DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

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Assessment of Hybrid Renewable Energy System: Application to Sichang Island, Thailand

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Copyright Declaration

Abstract

Climate change and global warming are vital issues affecting several countries, including Thailand. Among the pivotal factors contributing to this concern is the source of electric power generation. Currently, Thailand's primary energy source produce from fossil fuels, with natural gas occupying a prominent role, accounting for over 50% of the total generation. Furthermore, there has been a rapid growth in electricity consumption in Thailand over the past two decades, characterized by an average annual growth rate about 5.47%. Consequently, renewable energy will become a solution for environmental protection by minimizing an emission, energy security, and long-term growth. The aim of this project is to assess the viability of a hybrid renewable energy system design and promote the power generation that come from renewable sources, which consists at least 35% of renewable fraction based on Thailand Power Development Plan 2018 by governments. Sichang island, an island that currently relies primarily on diesel generators for power generation is selected into this study. The criteria for evaluating over this project will involve financial analysis and an assessment of the environmental impact.

Homer software was selected as a simulation tool due to its capability to assess the financial, emission, and technical aspects of various hybrid energy systems. Its selection was driven by the software's potential to analyse a wide array of feasible options. Before the simulation, it is necessary to add an input parameter, including electricity demand, the potential of solar irradiance, wind speed, and the cost of the components. However, there are some constraints in this software, particularly the changes in the cost of the components or energy price during the project lifetime, as well as the potential of renewable resources, which are fixed. Therefore, it can cause a discrepancy between some results from reality.

The results of this project were separated into 4 scenarios of hybrid renewable energy systems, which illustrated different proportions and input components in each scenario. As a result, Scenario 4 has been selected as it has the most feasible option in terms of financials and emissions aspects, as well as the greatest renewable fraction. Although there is a substantial amount of excess electricity production compared to Scenario 1, these amounts can be useful in the future due to the possibility of an annual growth in electricity consumption. Moreover, if energy sales to the grid are considered, it could enhance the performance of the systems and generate additional income for the community.

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Nomenclature

AC – Alternative Current

cm – Centimeter

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

COE – Levelized Cost of Energy

DC – Direct Current

DHI – Diffuse Horizontal Irradiation

DNI – Direct Normal Irradiation

EGAT – Electric Generating Authority of Thailand

EPPO – Electric Power Policy and Planning Office

ERC – Energy Regulatory Commission

FiT – Feed-in tariff

GBP – Great British Pound

GHI – Global Horizontal Irradiance

GVA – Gigavolt-ampere

GW- Gigawatt

GWh – Gigawatt-hour

IPPs – Independent Power Producer

kg – Kilogram

km – Kilometer

kV – Kilovolt

kW – Kilowatt

kWh – Kilowatt-hour

kWp – Kilowatt peak

L – Liter

Li-ion – Lithium-ion

m/s – Meter per second

MEA – Metropolitan Electricity Authority

MJ - Megajoule

mm – Millimeter

MSW – Municipal Solid

MW – Megawatt

NO_x - Nitrogen Oxides

NPC – Net Present Cost

O & M – Operation & Maintenance

PDP – Power Development Plan

PEA – Provincial Electricity Authority

PM – Particulate Matter

PPA – Power Purchase Agreements

PV – Photovoltaic

SO_2 – Sulphur Dioxide

SPPs – Small Power Producer

THB – Thai Baht

UHC – Unburned Hydrocarbons

VSPP – Very Small power Producer

℃ - Degree Celcius

1 Introduction

1.1 Problem definition

At present, climate change and global warming are vital issues that many countries around the world are facing. NOAA's 2021 Annual Climate Report states that the global temperature, comprising both land and ocean measurements, has risen by an average of 0.08 degrees Celsius per decade since 1880 [1]. One of the main factors is the source of electric power generation. Currently, the primary energy source in Thailand is natural gas. According to a report by the Electric Power Policy and Planning Office (EPPO), natural gas has consistently accounted for more than 50% of Thailand's total electricity generation [2]. However, given the decrease in domestic gas production and limited prospects for expanding pipeline infrastructure for procuring gas from other countries, Thailand will increasingly depend on imports of natural gas [3]. Unexpectedly, global natural gas buyers have faced significant challenges due to the conflict in Ukraine in recent year. This conflict has led to escalated costs and posed a substantial threat to the availability of fuel supplies from Russia, a major exporter of natural gas. The resultant effect has been a drastic reduction in gas supplies to Europe, reaching approximately 80 percent. It also had an effect in Thailand, as it occurred at a time when domestic gas production in the Gulf of Thailand has decreased significantly, resulting in an increased reliance on natural gas imports. Given the predominance of natural gas in Thailand's energy production, the price of electricity for Thai consumers is anticipated to rise substantially in 2023.

According to a report by Krungsri in 2020, the power generation sector in Thailand is projected to experience a slight growth with an annual electricity consumption increase of about 2.8-3.8% between 2021 and 2023 from COVID-19 pandemic recovery, population growth, and expected growth in tourism sector [3]. Renewable energy emerges as a viable option in this context, offering the potential to address the increasing demand while mitigating the potential impacts of geopolitical conflicts on natural gas supplies [4]. The adoption of renewable energy technologies aligns with the global shift towards sustainable energy systems. Not only does it contribute to reducing greenhouse gas emissions and combatting climate change, but it also offers long-term benefits in terms of environmental protection, energy sustainability, and public health.

However, renewable energy is still a minor source for energy production in Thailand, making up no more than 10.5% of the total production in the past decade, as indicated by the EPPO report. Under the Power Development Plan (PDP) in 2018, Thailand intends to increase its total power generation capacity to 77 GW by 2037 by boosting the generation from renewable power plants up to 35 %, designed to support cleaner production as a pathway to energy security and carbon neutrality [5]. While the use of natural gas-fired power plants aims to reduce to 42.5% and coal-fired power plants to 6.3%, respectively**.** Renewable energy is gaining popularity all over the world. Renewable energy technologies are frequently indispensable for environmental protection, energy security, and long-term growth. Particularly, wind and solar energy are two feasible choices for lowering carbon emissions while contributing to a cleaner and safer environment [6]. In order to promote more environmentally friendly power generation, Thailand's renewable energy resources, including solar, biomass, wind, and hybrid renewable energy sources, have lately been analysed that Thailand's power system needs to adapt to satisfy the rising need for flexibility resulting from changes in both demand and supply.

Currently, microgrids play a significant role in a number of segments, including academia to the energy supply sector. A microgrid is a collection of interconnected loads and distributed energy resources enclosed within well-defined electrical boundaries that functions as a single, controllable entity in relation to the main power grid. Due to its adaptability, a microgrid can operate in both grid-connected and island modes by connecting or disconnecting its connection with the grid [7]. Their abilities are to support renewable energy has led to their adoption in a variety of settings, involving rural and urban communities in local, national, and possibly even international contexts, as well as laboratory-scale demonstration sites. The operation of microgrid contains a number of key goals as follows: 1) achieving a balance between electricity supply and demand, 2) reducing technical losses in the electrical system, 3) expanding the lifespan of electrical equipment, 4) developing the quality, reliability, resiliency, efficiency, and safety of electricity supply, 5) lowering carbon dioxide (CO_2) emissions, 6) addressing energy poverty and inequities as well as 7) enhancing access to affordable clean energy.

The inclusion of microgrid initiatives in Thailand's 2015 energy development plan reflects essential national integration. Three state-owned electric utilities in Thailand, namely the Provincial Electricity Authority (PEA), the Metropolitan Electricity Authority

(MEA), and the Electricity Generating Authority of Thailand (EGAT), are principally responsible for these activities [8]. Presently, a number of studies are being carried out to design an optimal microgrid system in different regions of Thailand, especially in rural areas where 60% of the population dwells as there is extensive potential for renewable resources depending on the area. A Studies conducted by Chaleekure et al. (2018), Kasirawat et al. (2017), and Khamharnphol et al. (2023) have identified a significant barrier in terms of the intermittency of renewable sources such as wind and solar, which reduces the effectiveness of the system without the integration of energy storage technologies [9]–[11]. Therefore, the implementation of adequate energy storage capacity is necessary to ensure flexibility between energy generation and demand. Furthermore, one of the key challenges is achieving cost-effectiveness, particularly system installation costs.

Consequently, this project will concentrate on an investigation of the hybrid renewable energy system to enhance the production capacity of renewable energy. Moreover, a cost analysis, which includes installation, operation and maintenance (O&M), replacement, and net present cost as well as minimizing CO_2 emissions and environmental impact, are all taken into account. Sichang island, an island located on Chonburi province in the eastern of Thailand is selected as a case study site. The selection of this island for the project is based on the expense of the current power generation system, comprised of five diesel generators with a 1,000 kW capacity each. The recorded power consumption in 2022 was about 2.2 million British pounds. To address this issue, the government intends to install a microgrid on the island to operate with a submarine cable connecting the mainland to the island, with operations anticipated to begin in 2025.

1.2 Aim

The aim of this dissertation is to investigate the feasibility of a hybrid renewable energy system in Thai island in order to reduce or avoid energy generation from fossil fuels such as diesel generators and minimize the imported energy from the grid. It is complemented by detailed objectives as follows:

- Acquire the energy demand profile from Sichang Island
- Evaluate the feasibility of renewable energy solutions, taking into account the region's geographical characteristics, and designing a hybrid renewable energy system to meet the energy demand

- Propose alternative scenarios of energy supply and evaluate their cost, energy production and impact to environment
- Recommend the appropriate type of system and site for installing the hybrid renewable energy system

Not included in this study:

- Transportation
- Thermal energy in cooking and industrial process

1.3 Overview of methodology

By achieving all the objectives, the following methods are required to be complete as follows:

1) *Analyze a current demand consumption profile*: The current electricity demand will be evaluated over the course of a year in order to determine how it varies throughout different seasons.

2) *Evaluate energy generation resources*: The efficiency of current electrical infrastructure will be evaluated, taking into account its capacity and the use of both non-renewable and renewable fuels. Moreover, an in-depth study will be undertaken to determine the feasibility of difference energy resource for future installations.

3) *Study in cost analysis*: Once identifying the energy resources, the installation, operation and maintenance, and replacement costs of each technology will be projected.

4) *Using Homer software*: In order to obtain a viable hybrid combination design. The HOMER software has been considered for this project as it allows for the development of hybrid system designs and provides data on CO_2 emissions and financial aspects for a wide range of scenarios.

5) *Suggestion of suitable site for installing the system*: Even though the HOMER software assess the hybrid combination system, it doesn't take into account the societal impacts of the outcomes. Thus, it is necessary to suggest appropriate locations for configuring the model in order to analyse and avoid negative impacts on communities while increasing the advantages derived from energy resources.

6) *Results and conclusion*: This phase consists of a discussion and comparison of the benefits and drawbacks of each scenario. A summary of the results will be provided, along with recommendations for further project work.

1.4 Structure of the dissertation

This dissertation is structured into 6 chapters, as follow:

- *Chapter 1* – to define the main problems of this study about the investigation of hybrid renewable energy system installation to promote the renewable sources generation and mitigate the generation from fossil fuel and briefly introduce about current situations, the goal of Thailand's power system in national level along with limitation. The aim and objectives also mentioned in this chapter.
- *Chapter 2* – to focus on a comprehensive literature review that covers various aspects of Thailand's electricity infrastructure, including generation, transmission, and distribution as well as examines the energy demand and supply dynamics within the country. Additionally, the assessment of renewable resources in Thailand is discussed, with a specific focus on determining optimal scenarios for the selected case study island. The HOMER Pro software is introduced as a simulation tool that will be utilized to achieve the objectives.
- *Chapter 3* – to introduce the software that was used in this study along with the input parameters, including the electric demand profile and the renewable resource potential of solar and wind. Additionally, components and parameters for modelling a hybrid renewable system were also mentioned, particularly on economics, emissions, and renewable resources that were selected in the simulation, as well as project limitations and assumptions.
- *Chapter 4* – to convey the results and primary findings derived from the simulations discussed in previous chapter.
- *Chapter 5* – to suggest the possible areas to install the most feasible hybrid renewable energy system from the previous chapter.
- *Chapter 6* – to recap the main findings of this study and suggest areas for improvement for future research.

2 Literature Review

This chapter provides an in-depth overview of the theoretical framework of this dissertation from numerous perspectives. The chapter is divided into six major sections as follows:

1) Overview of Thailand
2) Availability of renewable resources
3) Energy Policy in Thailand
4) A case study island: Sichang Island
5) Energy storage technologies
6) HOMER software

2.1 Overview of Thailand

The Kingdom of Thailand is a country located in the central of Southeast Asia with a population of about 67 million people in an area of 513,120 km^2. There are 77 provinces, which are divided into 6 regions as follows: Northern Region (9 provinces), Northeastern Region (20 provinces), Central Region (22 provinces, including Bangkok, the capital of Thailand), Eastern Region (7 provinces), Western Region (5 provinces), and South Region (14 provinces) which present in Figure 1. Thailand's ecosystem is typically varied by the region. In the north and western regions, characterized by mountain ranges, the Northeast region consists of a vast plateau and is well known for being the most arid region during the summer period. There is a low-lying area with a river in the central region of Thailand that is most feasible for agriculture. The eastern and southern regions are known for their stunning beaches, islands, and marine life along the Gulf of Thailand and Andaman coasts, which in the southern is one of the main destinations for the majority of tourism where it covers both coastlines, while the eastern only covers the Gulf of Thailand coast [12].

Figure 1: Thailand Map

Thailand has a tropical climate that is affected by monsoon winds. The southwest monsoon delivers a stream of warm, humid air from the Indian Ocean to Thailand, leading to excessive precipitation in the months of May to October. From October to February, the northeast monsoon brings cold and dry air from the anticyclone in China across significant areas of Thailand, particularly the northern and northeastern regions, which are located at higher latitudes. Along the eastern coast of the South, the monsoon causes moderate weather and high rainfall. Then, From March to May is a summer period when the temperature in all the area will reach its peak. Figure 2 represents Thailand's seasonal climatic cycle for the last 30 years, from 1991 to 2020. April and May are the hottest months of the year in Thailand, while December and January are both the coolest. The seasonal temperature variance is 5.7 °C, with a yearly average temperature of 26.3 °C and a range of 23.2 °C to 28.9 °C. August and September recorded the most rain, with a total of about 255 mm. From May to October, the monsoon season in Thailand corresponds with the rainy months. The annual average precipitation is 1.542 cm [13].

