification load scenarios were proposed with three different combinations of energy systems. These two electrification loads were only assumed for the household sector by determining the typical electrical appliance needs. Moreover, these two loads were classified as basic and modern electrification scenarios, which implied the power availability was 12 h and 24 h for each scenario, respectively.

Three energy systems for the electrification supply options were simulated and analysed using HOMER as the selected software for each load profile, to find the most suitable solution based on technological and economical aspects. These three energy systems were conventional, fully renewable, and hybrid combinations. The lifetime of all energy systems was projected to be 20 years. HOMER simulated thousands of possible combinations, and three combinations of energy systems were presented and analysed for each load scenario.

Based on the simulation results and discussions, the following conclusions were obtained for both load scenarios:

- Conventional energy systems have the lowest initial capital outlay, but the most expensive NPC and COE throughout the project lifetime, compared to other energy systems.
- The fully-renewable energy systems are considered reliable, because their unmet electrical loads are below 1% for both electrification load scenarios. Thus, their NPC

and COE are the most expensive options compared to conventional and hybrid energy systems.

- The most techno-economic solution for electrification planning are systems that combine conventional power generation and renewable energy technologies (hybrid energy systems), because the renewable fractions were 91.8% in both scenarios and their COE are the most economical options.
- For the basic electrification scenario, the hybrid energy system configurations consist of a diesel generator (20 kW), PVs (17 kW), wind turbines (8 kW), Li-ion batteries (104 kW), and a converter (14.3 kW). Their total NPC and COE are $142,017 and $0.625, respectively.
- For the modern electrification scenario, the hybrid energy system configurations consist of a diesel generator (96 kW), PVs (151 kW), wind turbines (77 kW), Li-ion batteries (593 kW), and a converter (74.2 kW). Their total NPC and COE are $943,742 and $0.434, respectively.
- The diesel generator operation is limited to cover the load, which only occurs in periods where the renewable energy and the batteries are unable to cover demand (not used to also charge the batteries).
- The limited operation of the diesel engine contributed to decreased NPC, COE, and CO^2 emissions.

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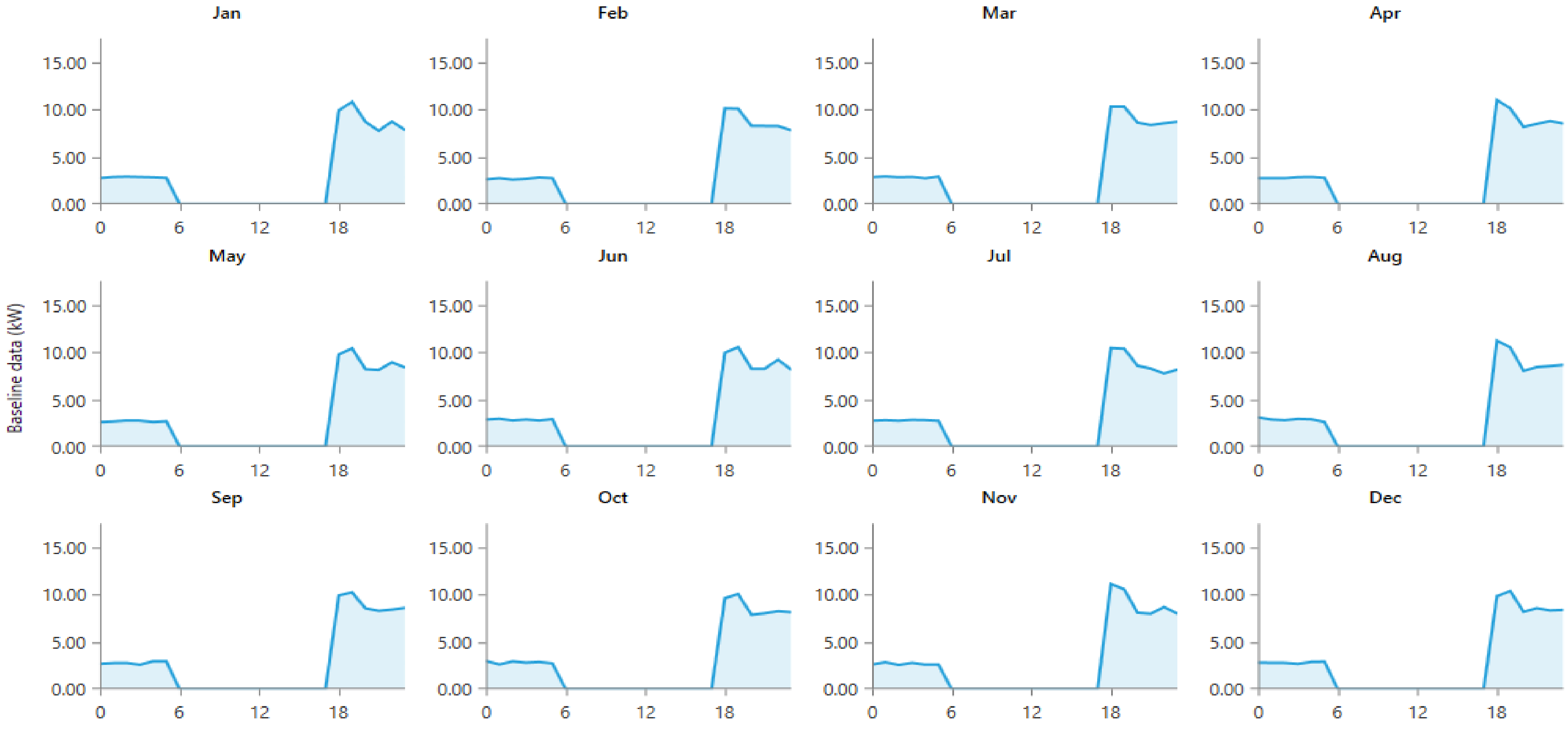
Appendix A: Daily Demand Profile for Electrification Scenario

Basic Electrification



Modern Electrification