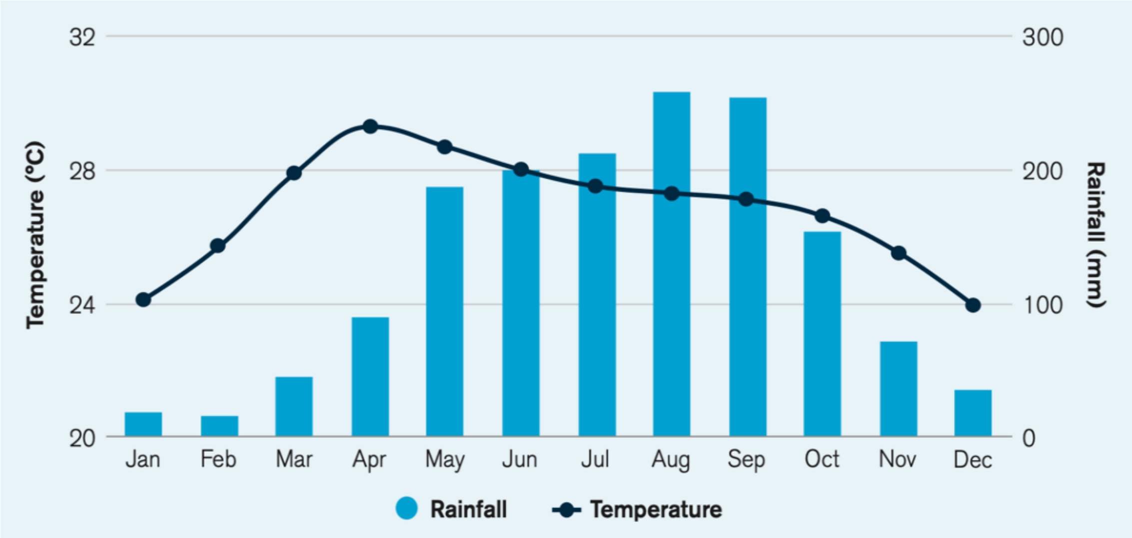

Figure 2: Average monthly temperature and rainfall in Thailand (1991–2020) (Source [13])

2.1.1 Electricity Infrastructure

In Thailand, the Ministry of Energy governs the energy and electricity sectors, which entail multiple agencies. Thailand's electrical system is organized as indicated in Figure 3 [14]. EGAT is a utility owned by the government that operates the entire transmission network and is accountable for the majority of the nation's power generation capacity. It performs the roles of system operator and principal buyer. MEA and PEA are two state-owned companies, whereby EGAT sells nearly all of the electricity it produces or purchases from private power suppliers and that borders countries. MEA and PEA are responsible for the distribution of electricity to residential, commercial, and industrial consumers across Thailand. They are responsible for owning and operating the power distribution systems in their respective areas. In the Bangkok metropolitan area, the MEA has the sole right to distribute and sell power to end consumers, but the PEA has this right for the provincial area. The state agencies and Energy Regulatory Commision (ERC) establish the regulatory cost for which EGAT sells electricity to MEA and PEA.

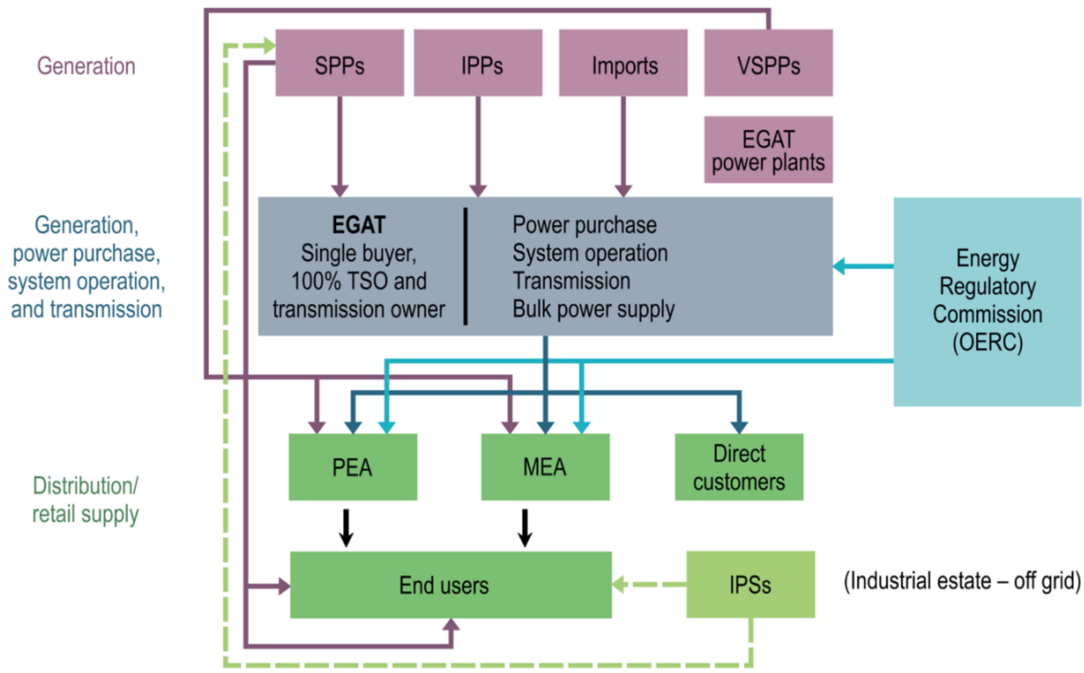

Figure 3: Electricity Industry Infrastructure in Thailand (Source [15])

The government has permitted the private sector to participate in the generation of renewable energy. Through the small power producer program, private developers have the right to construct, own, and manage renewable energy projects with capacities in the range of 10 MW to 90 MW as well as enter into power purchase agreements (PPA) with EGAT. The classification of private sector can separate into 3 types based on amount of install capacity as follows:

1) Independent Power Producer (IPPs) - generation with a capacity over 90 MW with the power purchase agreement (PPAs)
2) Small Power Producers (SPPs): generation output between 10 and 90 MW under the PPA and selling electricity to nearby industrial estates.
3) Very Small Power Producers (VSPPs): generation with an output less than 10 MW without PPA agreement by selling to PEA and MEA directly.

Figure 4 displays the percentage of installed capacity share by four different sources: EGAT's power plants, private producers (IPPs and SPPs), and imported power for a period of 20 years from 2002 to 2022. According to the bar chart, the private sector progressively contributed to the installation of power generation, accounting for 23 percent from 30–53% from 2022 to 2022, while power generation from EGAT was conversely reduced by 27% from 61% down to 34%.

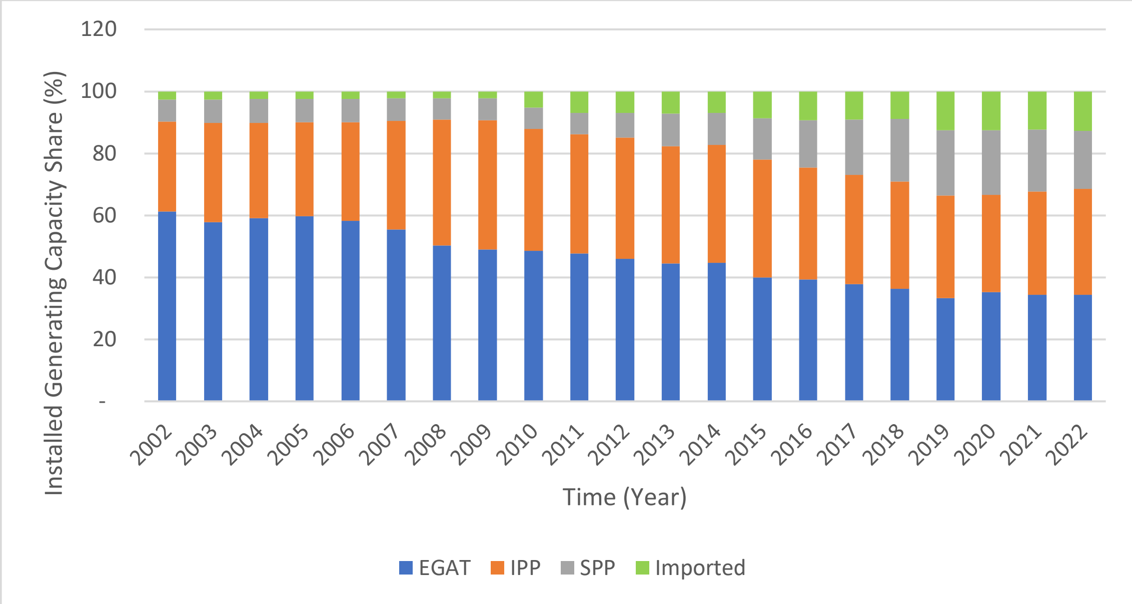

Figure 4: Shared installed generating capacity (Classified by producer) (Source [2])

For transmission system, EGAT operates a comprehensive grid network that facilitates the transmission of electricity generated from its own power plants and private power producers. This network spans the whole country which illustrate in Figure 5. EGAT owned transmission lines with different voltage levels, including 500 kV, 230 kV, 132 kV, 115 kV, and 69kV at a frequency of 50 Hz. EGAT also exports electricity to the power utilities of nearby countries. Particularly, EGAT supplies Laos's power utilities with electricity via 115 kV and 22 kV lines as well as a high-voltage direct current (HVDC) connection has been established in the southern region of Thailand, capable of transmitting 300 MW of power to and from Malaysia [15].

Figure 5: National Grid Network in Thailand

(Source [16])

Table 1: Transmission System statistical in Thailand

Voltage Level (kV)	Line Length (Circuit-km)	Number of Substations	Transformer Capacity (GVA)
500	8,275.2	25	49.9
300	23	–	0.3
230	15,444.6	86	70.4
132	8.7	–	0.1
115	14,690.9	125	15.6
69	18.8	–	–
Total	**38,461.2**	**236**	**136.3**

Table 1 presents the recently updated transmission system statistics in April 2023. Currently, the transmission system in Thailand exhibits varying characteristics across different voltage levels. At the highest level of 500 kV, there are extensive transmission lines spanning over 8,275.2 circuit-km, supported by 25 substations with a transformer capacity of 49.9 GVA. The 230 kV level features widespread coverage of transmission lines spanning 15,444.6 circuit-km, with 86 substations and a transformer capacity of 70.4 GVA. The 115 kV level demonstrates an extensive line length of 14,690.9 circuit-km, supported by 125 substations and a transformer capacity of 15.6 GVA.

2.1.2 Energy Consumption

Thailand is located in a tropical climate characterized by high temperatures, humidity, and distinct wet and dry seasons. The climate data in Thailand plays a crucial role in understanding the energy consumption patterns and demands within the country. The hot and humid climate leads to a rise in cooling and ventilation energy consumption, particularly in residential and commercial buildings. In addition, seasonal variations in precipitation have an impact on the demand for irrigation and agricultural activities, which in turn affect the energy consumption of the agricultural sector.

Figure 6 illustrates the electricity consumption data in Thailand provided by EPPO. As a result, electricity consumption has steadily increased over the years 2002–2022, except in 2009, 2011, and 2020. There are rising numbers, from 100,000 to 190,000 GWh between 2002 and 2022, which accounted for 90% of the increase.

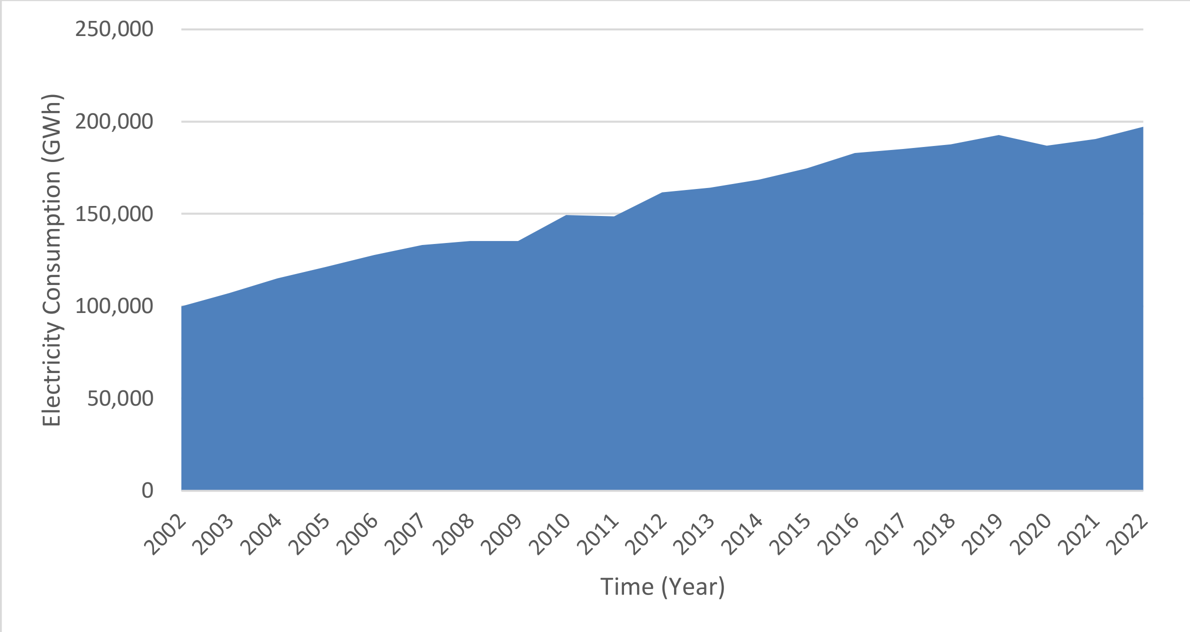

Figure 6: Annual Electricity Consumption in Thailand (Source [2])

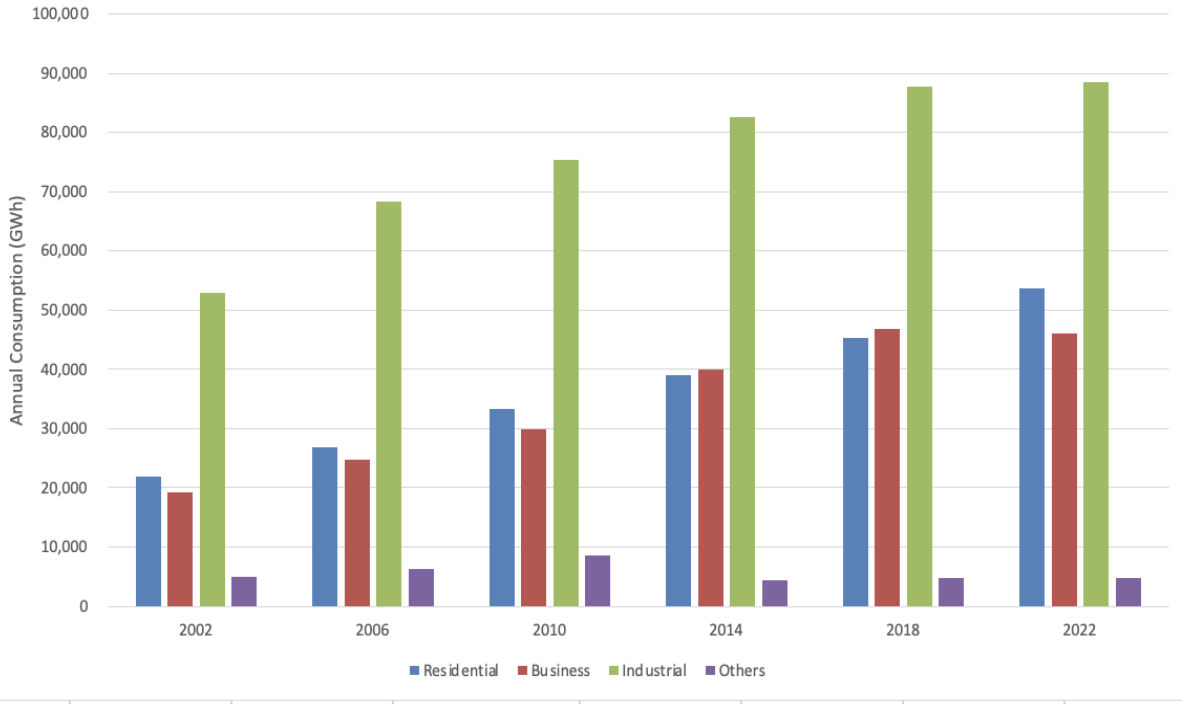

Figure 7: Annual Electricity Consumption in Thailand (Classified by sector) (Source [2])

In addition, Figure 7 illustrates the annual electricity consumption by narrowing it down into four different sectors: residential, business, industrial, and others. According to the bar chart, the industrial sector accounted for the largest share of electricity consumption in 2002, reaching 52,965 GWh, which represented 52.9% of the total. Conversely, residential, business, and other sectors consumed 21.9%, 19.2%, and 6%

respectively. Although the overall energy demand experienced a slight increase over the years until 2022, the proportion of electricity consumed by the industrial segment decreased to 44.9%. Meanwhile, the shares of electricity consumption in the residential and business sectors saw an increase, reaching 27.2% and 23.3%, respectively.

2.1.3 Energy Supply

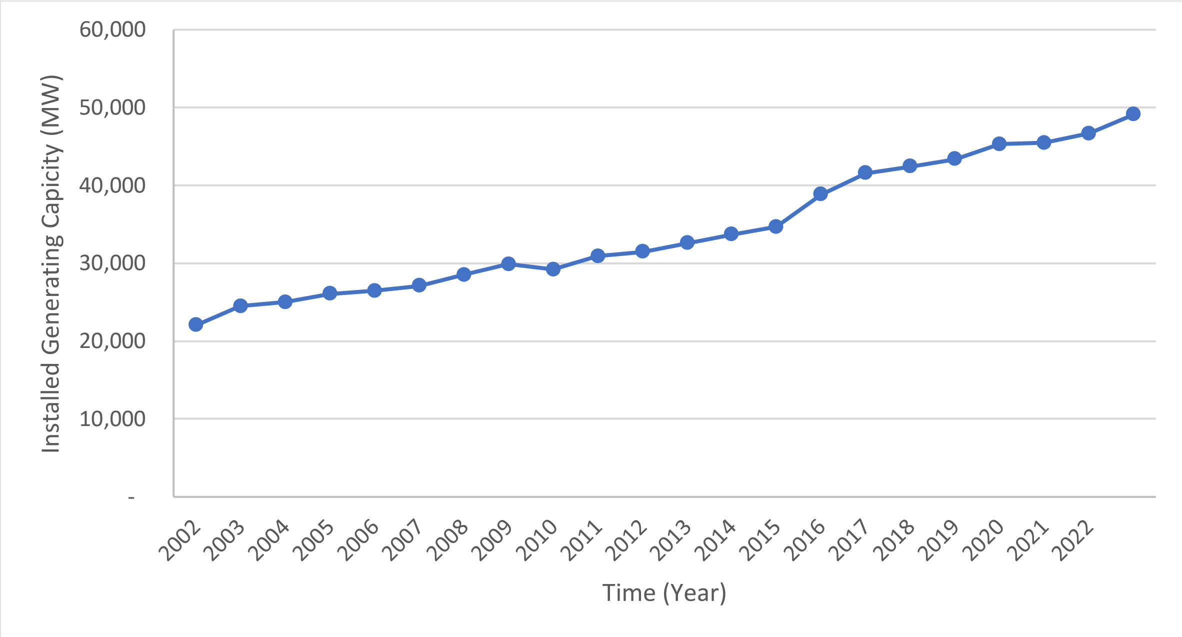

Figure 8: Annual Installed Generating Capacity in Thailand (Source [2])

The data in Figure 8 represents the installed electricity generation capacity in Thailand from 2002 to 2022. Over this time period, there has been a noticeable upward trend in capacity, indicating the continuous growth of the electricity generation sector in Thailand. The capacity has increased steadily from 24,479 MW in 2002 to 49,098 MW in 2022. Nevertheless, Figure 4 reveals that the current power generation capacity in Thailand is inadequate to fulfil the growing energy demand throughout the entire nation. This is evident from the rising proportion of imported energy, which poses a significant concern as it may potentially result in future electricity shortages. The reliance on imported energy sources highlights the need for further investment in domestic power generation infrastructure to ensure long-term energy security and mitigate the risks associated with relying heavily on external energy supplies.

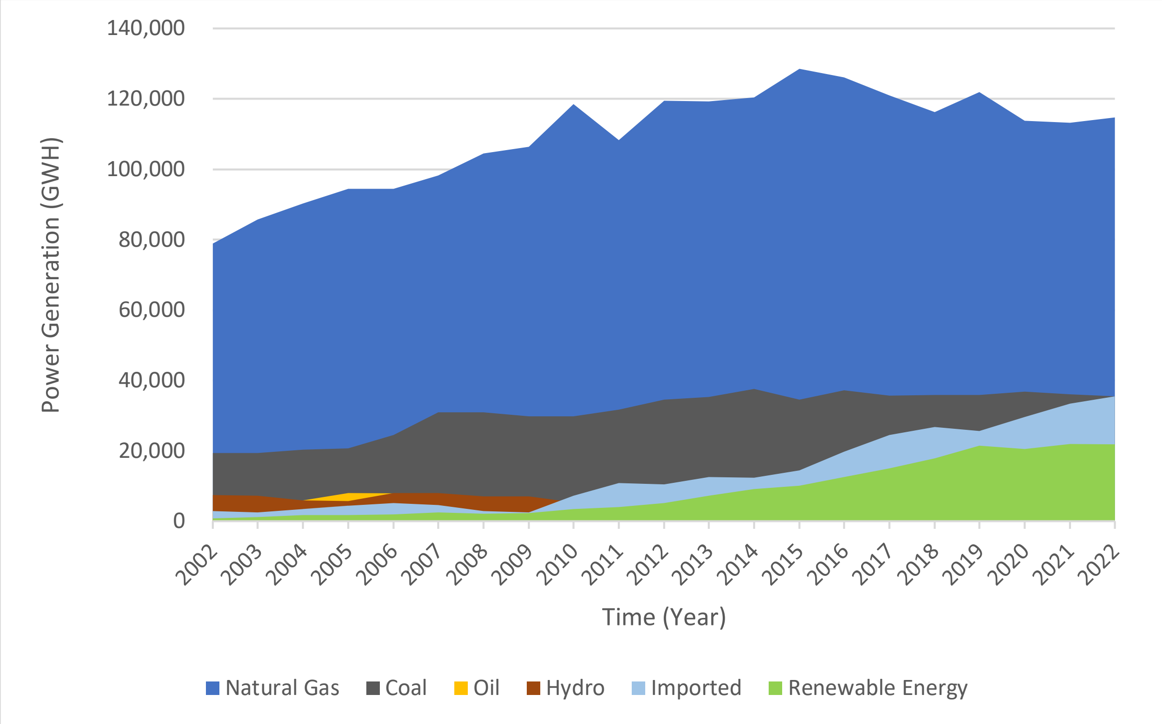

Figure 9: Annual Power Generation (Classified by fuel types) (Source [2])

The provided graph in Figure 9 presents a comprehensive overview of power generation in Thailand from 2002 to 2022, categorized by different fuel sources. Natural gas has consistently been the dominant source of energy throughout this period, with varying levels of contribution. It is remarkable that the utilization of renewable energy sources, such as hydropower and imported energy, has grown progressively over time.

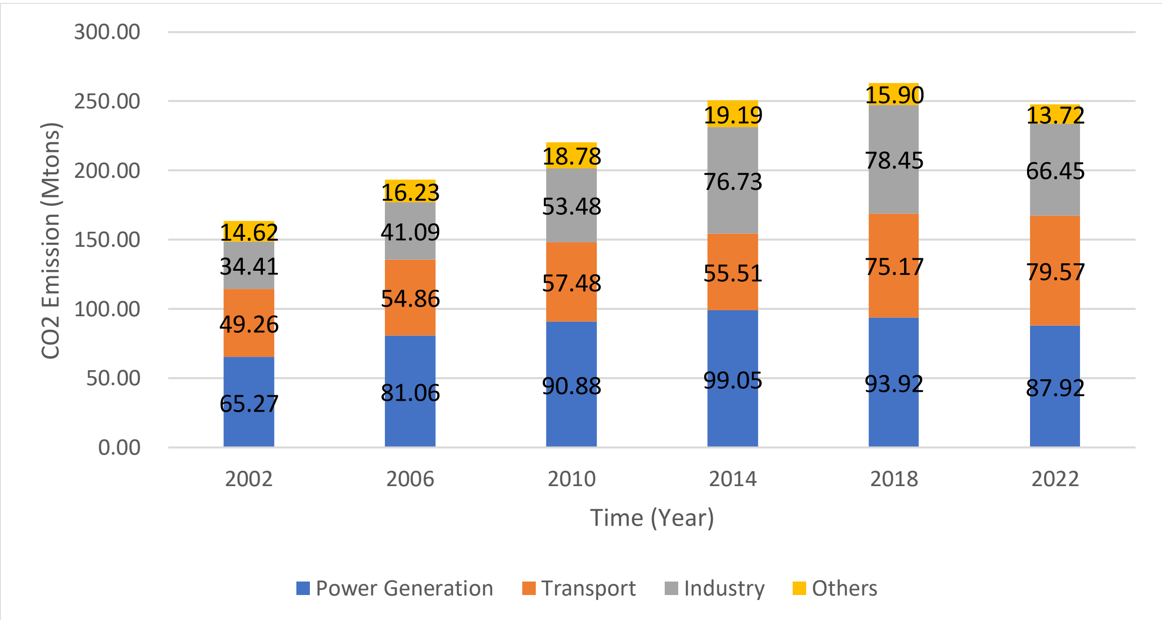

Figure 10: Annual CO_2 Emission (Classified by sector) (Source [2])

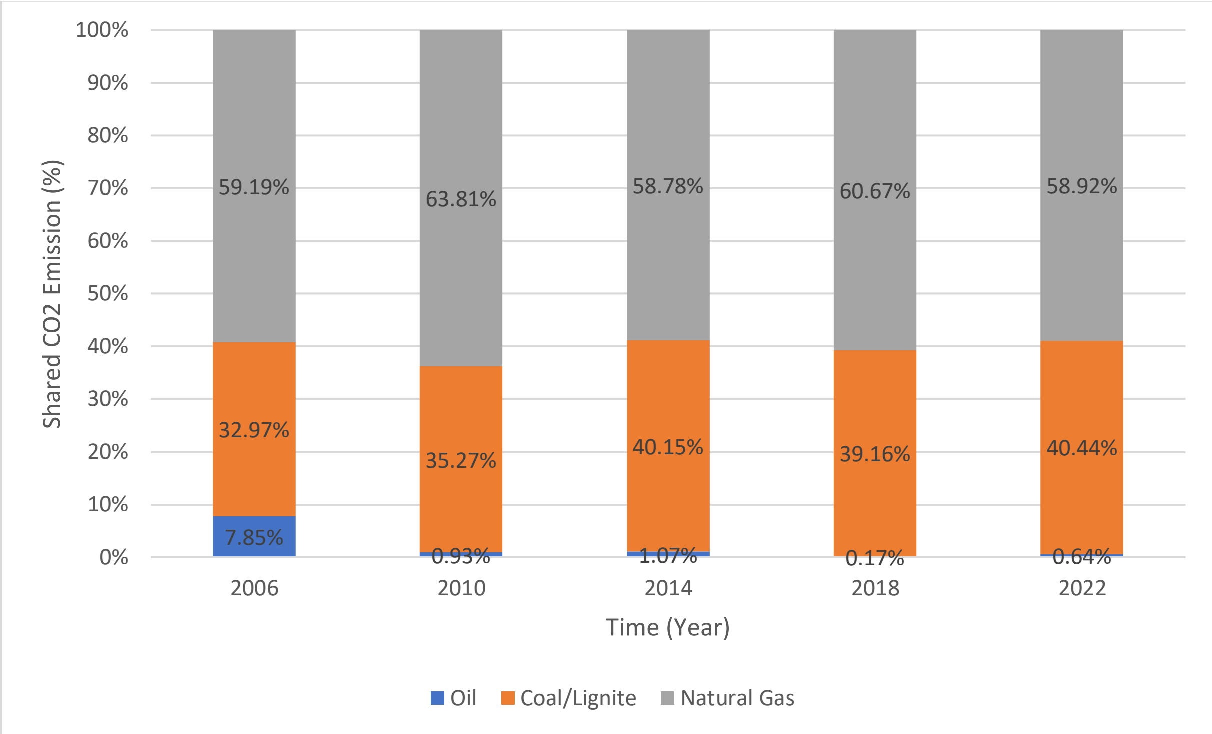

Figure 11: Shared Annual CO_2 Emission (Classified by fuel types) (Source [2])

Moreover, the bar chart of emissions in Figures 10 and 11 reveals the trends in Thailand's power generation and its impact on carbon emissions. In Figure 10, the power generation sector has experienced fluctuations in emissions over the years. In 2002, it emitted 65.27 Mtons, which increased to a peak of 99.05 Mtons in 2014. However, by 2022, the emissions had decreased to 87.91 Mtons. Also, Figure 11 breaks down the percentage of emissions from fossil fuel sources into the changing composition of fuel types used for energy generation in Thailand. From 2006 to 2022, the proportion of oil used for generating energy decreased from 7.85% to 0.64%. Similarly, coal consumption decreased slightly from 32.97% in 2006 to 40.44% in 2022. During the same time period, natural gas remained the dominant fossil fuel source, ranging from 58.78% to 63.81%. This information indicates a shift towards more nutritious energy sources, with a significant decrease in oil consumption and a slight decrease in coal consumption, while natural gas remains to play a significant role in Thailand's energy production.

These statistics emphasise the significance of transitioning to renewable energy sources in the power generation sector in order to decrease emissions. In addition, efforts to promote sustainable transportation behaviours and enhance energy efficiency are crucial for attaining carbon reduction and addressing climate change issues.

2.2 Renewable Energy in Thailand

The development of renewable energy sources and energy conservation initiatives have long been actively encouraged and subsidized in Thailand. The goal of this commitment is to improve overall life quality, ensure economic stability, and enhance energy security. Thailand aims to reduce its reliance on imported fossil fuels by progressively increasing the use of alternative energy sources and improving energy efficiency. This approach provides several co-benefits in terms of environmental sustainability, social well-being, and economic growth, along with limiting the long-term risks related to energy imports. Furthermore, the development of indigenous renewable energy sources supports job creation and encourages a more resilient and environmentally friendly society [17].

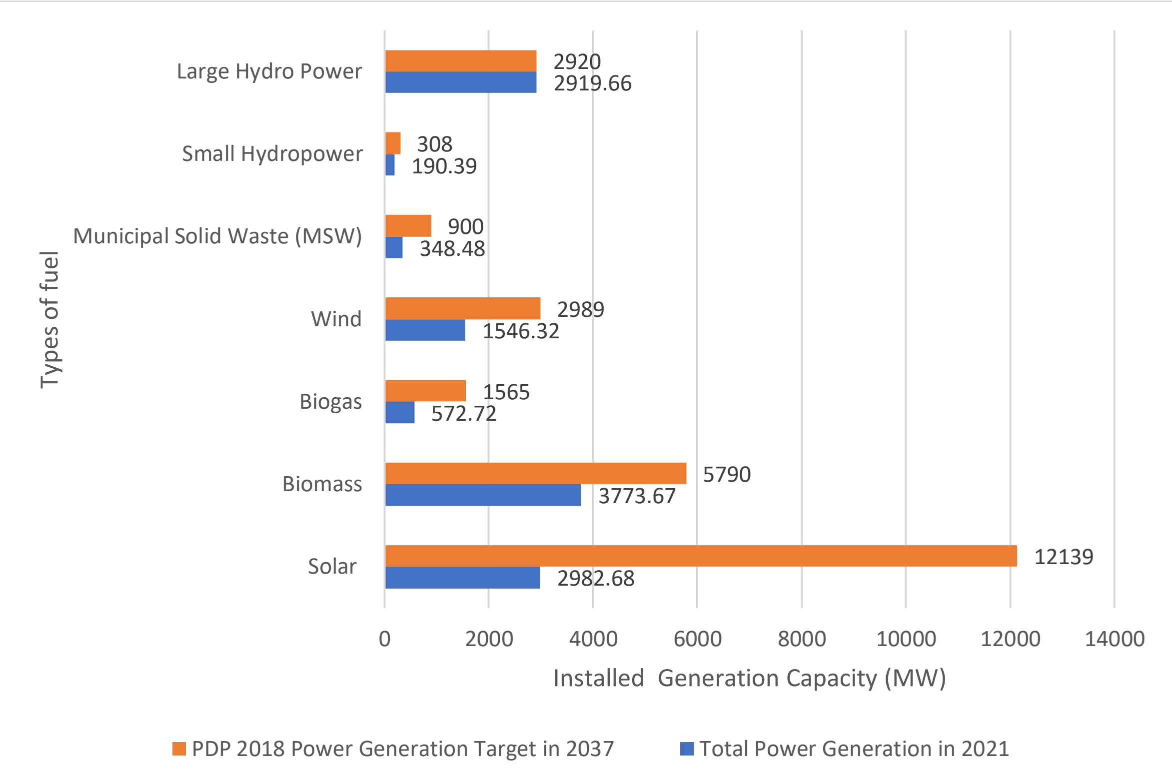

Figure 12: Comparison of Total Power Generation Source and Targets from PDP 2018 (Translated from [18])

As aforementioned in Figure 9 about the annual power generation by fuel types. The installed generation capacity from renewable energy sources is considered as a minority source, with approximately 10% from total power generation. The data in Figure 12 presented the total installed generation capacity of various renewable energy sources in Thailand in 2021, compared to the targets set in the PDP 2018 to achieve the total energy production from renewable resources at 35 % by 2037. In terms of solar energy, the installed capacity in 2021 reached 2,982.68 MW, which falls short of the PDP 2018 target of 12,139 MW. Similarly, biomass, biogas, and wind energy also exhibited lower installed capacities in 2021 compared to the PDP 2018 targets. Municipal solid waste (MSW) and small hydropower installations were also below the set targets. However, the installed capacity for large hydropower exceeded the PDP 2018 target. These findings highlight the need for further efforts and strategies to accelerate the deployment of renewable energy sources in Thailand to meet the ambitious targets outlined in the PDP 2018. Thus, the section below will provide an assessment of the potential of solar, wind, and biomass renewable resources in Thailand.

2.2.1 Solar

The assessment of solar energy potential is dependent on solar irradiation, specifically the measurement of global horizontal irradiance (GHI). GHI is a crucial indicator of the amount of irradiation and a crucial criterion to determine solar potential. Integrating direct normal irradiation (DNI) and diffuse horizontal irradiation (DHI) determines it. GHI is impacted by the area's geographic location and weather conditions. Thailand has areas with a lot of potential for solar energy [19]. Figure 13 represents the potential intensity of solar radiation in Thailand, it shown that the areas primarily occur in the southern and northern parts of the Northeastern region, especially in the Udonthani province, as well as certain areas in the Central region. These regions constitute approximately 14.3 % of the nation's land surface and also receive an average daily solar irradiation ranging from 19 to 20 MJ/m2/day [20]. The remaining 50 % of the country gets an average solar irradiation of 18 to 19 MJ/m2/day. When comparing between Thailand and some other countries, Thailand has a higher potential than some regions such as Japan, Ireland, and United Kingdom as shown in Figure 14 [21].

Figure 13: Solar Irradiation Map
(Source [20])

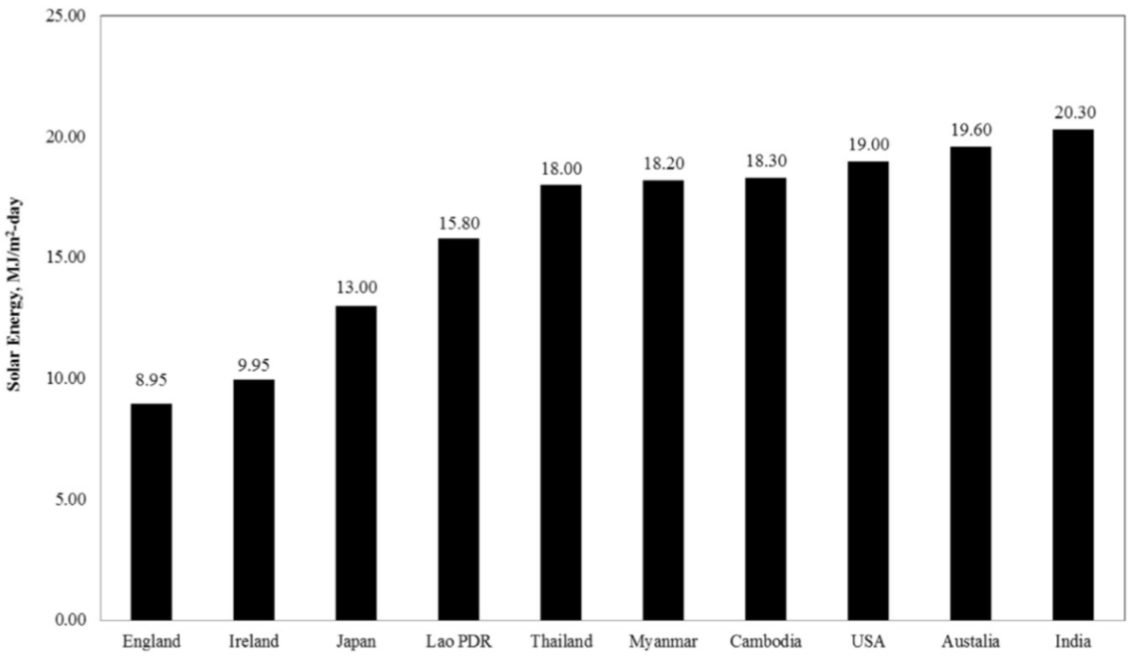

Figure 14: Comparison of Solar Energy Output in difference countries

Direct and diffuse solar radiation are received in Thailand, with direct radiation being more efficient for generating heat and power than diffuse radiation. In Figure 15, the annual peak direct radiation density varies between 1,350 and 1,400 kWh/m2. Approximately 4.3% of the country is occupied by this populated region, which is primarily located in the central and southern parts of the northeastern region. In addition, about 19.5% of the country receives direct radiation at a density of between 1,200 and 1,300 kWh/m2 per year. Throughout the year, the amount of direct radiation in Thailand follows a consistent trend. Typically, it starts to rise in January, hits its peak in April, then proceeds to gradually drop until it reaches its lowest point in December. This variation in time impacts the total solar energy capability.

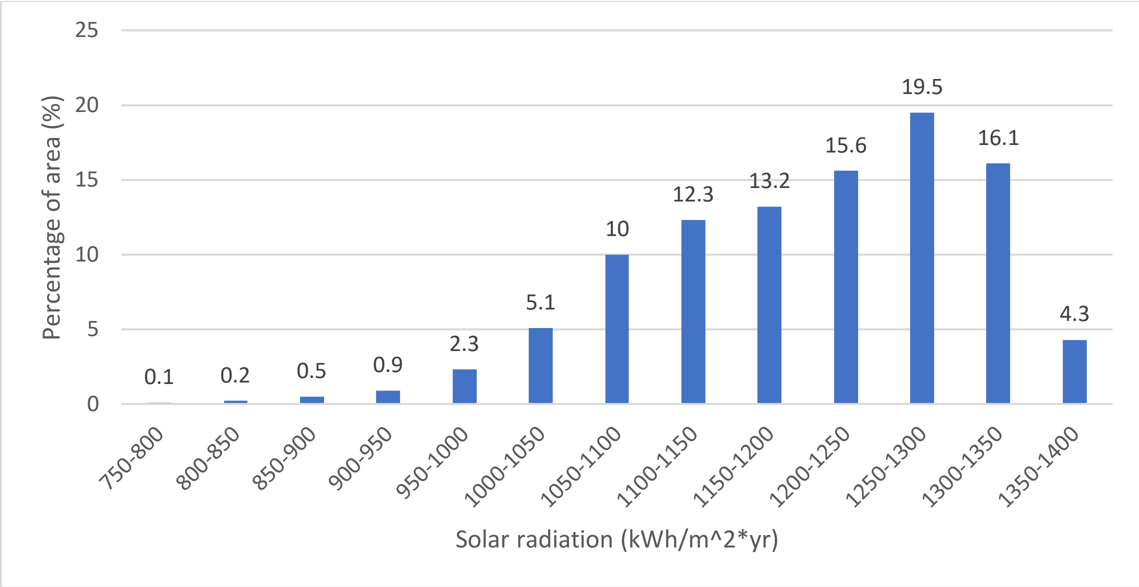

Figure 15: Percentage of Solar radiation in Thailand by area (Source [20])

According to the National Survey of Solar PV Power Application Report in Thailand from the Department of Alternative Energy Development and Efficiency (DEDE), Thailand's decentralized sector, especially building-attached PV (BAPV) in commercial and residential settings, has continued to thrive. Due to the national goal Thailand has set, it will commission a power plant with a capacity of 18,696 MW from renewable resources, including a PV power plant with a capacity of 8,740 MW, or approximately 46.7% of the total, and a hybrid system with 550 MW of capacity [22].

Table 2: PV power installed during calendar year 2020

			Installed PV capacity [MW]	Installed PV capacity [MW]	AC or DC
Grid-connected	BAPV	Residential	127,25	2,22	DC
		Commercial		125,03	DC
		Industrial			
	BIPV	Residential	-	-	-
		Commercial		-	-
		Industrial		-	-
	Utility-scale	Ground-mounted	16,39	3,7	DC
		Floating		12,69	DC
		Agricultural		-	-
Off-grid		Residential	80 kW	n/a	DC
		Other		15 kW	DC
		Hybrid systems		65 kW	DC
Total			143,72		DC

From the data in the Table 2, the annual PV installation capacity for grid-connected systems in Thailand was 143.72 MW through DC mode. Data illustrated that commercial rooftop PV systems dominated the highest capacity with 125.03 MW of installations. Additionally, 12.69 MW of floating PV systems and 3.7 MW of ground-mounted systems were installed in 2020. While installing an 80 kW off-grid system.

2.2.2 Wind

Based on the wind potential assessment conducted by DEDE, Thailand has a wind potential of approximately 5 metres per second (m/s) at a height of 90 m, as shown in Figure 16. In terms of technical potential, wind power generation has the capacity to generate 13 GW in 21 identified regions around the country [17]. Particularly, the parts of Thailand with the greatest wind potential are found in the northeast, west, and south. Several studies have been conducted to evaluate the wind power potential in different regions of Thailand. In the northern region, the average wind speed ranges from 0.47 to 3.41 m/s [23]. Moving to the central region, the average wind speed varies between 3.25 and 4.51 m/s due to the influence of the local monsoon [24]. In the southern region, an offshore wind high-resolution map was developed, and wind maps were created using mesoscale and microscale wind flow models at heights of 80, 100, and 120 m above sea level along the Gulf of Thailand. These models were further validated by actual wind data collected from 28 wind measurement sites along the coast. The recorded wind speeds were 4.69, 4.91, and 4.95 m/s for the respective heights of 80, 100, and 120 m [25]Moreover, A study from Manomaiphiboon et al. (2017) reveals that Thailand possesses a technical wind energy potential of up to 17 GW when employing modern low-speed wind turbines. However, if conventional wind turbines were to be adopted, only approximately one-third of this potential could be realized. The findings emphasize the importance of utilizing advanced wind turbine technologies to effectively harness Thailand's wind energy resources [26].

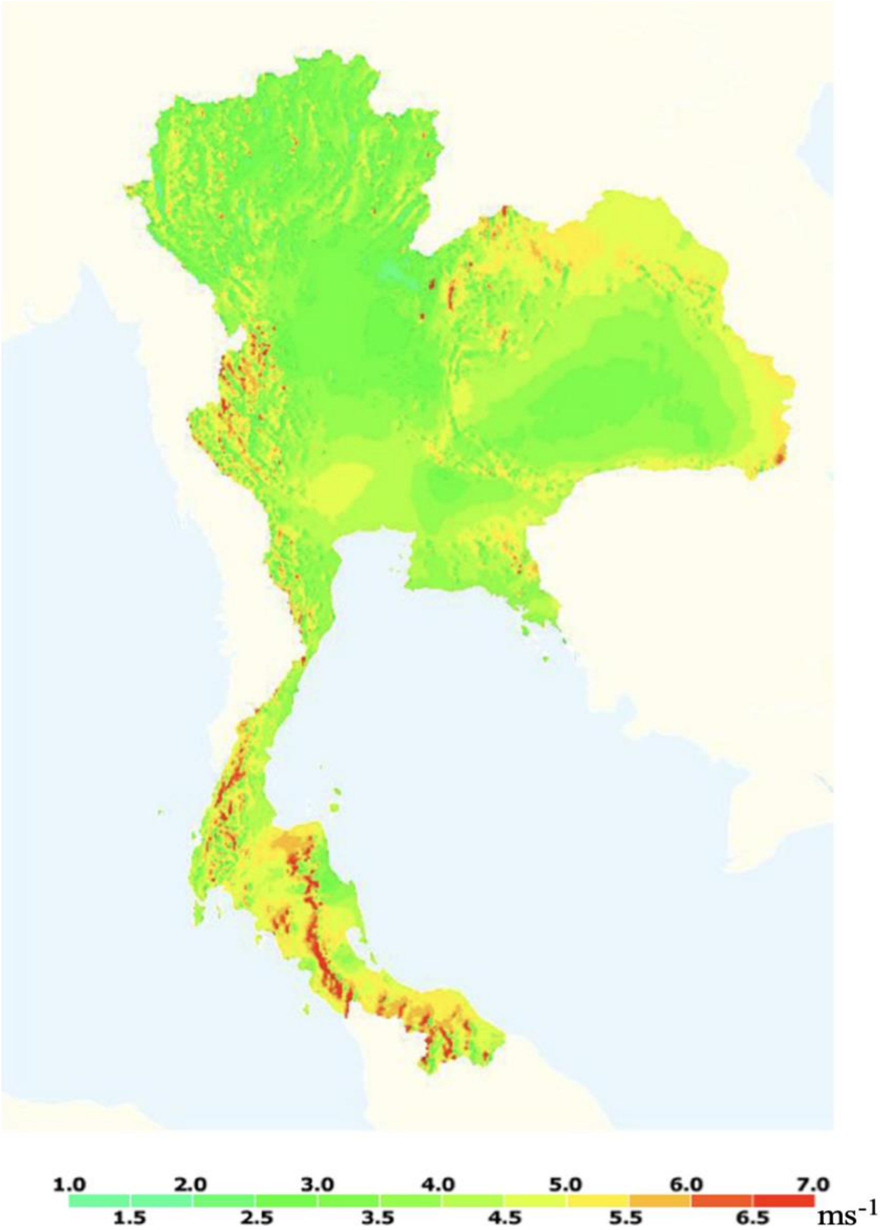

Figure 16: Wind Power Map

(Source: [27])

However, there are certain limitations that impede the widespread development of wind power plants in Thailand. Although certain regions exhibit above-average wind speeds, these areas are predominantly characterized by mountainous terrain, making them unsuitable for wind power plant installations as well as legal constraints and land usage regulations prohibit the development of wind power plants in some areas [28]. According to data from 2021, Thailand's total installed wind power capacity was close to 1500 MW. The viability of wind power development in Thailand will rely on the following three factors: 1) Wind power plants are developed in suitable areas; 2) Commercial utility-scale wind turbines generator (WTG) is presently well-developed to exploit moderate wind structures; and 3) government policies offer adequate financial support for investment.

2.2.3 Biomass

Thailand's economy has historically been heavily reliant on agriculture. Despite the growth of the industrial and tourism sectors, agriculture continues to play a significant role due to the huge number of farmers who frequently encounter challenging circumstances in their lives. Therefore, the government has an intense desire to provide incentives for producers to diversify their income streams. This strategy aims not only to generate additional revenue streams but also to mitigate the negative effects of global food price fluctuations.

Table 3: Potential of biomass plants and top three locations

	Biomass	Parts used	Top three available sources (provinces)	Energy content (MW h/ton)	Price (THB/ton)
1	Corn	Corn cob	Phetchaboon Nan Nakonratchasima	5	450
2	Rice	Rice husk	Ubonratchathani Nakonratchasima Surin	3.9	1590
3	Oil palm	Empty fruit bunch	Suratthani Krabi Chumpohn	4.9	300
4	Cassava	Cassava rhizome	Nakonratchasima Kampangphet Chaiyaphum	5.1	500
5	Rubber	Scraps of wood	Suratthani Songkla Nakonsitammarat	4.2	720
6	Sugar cane	Bagasse	Kampangphet Kanchanaburi Nakhonsawan	8.4	350
7	Eucalyptus	Bark	Nakhon Panom Kalasin Sa Kaew	2.2	850

Table 3 provides an assessment of the biomass potential produced by agricultural residues across several provinces in Thailand [29]. The study takes account of seven major types of biomasses as well as the main producing provinces. Furthermore, the table contains information on the local prices of biomass raw materials. The outcomes indicate that in the northeastern and central region of Thailand has a substantial amount of biomass resources, with the exception of oil palm and rubber, which have more potential in the south of the country. Notably, sugar cane stands out as a promising biomass raw material for electricity generation due to its high energy content and comparatively lower cost.

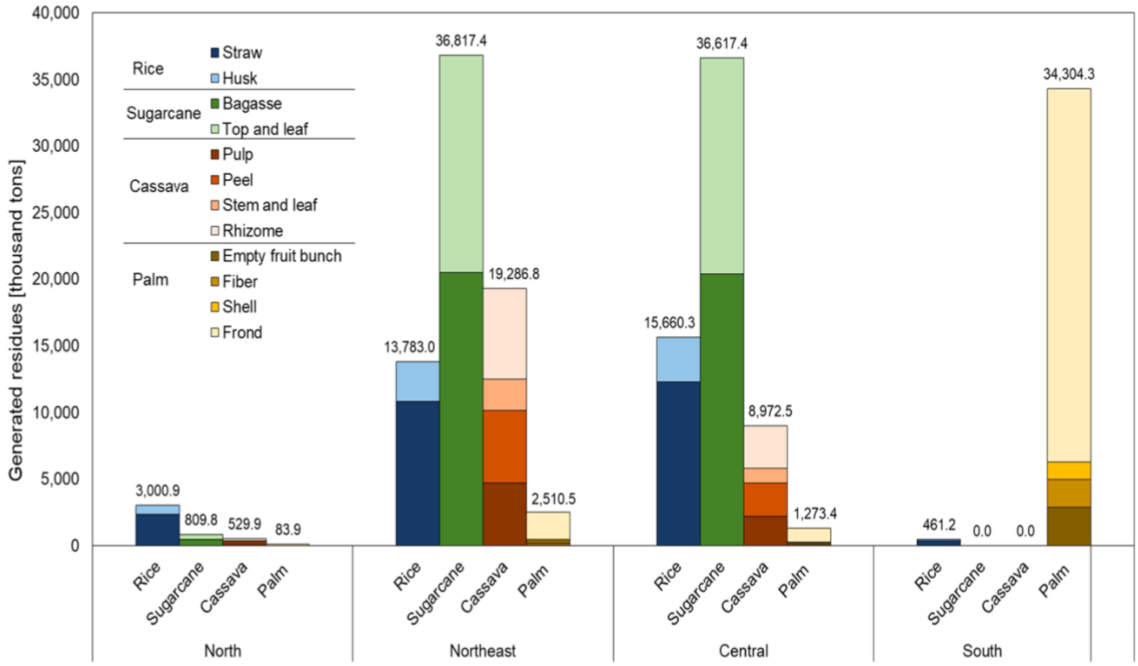

Figure 17: Distribution of the regional agricultural residues from rice, sugarcane, cassava and palm

Additionally, the graph in Figure 17 shows the regional distribution of agricultural residue quantities across Thailand [30]. It reveals that sugar cane residue is the most prevalent, which amounts to 36.8 million tonnes in the northeastern region and 36.6 million tonnes in the central region. The production from rice and cassava residues in the northeast and central regions is equivalent. In the northeastern region, cassava residue production is greater than rice residue production by about 19.3 million tonnes and 13.8 million tonnes, respectively. Similarly, rice and cassava productivity in the central region is 15.7 million tonnes and 9.0 million tonnes, respectively. In particular, the southern region of Thailand contains an individual sort of residue that is predominantly generated by palm, which accounts for approximately 34.3 million tonnes. In comparison to other regions, the humid temperature of this region makes it more appropriate for palm cultivation.

2.3 Energy Policy in Thailand

Likely several countries around the world, the Thai government is taking steps towards the advancement of renewable energy in order to mitigate climate change and global warming. In 2007, the Thai government implemented a policy called "Adder", which aimed to encourage private sector investments in renewable electricity generation. This scheme provides intriguing power purchasing rates, allowing those who qualify to sign long-term contracts with local providers to sell electricity at predetermined tariffs for a particular amount of time. The three main energy utilities in Thailand, EGAT, MEA, and PEA, allow the Adder to implement by purchasing renewable electricity from private producers (VSPP and SPP). The Adder is an essential encouragement for renewable energy adoption and an accelerator for Thailand's transition to more sustainable energy in the future.

Table 4: Thailand's Adder rates

Type of RE	Unit: US Dollars per kWh					Years supported
	2007 Adder rate	2009 Adder rate	2010 Adder rate	Special Adder for diesel replacement	Special Adder for three southernmost provinces	
Biomass						
Installed capacity ≤1 MW	0.010	0.017	0.017	0.033	0.033	7
Installed capacity >1 MW	0.010	0.010	0.010	0.033	0.033	7
Biogas						
Installed capacity ≤1 MW	0.010	0.017	0.017	0.033	0.033	7
Installed capacity >1 MW	0.010	0.010	0.010	0.033	0.033	7
Waste						
Landfill and digestor	0.083	0.083	0.083	0.033	0.033	7
Thermal process	0.083	0.117	0.117	0.033	0.033	7
Wind						
Installed capacity ≤50 kW	0.117	0.150	0.150	0.050	0.050	10
Installed capacity >50 kW	0.117	0.117	0.117	0.050	0.050	10
Small/micro hydro						
50 kW < installed capacity < 200 kW	0.013	0.027	0.027	0.033	0.033	7
Installed Capacity ≤ 50 kW	0.027	0.050	0.050	0.033	0.033	7
Solar	0.267	0.267	0.217	0.050	0.050	10

ote: the current (July 2014) Adder rate remains at 2010 levels, with the exception of solar power Adder program, which no longer accepts new applications.

According to Table 4, the Adder measure in Thailand is provided for six types of renewable energy technologies as well as the adder rates (1 US Dollars = 30 Thai Baht) are distinguished by the technology type, installed capacity, and location [31]. The Adder program has been successful in stimulating the investment on renewable energy. Until 2010, The support for solar power through the Adder program was paused due to oversubscription to the solar Adder as well as policymaker concerns on the impact of electricity pass-through costs to ratepayers.

Afterwards, National Energy Board has been announced feed-in tariffs (FiT) policy in 2013 to replace adder policy since adder only paid on top of the retail electricity price but FITs rate is a fixed wholesale price as well as the period of support has increased to 20-25 years [32]. The FiT policy had firstly use on rooftop solar systems while other resources of power generation still had supported from Adder policy until 2015. Subsequently, the FiT policy introduced for the rest of renewable sector.

Table 5: FiT Rate of Natural Resources in 2015 (Translated from [33])

FiT Rate in 2015: VSPP project (Natural Resources)			
Total Capacity	FiT (THB/kWh)	Period of Support (Year)	FiT Premium (THB/kWh)
1) Hydropower			
Capacity ≤ 200 kW	4.9	20	0.5
2) Wind			
All capacity size	6.06	20	0.5
3) Solar			
Solar rooftop (Capacity 0-10 kWp)	6.85	25	0.5
Solar rooftop (Capacity > 10-250 kWp)	6.4	25	0.5
Solar rooftop (Capacity > 250-1000 kWp)	6.01	25	0.5
Solar Farm (Any capacity size)	5.66	25	0.5

Table 6: FiT Rate of Bio Resources in 2015 (Translated from [33])

FiT Rate in 2015: VSPP project (Bio Resources)					
	FiT (THB/kWh)				
Total Capacity	Fit_F	$FiT_{V,yr}$	Fit Total	Period of Support (Year)	FiT Premium (THB/kWh)
1) Municipal Solid Waste : Integrated solid waste disposal					
Capacity ≤ 1 MW	3.13	3.21	6.34	20	0.5
Capacity > 1-3 MW	2.61	3.21	5.82	20	0.5
Capacity > 3 MW	2.39	2.69	5.08	20	0.5
2) Municipal Solid Waste : Landfill					
All capacity size	5.6		5.6	10	0.5
3) Biomass					
Capacity ≤ 1 MW	3.13	2.21	5.34	20	0.5
Capacity > 1-3 MW	2.61	2.21	4.82	20	0.5
Capacity > 3 MW	2.39	1.85	4.24	20	0.5
4) Biogas: Waste					
All capacity size	3.76		3.76	20	0.5
5) Biogas: Crop					
All capacity size	2.79	2.55	5.34	20	0.5

FiT rates applicable to renewable resources, which can be categorized into two distinct groups based on the associated risk factors in energy generation [34].The first group comprises natural resources such as hydro, wind, and solar, which do not incur any capital costs for fuel. However, these sources are subject to intermittent energy production, which can be perceived as the primary risk factor within this group. Conversely, the second group comprises bio resources, including municipal solid waste, biomass, and biogas, which are vulnerable to fuel price fluctuations. Therefore, two parameters must be considered when determining FiT rates as follows:

1) **FiT-Fixed ($\mathbf{Fit}_F$)** : This scheme determines the tariff rate based on the capital cost of the power plant and the associated operation and maintenance expenses over the entire support period. By both groups utilize this approach.

2) **FiT- variable ($\mathbf{FiT_V}$)** :This scheme calculates the tariff rate based on the initial cost of fuel required for energy generation, which is dependent on the prevailing market conditions. This particular parameter is applicable only to bio resources.

Furthermore, a FiT premium has been established for certain renewable technologies to incentivize investment in renewable energy, particularly in the southern border region of Thailand. This initiative aims to enhance flexibility and promote the adoption of renewable energy sources within the specified area.

As a number that presented in Tables 5 and 6, all solar energy project acquired the longest period of support at 25 years, by the highest rate is solar rooftop with capacity 0-10 kWp. It indicates that the government is strongly emphasis on promoting self-energy production in residential areas. Conversely, biogas and biomass projects receive the lowest FiT rates compared to other renewable technologies since the growth in renewable power generation from biomass and biogas has already achieved a significant level of success.

2.4 A case study island: Sichang Island

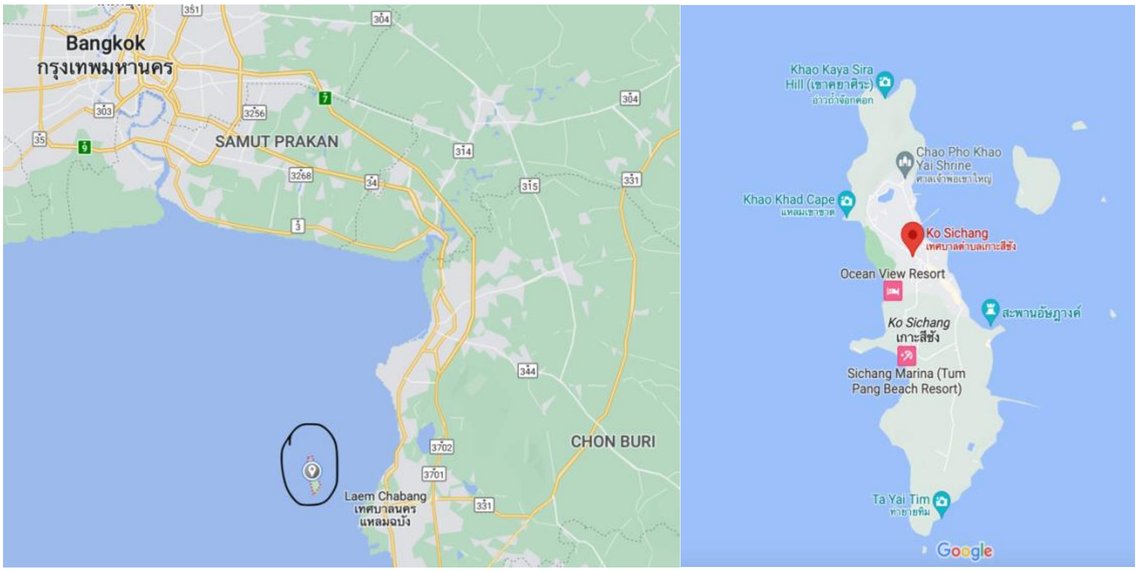

Figure 18: Map of Sichang Island

Sichang Island is located in Chonburi, a province in the eastern part of Thailand, in the Gulf of Thailand, at latitude 13.1499° N and longitude 100.8085° E, and the island is 10.4 km from the mainland as shown in Figure 18. The total area in this island is approximately 7.65 km^2 , and accommodating a population of approximately 4,500 people.

2.4.1 Electricity Consumers

Table 7: Statistics of Electricity Consumer on Sichang Island

Lists	Categories of Electricity Tariffs	No. of Electricity Consumer	Cost of Electricity Bill (THB/Month)	Cost of Electricity Bill (GBP/Month)
1	Residential	1,421	2,102,150.	48,661
2	Small General	178	1,223,661.	28,325
3	Medium General	9	546,984	12,662
4	Large General	-	-	-
5	Specific Business	5	572,419.	13,250
6	Non-Profit Organizations	-	-	-
7	Water Pumping for Agricultural Purposes	-	-	-
8	Temporary Tariffs	26	47,646.51	1,103
9	Emergency Generators	-	-	-
	Public light	22	-	-
	Total	**1,661**	**4,492,862.11**	**104,001**

Table 7 indicates the data regarding the number of electricity consumers on Sichang Island in the year 2022, with a cumulative measure of 1,661 individuals. The electricity tariffs are categorised based on consumer groups, with the residential group comprising the largest number of users at 1,421 [35]. However, certain groups, such as large general consumers, non-profit organisations, those using electricity for water pumping in agricultural activities, and emergency generators, are not included in the list above. In addition, the system also presented the comprehensive amount of the electricity bill, taking into account the average exchange rate of 43.2 Thai Baht (THB) to 1 Great British Pound (GBP) in 2022. The average total electricity bill was recorded as 104,001 GBP per month.

2.4.2 Electricity Supply

In 2009, the submarine cable was constructed to distribute electricity from the Ao Pai substation to the island, with a total distance of 13.9 km, 10.4 km from the island to the mainland, and 3.5 km from the coast to the substation as shown in Figure 19, with a maximum load capacity of 7,800 kW. Unfortunately, the anchor collision resulted in three significant damages, as depicted in Figure 20, which rendered the submarine inoperable and currently repair by increasing the depth of submarine cable from 1.5 m to 7 m.

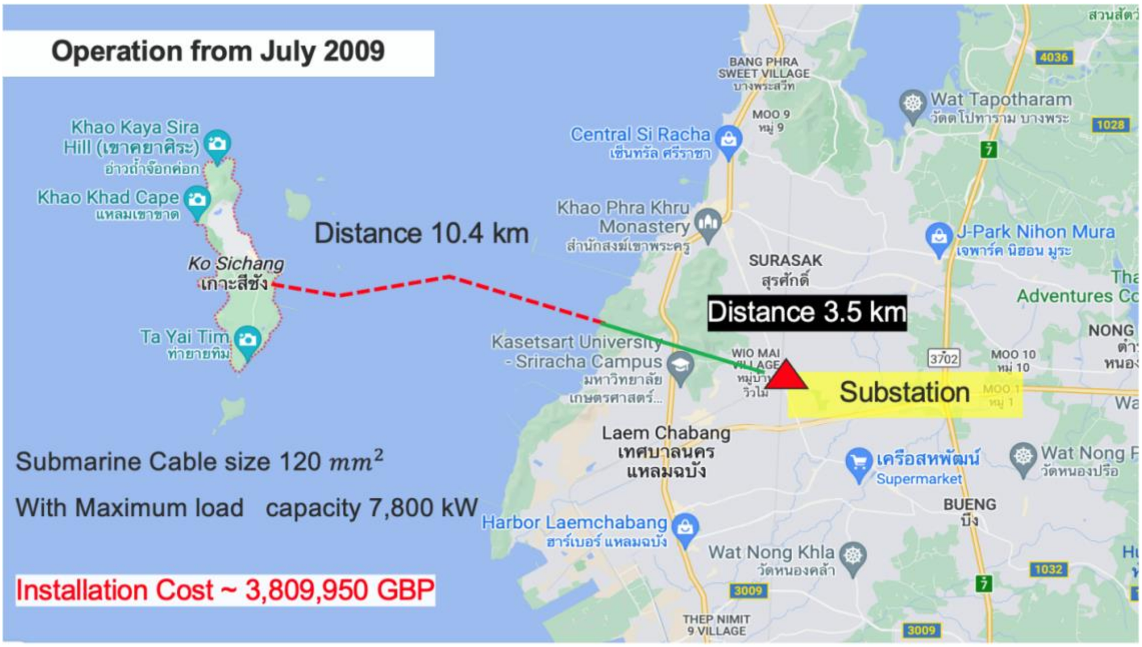

Figure 19: Transmission system by submarine cable to Sichang Island

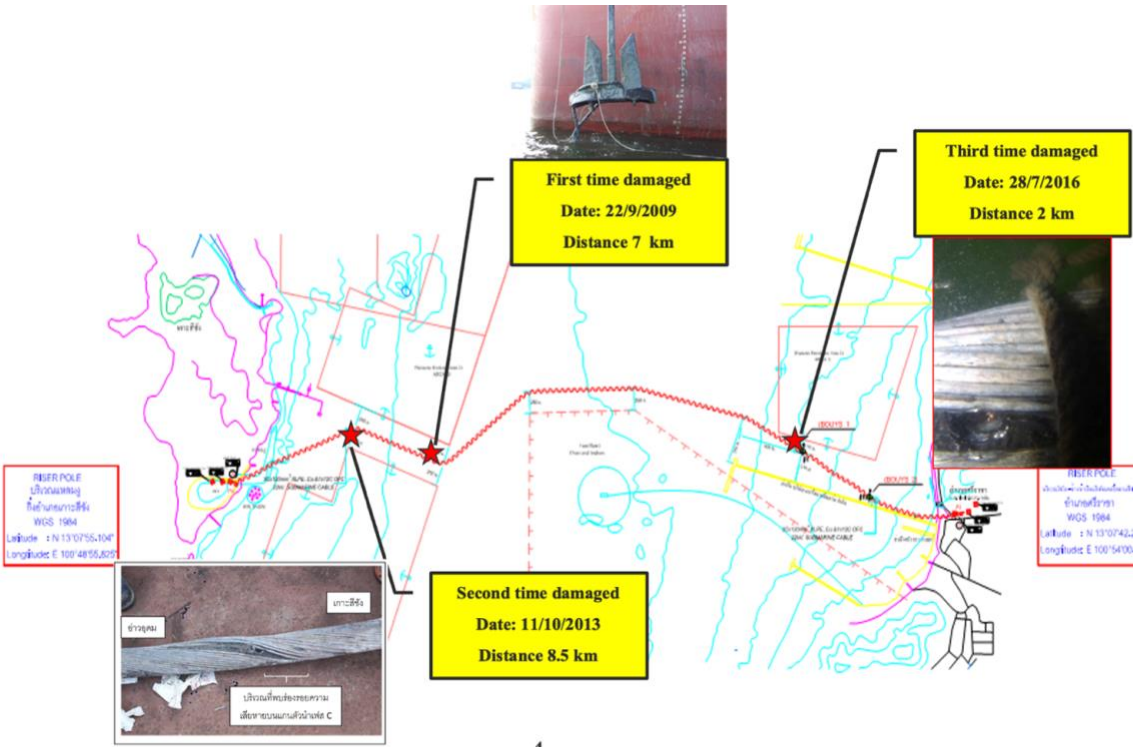

Figure 20: Damages on submarine cable

(Source: [36])

Table 8: Operation timeframe of Sichang Island's submarine cable

	Detail	Date	Duration	
			Supply Electricity ✅	Non-Supply Electricity ❌
1	Submarine cable operation	1/7/2009-22/9/2009	2 Months 22 Days	-
2	1st damaged of submarine cable	22/9/2009-/29/8/2011	-	1 year 11 Months
3	Completed repairs and return to operate	29/8/2011-11/10/2013	2 Years 2 Months	-
4	2nd damaged of submarine cable	11/10/2013-16/6/2016	-	2 Years 8 Months
5	Completed repairs and return to operate	16/6/2016-28/7/2016	42 Days	-
6	3rd damaged of submarine cable	28/7/2016- Present		6 Years 11 Months
		Total	**2 Years 4 Months**	**11 years 6 Months**

Table 8 provides a summary of the submarine cable's operational timeline since its launch in July 2009. Surprisingly, it has only been working for 2 years and 4 months, with the entirety of the decade prior being dedicated on system repair due to cable damage. The duration of repair for the first and second instances lasted for a minimum of about two years. Following the third occurrence of cable damage, the system stopped operating and has since relied on a private company's management of five 1000 kW diesel generators as an alternative source of electricity supply.

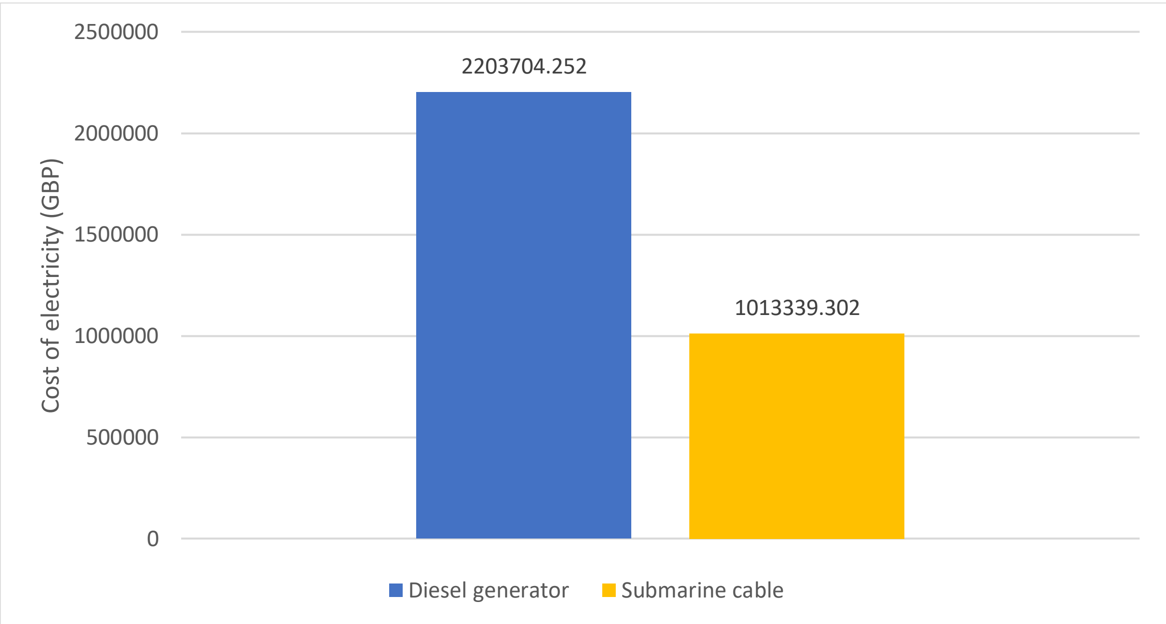

Figure 21: Cost comparison between power generation from diesel generator and submarine cable

The chart in Figure 21 compares the cost of diesel generator electricity generation to that of the submarine cable based on the total electricity demand on Sichang Island in the year 2022. The price of a diesel generator is determined by the total amount of fuel used, which was measured at 2,983,682 L, and the cost per litre of fuel, which is 0.73 GBP/L [36]. The price of a submarine cable is calculated by the total electricity demand, which is 10.29 GW (10.29 million kW), and the transmission cost, which is approximately 0.098 GBP/kW. Consequently, it is revealed that the total cost of a diesel generator is more than double that of a submarine cable. Therefore, using diesel generators as a backup source of electricity generation over the long term is not a viable option. Presently, the Thai government is already planning a project to install a hybrid renewable energy system with the submarine cable on Sichang Island that connect to the mainland’s substation with a budget approximately 250,000,000 THB or around 5,538,790 GBP, which is expected to operate by the beginning of 2025.

2.5 Energy Storage Technologies

In fact, there is a fluctuating and unpredictable nature to power generation from these renewable sources such as solar and wind. The generation of wind power is subject to fluctuations in both wind speed and direction, leading to intermittent periods characterised by reduced or lacking of electricity production. Similarly, solar photovoltaic systems are subject to the impact of dynamic factors, including cloud cover, time of day, and seasonal changes in sunlight intensity. Consequently, the generation of electricity from wind and solar sources displays transient variations and may not consistently align with instantaneous demand. Therefore, it is significant to consider implementing supplementary components like energy storage systems in order to mitigate the issue of intermittency and provide a consistent and uninterrupted supply of electricity.

Batteries have emerged as one of the most achievable solutions for energy storage across a wide range of applications. Batteries possess multiple benefits, including a high energy density, scalability, rapid response times, and compatibility with variable renewable energy sources [37]. The growth of battery technologies, featuring improved efficiency and prolonged cycle life, has made them reliable as well as environmentally feasible options for energy storage. Furthermore, batteries provide the advantage of being adaptable in terms of capacity adjustments, efficient load balancing and the compact size of the battery is appropriate for a variety of environments.

Table 9: Comparison of battery technologies

Characteristics	Pb-acid	Li-ion	NiCd	NiMH	NaS	VRFB
Specific energy [Wh/kg]	25 – 50	80 – 250	30 – 80	40 – 110	150 – 240	10 – 130
Specific power [W/kg]	150 – 400	200 – 2000	80 – 300	200 – 300	90 – 230	50 – 150
Energy density [kWh/m³]	25 – 90	95 – 500	15 – 150	40 – 300	150 – 350	10 – 33
Power density [kW/m³]	10 – 400	50 – 800	40 – 140	10 – 600	1.2 – 50	2.5 – 33
Energy cost [€/kWh]	40 – 170	500 – 2100	680 – 1300	170 – 640	250 – 420	130 – 850
Power cost [€/kW]	250 – 500	1000 – 3400	420 – 1300	200 – 470	850 – 2500	500 – 1300
Lifetime [years]	2 – 15	5 - 15	10 - 20	2 - 15	10 - 15	5 - 15
Lifetime cycles [cycles]	250 – 2000	100 – 10000	1000 – 5000	300 – 1800	2500 – 40000	10000 – 16000
Cell voltage [V]	2 – 2.1	2.5 – 5	1.2 – 1.3	1.2 – 1.35	1.8 – 2.71	1.2 – 1.4
Efficiency [%]	63 – 90	75 – 97	60 – 90	50 – 80	75 – 90	75 – 90

Table 9 provides a comparative analysis of six different battery storage technologies, particularly lead-acid (Pb-acid), Lithium-ion (Li-ion), Nickel-cadmium (NiCd), Nickel-metal hydride (NiMH), Sodium-sulphur, and vanadium-redox flow batteries [38]. As a result, lithium-ion battery technology currently appears to be the most sophisticated and widely used form of battery technology. As a result, lithium-ion technology is currently the dominant and most widely adopted battery technology due to its outstanding characteristics. Lithium-ion batteries have the maximum specific power and energy, providing higher energy density and power. In addition, it has the maximum cell voltage and efficiency, which further expands the potential for an extensive range of uses. Despite the fact that Lithium-ion batteries are typically more expensive than other technologies. Therefore, the project will prioritise the implementation of lithium-ion as an energy storage system, as it is accessible for simulation in Homer software.

2.6 HOMER software

The Hybrid Optimization Model for Electric Renewables (HOMER) is a simulation software developed by the US Department of Energy and the National Renewable Energy Laboratory (NREL) in 1993. Its primary goal is to facilitate the analysis and optimization of both off-grid and on-grid hybrid renewable energy systems, such as wind and solar power generation options. HOMER serves a diverse range of sectors, including small villages, grid-connected islands, military bases, and community-scale installations. Afterwards, NREL determined to make this tool available to the public in order to support engineers in refining and selecting viable solutions based on technical, economic, and environmental factors [39].

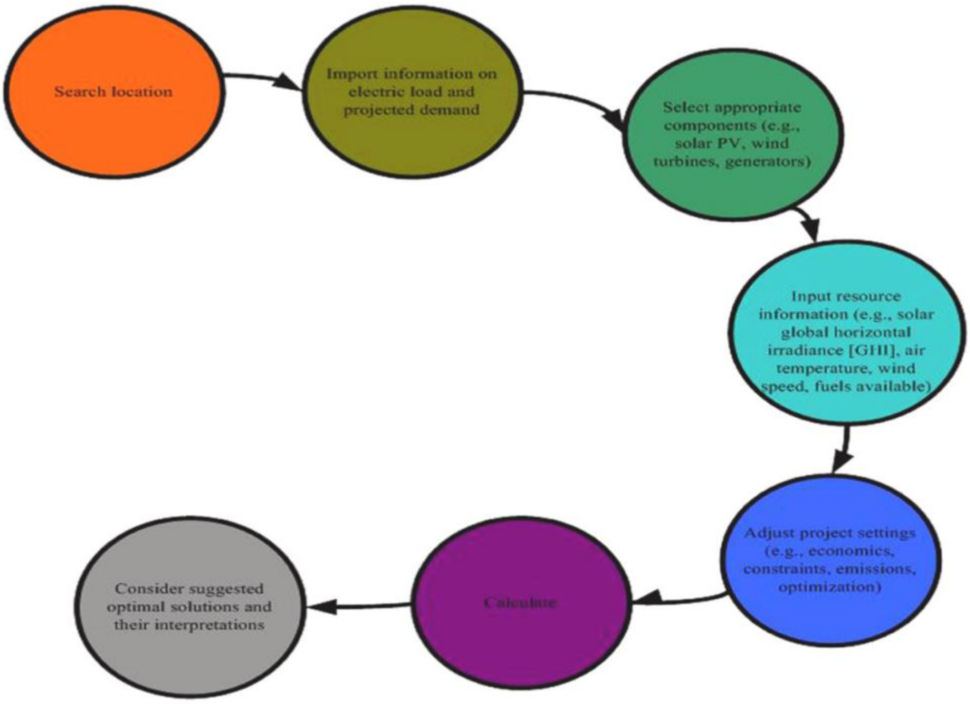

Figure 22: Workflow diagram of HOMER

Figure 22 illustrates the workflow for the Homer simulation, which allows users to customize various input variables. These include location, electric load profile, and the selection of appropriate components such as solar photovoltaic (PV) panels, wind turbines, and generator as well as users can input resource information such as solar GHI, air temperature, wind speed, and available fuel data. Furthermore, users have the ability to modify project settings pertaining to economics, constraints, emissions, and optimization based on project-specific requirements prior to performing calculations [40].

3 Method & Methodology

In the context of this study, Homer software was chosen due to its capability to assess both financial and technical aspects of various hybrid energy systems. Its selection was driven by the software's potential to analyse a wide array of feasible options, taking into account factors such as energy resource availability and other relevant parameters. By using Homer, users were able to calculate critical metrics like the renewable fraction, levelized cost of energy (COE), and CO_2 emissions, providing an evaluation of each potential hybrid energy system as indicated in Section 2.6.

The following section will explain the simulation of a hybrid energy system on Sichang island in Homer software which separated into six sub-topics as follows:

1) Electricity Load Profile Modelling
2) Renewable Resources Potential on Sichang Island
3) Components and Parameters of Hybrid Renewable Energy Systems
4) Economics Modelling
5) Emission Modelling
6) Scenario Modelling
7) Limitations and Assumptions of the project in Homer

3.1 Electricity Load Profile Modelling

According to the information provided in Chapter 2.5.2, the Thai government has proposed a project to implement a hybrid renewable energy system on Sichang Island, operated with a submarine cable. This initiative is projected to begin operations in 2025. Hence, the collection of the daily electricity demand profile by EGAT for the year 2022 maintains significance as a foundational element for projecting future electricity demand in 2025. Meanwhile, the growth rate of electricity demand will be determined by referring to Figure 6, which depicts the annual electricity consumption in Thailand. The data indicates that over the course of the previous two decades, there has been an average annual growth rate of approximately 5.47% in demand. The projected demand for the year 2025 is determined through the utilisation of Equation 1 below:

Equation 1: Forecasted Demand in 2025

$$\boldsymbol{Forecasted\ Demand = Current\ Demand \times (1 + Average\ Increase\ Rate)}$$

Considering the monthly variations, it is anticipated that the electricity demand for the year 2025 will experience a substantial rise, reaching approximately 12.07 GW. This corresponds to a daily average demand of 33,075.72 kWh and a peak demand of 3,190.35 kW. The graph illustrated in Figure 23 indicates that the month of April exhibits the highest level of consumption, characterised by a peak electricity demand of 3,190.35 kW during the summer period. As Thailand is located in a tropical area where high temperatures contain throughout the year, especially in the summer. Thus, the requirement for cooling loads becomes essential, whereas February displaying the lowest levels of consumption and a peak electricity demand of 2,377 kW during the winter season.

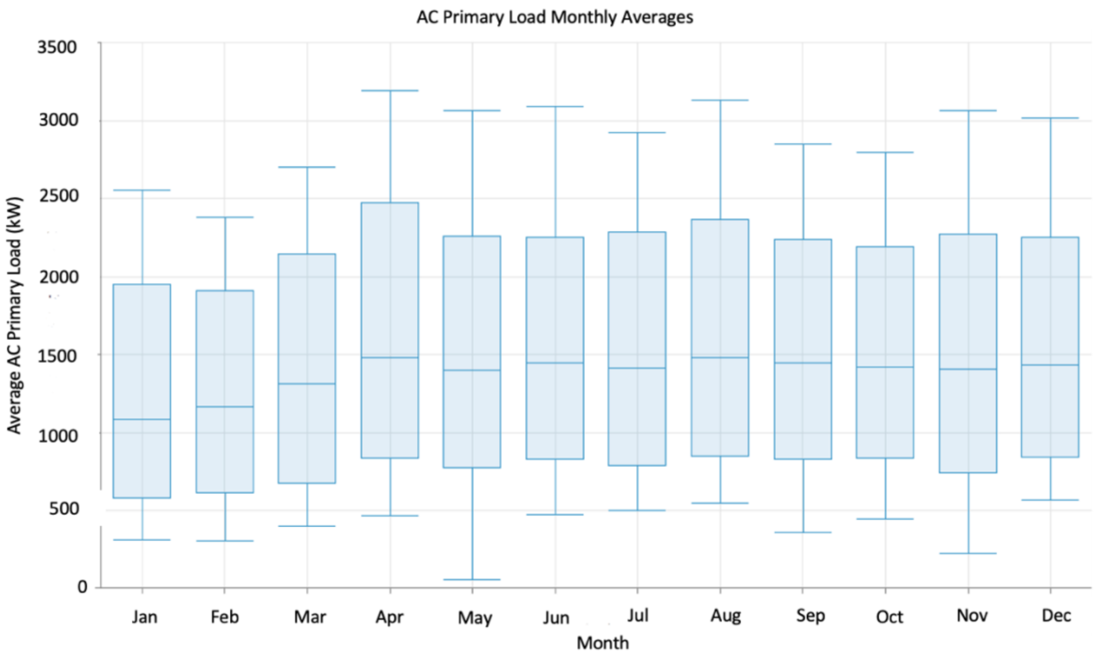

Figure 23: Seasonal Electric Load of Sichang Island by Homer

Since there are 3 seasons in Thailand, the summer season covers the period from the middle of February to the middle of May, followed by the rainy season from the middle of May to the middle of October. Lastly, the winter season begins in the middle of October and goes until the middle of February. Figure 24 illustrates the electricity demand for each season, specifically focusing on the average hourly demand in the months of April, July, and January.

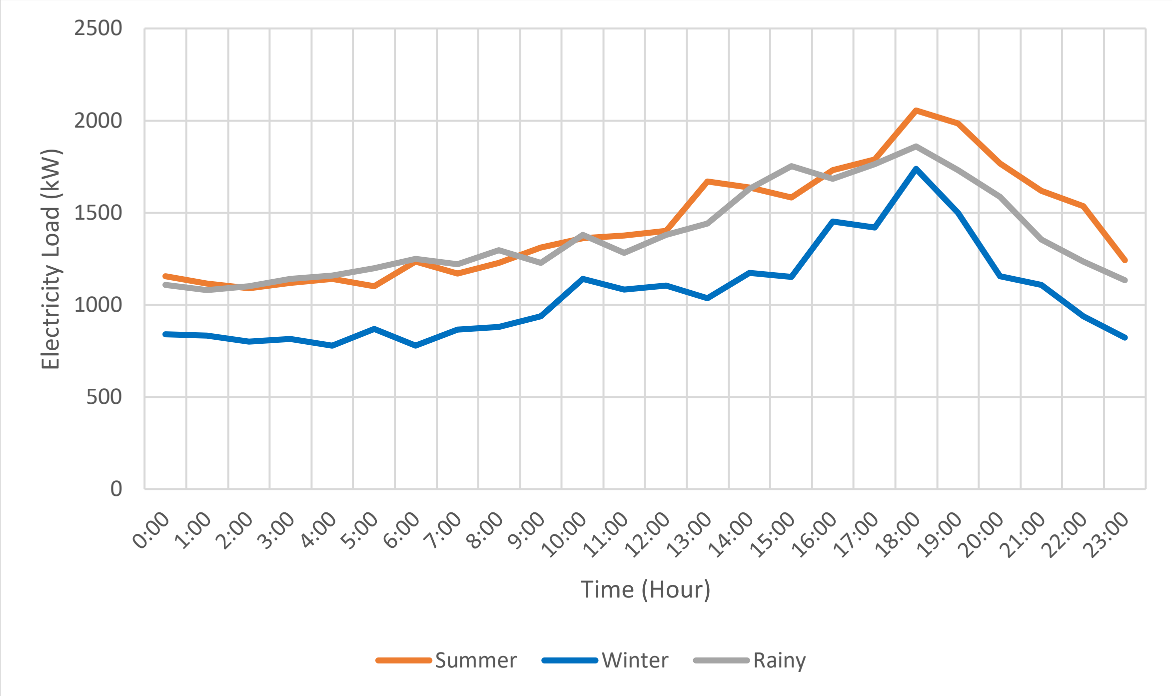

Figure 24: Seasonal estimated daily electric demand on Sichang Island

Overall, there is a noticeable trend of increasing daily demand during typical seasons, starting at 7:00 and continuing until 17:00. However, there are intermittent periods of fluctuating decreases within this time frame. Eventually, the demand reaches its highest point, which is typically recorded between 18:00 and 19:00. During the summer season, the electricity demand reaches its maximum level, which leads to a peak load of 2,054.86 kW. This surge in demand can be attributed to various factors, including higher temperatures and the necessity for air conditioning systems to maintain optimal indoor comfort. Conversely, the winter season demonstrates a reduction in demand, reaching a peak load of 1,737.91 kW due to the relatively mild winter temperatures. Furthermore, there is a rapid decrease in demand from 19:00 to 23:00, followed by a period of stability at a low point from 23:00 to 5:00 during the sleeping hours. Therefore, the projected aggregate daily electricity consumption during the summer season amounts to 34410.54 kWh/day, followed by the rainy season with 32,988.05 kWh, and the winter season with a daily average of 25,215.39 kWh.

3.2 Renewable Resources Potential on Sichang Island

3.2.1 Solar Irrandiance

Figure 25 reveals the average monthly of solar GHI and clearness index from the NASA POWER database. As described in Chapter 2.2.1, solar GHI is radian energy from the sun in both direct and diffuse radiation in certain regions. As shown on the graph, the average solar GHI on Sichang Island is 5.14 kWh/day, or roughly 18.5 MJ/day, which is inside the range of the average solar GHI in Thailand, which is between 18 and 19 MJ/day. While the Clearness Index is the ratio of solar radiation transmitted through the atmosphere and reaching the Earth's surface to the amount of solar radiation incident on a horizontal plane at the top of the atmosphere [41]. The value of the clearness index fluctuates based on the weather, becoming higher when it's clear and sunny and dropping when it is cloudy.

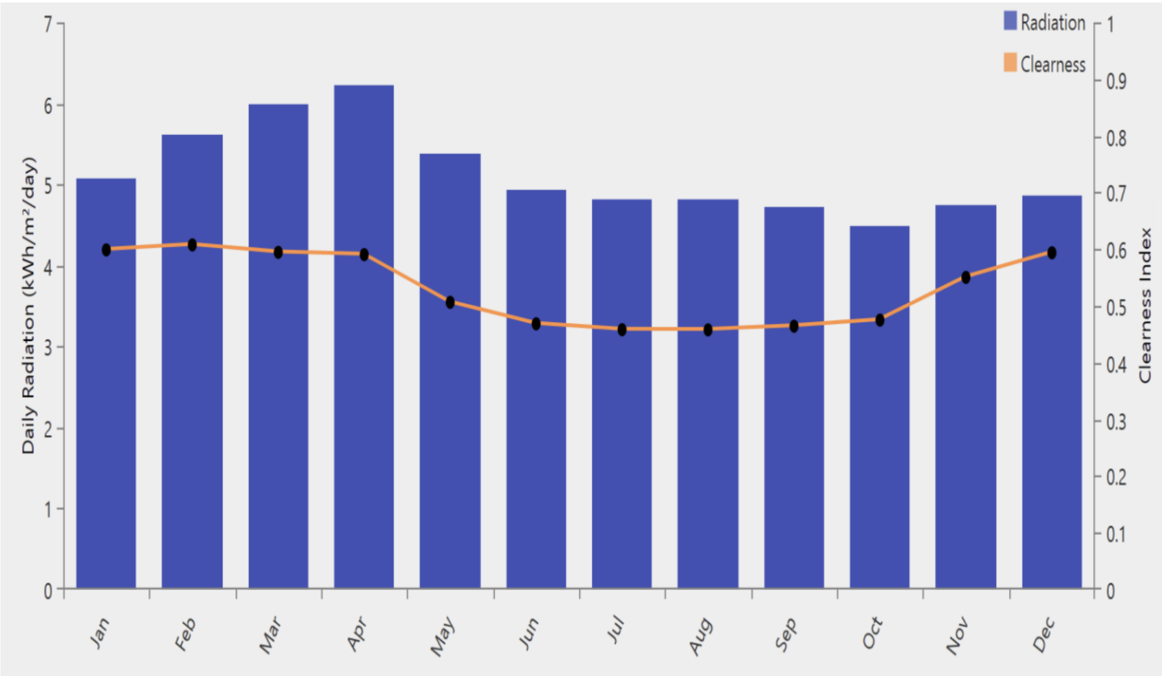

Figure 25: Daily Radiation and Clearness Index on Sichang Island by Homer

Generally, the solar GHI gradually climbed from January until April, until it hit a peak in April during the summer season. After May, the trend progressively declined and remained stable throughout the rainy season until October, when it reached its lowest point. Furthermore, the trajectory of the clearness index parallels that of the solar GHI, with a constant high during the summer and a declining trend during the rainy season.

3.2.2 Wind Speed

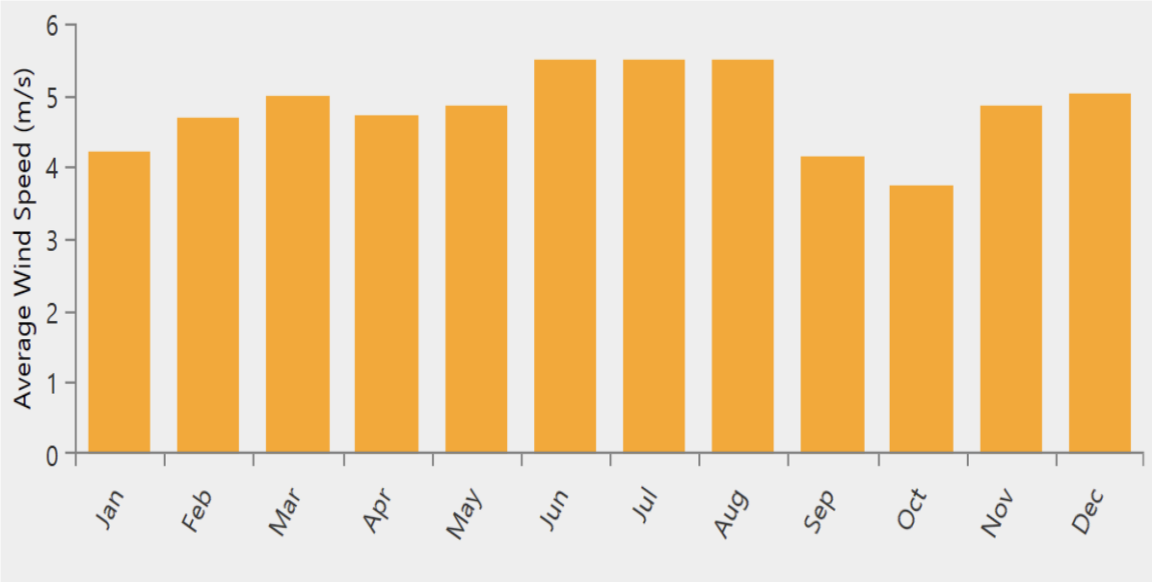

Figure 26: Average Wind Speed on Sichang Island by Homer

Figure 26 presents data on the average wind speed observed on Sichang Island. As a results, it reaching a maximum wind speed of 5.5 m/s in July during the rainy season. Subsequently, it experiences a slight decline in September and reaches its lowest point in October at 3.74 m/s. Afterwards, there is an increase in rebounding during the winter season starting in November.

3.3 Components and parameters of Hybrid Renewable Energy System

3.3.1 Solar Photovoltaic (PV)

There are various catalogues of Solar PV systems in Homer. In order to simulate the scenarios, a generic flat plate PV module has been selected based on its specifications provided in Table 10. The capital cost and O&M cost of the PV module per kW are derived from the IRENA report, whereas the replacement cost is assumed as a half of the capital cost [42].

Table 10: Details of Solar PV model

Details	Value
Model	Generic Flat Plate PV
Capacity (kW)	1
Temperature Coefficient	-0.5
Operating Temperature (℃)	47
Efficiency (%)	15
Capital Cost (GBP)	656
Replacement Cost (GBP)	328
O&M Cost (GBP/year)	20
Lifetime (Years)	25

3.3.2 Wind Turbine

Homer also features a variety of wind turbine models as well as solar PV. The Leitwind 80, an Italian product with a capacity of 1 MW, has been determined through the simulation. The capital cost and O&M cost of the turbine per kW are referred to the U.S. Department of Energy report for 2022, which accounted to 1,146.7 GBP/kW and 33.57 GBP/kW per year respectively [43]. While the replacement cost is also assumed to be 50% of the capital cost. The specification of the turbine is shown in Table 11.

Table 11: Details of Wind Turbine model

Details	Value
Model	Leitwind 80
Capacity (kW)	1000
Hub Height (m)	80
Capital Cost (GBP)	1,146,700
Replacement Cost (GBP)	573,350
O&M Cost (GBP/year)	33,570
Lifetime (Years)	15

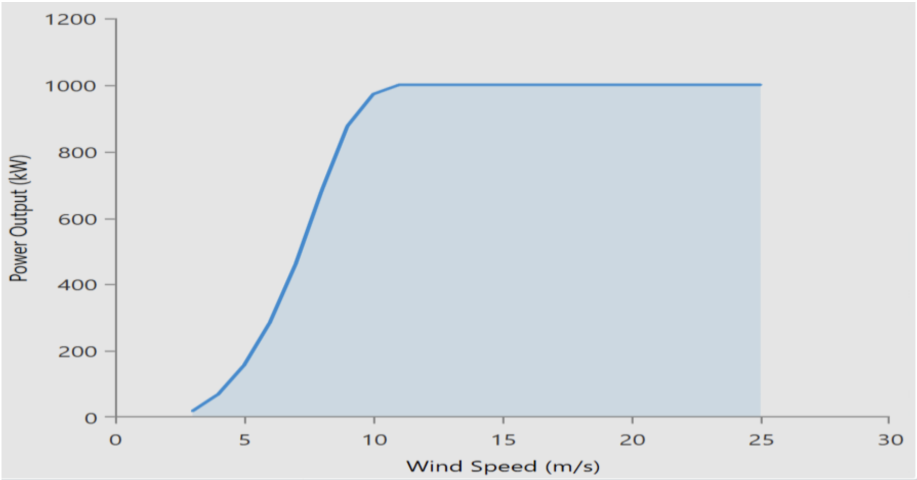

Figure 27: Power Output Curve of Leitwind 80 wind turbine

Figure 27 illustrates the power curve of the Leitwind 80 wind turbine. It reveals that the turbine is unable to operate at wind speeds below 3 m/s. The power output of the system displays a gradual increase, commencing at a wind speed of 3 m/s with a power output of 19 kW, until it reaches the maximum output of 1 MW at an 11 m/s wind speed, and the system will automatically switch off at wind speeds above 25m/s due to the safety condition. According to Figure 26, the average wind speed on Sichang Island is 5.5 m/s, with the average lowest point in October at 3.74 m/s. Hence, the turbine is capable of operating regularly throughout the year.

3.3.3 Diesel Generator

A diesel generator has been simulated as a backup power source in case a production from renewable energy resources is unable to meet electricity demand. The 1 MW Generic generator has been selected, and its specifications are listed in Table 12. The capital and O&M costs of 1 MW diesel generator have been projected at 76,431 GBP and 10 GBP/op. hour, respectively, and the replacement cost is estimated to be equal to one-half of the capital cost [44]. Additionally, Figure 28 shown the fuel curve of the diesel generator, and the price of fuel is fixed at 0.73 GBP/L based on the present cost of diesel fuel in Thailand.

Table 12: Details of Diesel Generator Model

Details	Value
Model	Generic 1MW Geneator
Capacity (kW)	1000
Capital Cost (GBP)	76,431
Replacement Cost (GBP)	38,215
O&M Cost (GBP/op.hour)	10
Fuel Price (GBP/L)	0.73
Lifetime (Hour)	15,000

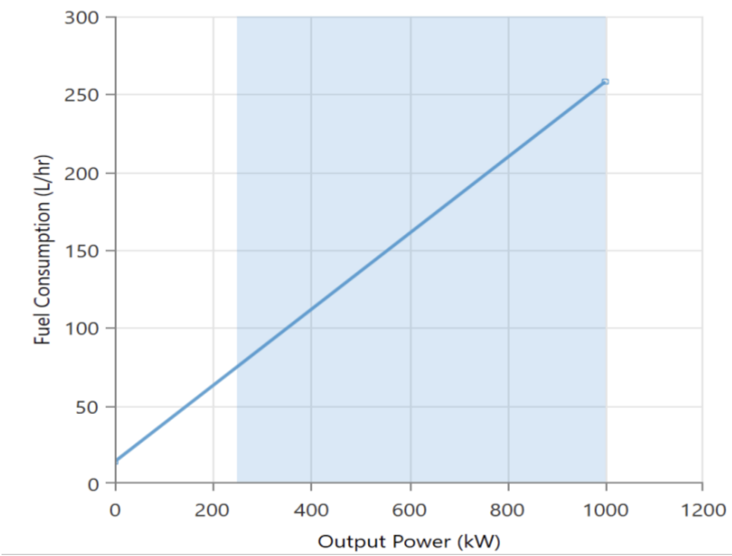

Figure 28: Fuel curve of Diesel Generator

3.3.4 Converter

A converter is a device that transforms the voltage of an electrical device, typically converting alternating current (AC) to direct current (DC). The voltage of an electrical power source is altered, generally through integration with other components, in order to generate a power supply. Table 13 presents the specifications of the converter used in the simulation and the number of converters in the simulation is determined through Homer optimization.

Table 13: Details of Converter Model

Details	Value
Model	Generic System Converter
Capacity (kW)	1
Capital Cost (GBP)	330
Replacement Cost (GBP)	165
O&M Cost (GBP/year)	0
Efficiency (%)	90
Lifetime (Years)	15

3.3.5 Battery Storage

Due to the intermittent nature of wind and solar resources, Hybrid Renewable Energy Systems require a form of battery storage. Its primary function lies in facilitating the efficient and dependable integration of renewable energy sources by storing surplus energy for later use or supplying additional power during periods of insufficient generation. The 1 MW of lithium-ion batteries has been identified by simulating some scenarios with the specifications provided in Table 14. The report from the U.S. Department of Energy in 2022 provides the capital cost and O&M cost per kWh of the lithium-ion battery as 342.07 GBP/kWh and 3.85 GBP/kWh per year, respectively [45]. While the replacement cost is assumed to be equal to 50% of the capital cost. Additionally, the number of li-ion batteries in the simulation is determined through Homer optimization.

Table 14: Details of Li-ion Batteries Model

Details	Value
Model	Generic 4hr 1MW Li-ion
Capacity (MWh)	1
Capital Cost (GBP)	342,070
Replacement Cost (GBP)	171,035
O&M Cost (GBP/year)	3,850
Minimum State of Charge (%)	0
Roundtrip Efficiency (%)	90
Throughput (kWh)	21,081,851.07
Lifetime (Years)	15

3.4 Economics Modelling

Economics analysis is also an essential factor because it provides an assessment of the project's economic feasibility and viability, ensuring efficient resource allocation and an optimal design process for decision-making. The three variables are used to determine this in the project as follows:

1) **Levelized Cost of Energy (COE):** a variable that defines direct cost comparisons between different energy system configurations per kWh, taking into account both their installation and operation costs over the duration of their lifetime by using the equation below [46]:

Equation 2 The Levelized Cost of Energy

$$COE = \frac{C_{TOT}}{E_{serve}}$$

Where: C_{TOT} = Total annualized cost of the system [THB/year]

E_{serve}= Total energy served to the load per year [kWh/year]

2) **Total Net Present Cost (NPC):** it involves the consolidation of all expenses and revenue associated such as initial capital costs, replacement costs, and operation and maintenance cost over the project’s lifetime by using the provides equation below [47]:

Equation 3 The Total Net Present Cost

$$NPC = \frac{C_{TOT}}{CRF(i, R_{proj})}$$

Where: CRF = The capital recovery factor, which i is the interest rate in % and R is the project lifetime (years)

Therefore, the capital recovery factor can calculate by using the equation below:

Equation 4 The Capital Recovery Factor

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

3.5 Emission Modelling

As mentioned earlier in the introduction, climate change and global warming are currently significant global concerns. To assess the environmental impacts of the undertaking and enhance the system's efficiency by minimizing the emissions and air pollution, conducting an emission analysis is imperative. Within the framework of the Homer software, six primary pollutants are taken into account: Carbon Dioxide (CO_2), Carbon Monoxide (CO), Unburned Hydrocarbons (UHC), Particulate Matter (PM), Sulphur Dioxide (SO_2), and Nitrogen Oxides (NO_x), with descriptions of each pollutant given in the Table 15 [48]. These pollutants are the result of the generation of electricity by generators and the consumption of electricity from the grid.

Table 15: Description of Pollutant parameters by Homer

Pollutant	Description
Carbon Dioxide (CO_2)	Nontoxic greenhouse gas.
Carbon Monoxide (CO)	Poisonous gas produced by incomplete burning of carbon in fuels. It prevents delivery of oxygen to the body's organs and tissues, causing headaches, dizziness, and impairment of visual perception, manual dexterity, and learning ability.
Unburned Hydrocarbons (UHC)	Products of incomplete combustion of hydrocarbon fuel, including formaldehyde and alkenes. They lead to atmospheric reactions causing photochemical smog.
Particulate Matter (PM)	A mixture of smoke, soot, and liquid droplets that can cause respiratory problems and form atmospheric haze.
Sulfur Dioxide (SO_2)	A corrosive gas released by the burning of fuels containing sulfur (like coal, oil, and diesel fuel). It causes respiratory problems, acid rain, and atmospheric haze.
Nitrogen Oxides (NO_X)	Various nitrogen compounds like nitrogen dioxide (NO_2) and nitric oxide (NO) formed when any fuel is burned at high temperature. These compounds lead to respiratory problems, smog, and acid rain.

The HOMER software applies emissions factors to estimate the quantity of pollutants released per unit of fuel consumed during the simulation of power systems that incorporate generators. The annual emissions of pollutants are calculated by multiplying the total annual fuel consumption by the emissions factor. In contrast, during the simulation of a grid-connected system, HOMER calculates the net grid purchases by subtracting the grid sales from the grid purchases. The HOMER software uses the emission factor, expressed in grammes per kilowatt-hour (g/kWh), to determine the emissions associated with the net grid purchases, which are measured in kWh. This calculation involves multiplying the net grid purchases by the appropriate emission factor for each pollutant. However, the primary focus of this project will be on a comparison of the lowering of CO_2 emissions, a significant pollutant that particularly leads to global warming issue.

3.6 Scenario Modelling

In order to design an individual four-scenario model in Homer. The assessment of the potential for renewable energy sources is a significant factor. Due to its geographical location in a tropical zone, Thailand has considerable solar potential. Although Sichang Island may not be the most optimal location for solar energy generation, but its average solar GHI is within the average range when compared to the whole of Thailand as stated in Section 3.3.1.

The wind energy potential in Thailand is not as robust as solar. However, certain regions, particularly in the Eastern region (which includes Chonburi Province, where Koh Sichang is located) and parts of southern Thailand, are viable for wind energy due to consistent monsoon winds. The coastal location of Koh Sichang could provide an added advantage for harnessing wind energy.

Even Thailand contains a substantial amount of biomass resources, predominantly derived from agricultural residues such as rice, sugarcane, and oil palm waste. Given that Koh Sichang is not a major agricultural centre, there are no electricity consumption in agricultural purposes, as described in Table 7 in Section 2.4.1. It is unlikely that the island currently produces agricultural residues suitable for bioenergy production. Due to the lack of precise data on Sichang Island's biomass production. Thus, biomass energy generation will not be included in the simulation.

3.7 Limitations and Assumptions of the project in Homer

After the input parameters for the project have been added to the base model in Homer, it is necessary to set limitations and assumptions for a scenario design in order to produce the best possible results, as some parameters in Homer are not properly matched to the outcome, and to obtain an accurate result from some renewable resources. Therefore, the following lists will provide an explanation of the project's limitations and assumptions, which will help in better understanding:

Project Limitations

1. Project lifetime: 25 years
2. Contain a minimum of 35 percent of renewable energy fraction in each scenario
3. 6% discount rate
4. Maximum total capital cost is 250,000,000 THB, or around 5538790 GBP
5. Maximum 0.1 % of annual capacity shortage
6. 10% spare of a peak demand
7. Energy sales to the grid is not included in the project
8. Average electricity load: 33,075.72 kWh/day

Project Assumptions

1) The replacement cost for all components accounted for 50% of the capital cost
2) The operation of five diesel generators in base model is scheduled by Homer
3) The initial capital cost is referred to another research journal with the same capacity size due to the lack of information on the price of the current diesel generator on Sichang Island
4) The electric load profile in 2025 will increase by 5.47% based on the growth rate of electricity demand over the past 20 years in Thailand

4 Scenario Results and Discussion

The result can be classified into four different scenarios, which are defined by varying components and sizes of renewable source input under the project limitations and assumption which previously mentioned in Section 3.7. These scenarios are compared with a base model that has been simulated using HOMER software. The configuration of the four scenarios is divided as follows:

1) Base Model – 5 MW Diesel Generator
2) Scenario 1 – 5 MW Solar PV + 3 MW 4hr Lithium-ion batteries + Grid
3) Scenario 2 – 3 MW Wind Turbine + Grid
4) Scenario 3 – 2 MW of Diesel Generator + 1 MW Wind Turbine + 3 MW Solar PV + 3MW 4hr Lithium-ion batteries
5) Scenario 4 – 3 MW Solar PV + 2 MW Wind Turbine + Grid

4.1 Base Model and Discussion

The schematic model represented in Figure 29 is considered as a base model that currently use on Sichang island for the purpose of assessing and comparing the economic aspects, such as COE and the total NPC of scenarios 1–4, as well as promoting the implementation of renewable energy sources while maintaining an initial capital cost that does not exceed 5,538,790 GBP since this model contains no renewable fraction. Furthermore, the mitigation of CO_2 emissions has also been taken into account. The model consists of five diesel generators, each possessing a capacity of 1,000 kW.

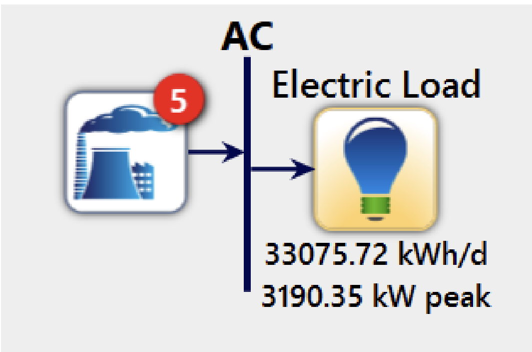

Figure 29: Schematic of Base Model

4.1.1 *Base Model Result*

Table 16: Performance of Base Model

Parameter	Value
Renewable Fraction (%)	0
COE (GBP/kWh)	0.21
Total NPC (GBP)	32,837,830
Initial Capital Cost (GBP)	382,350
CO_2 Emission (kg/yr)	8,377,840
Annual Capacity Shortage (%/yr)	0
Unmet Electric Load (%/yr)	0
Excess Electricity (%/yr)	0.00180

Table 17: Cost Summary of Base Model

Component	Capital (£)	Replacement (£)	O&M (£)	Fuel (£)	Salvage (£)	Total (£ Million)
1MW Diesel Generator (1)	76,470.00	274,265.17	1,119,822.00	19,604,235.42	-3,563.48	21.07
1MW Diesel Generator (2)	76,470.00	29,586.45	166,822.80	1,027,047.94	-7,349.68	1.29
1MW Diesel Generator (3)	76,470.00	0.00	3,707.17	20,296.77	-8,478.12	0.09
1MW Diesel Generator (4)	76,470.00	0.00	0.00	0.00	-8,685.99	0.067
1MW Diesel Generator (5)	76,470.00	236,672.40	984,701.92	9,163,076.46	-1440.24	1.04
System	382,350.00	540,524.02	2,275,053.90	29,814,656.59	-29,517.50	32.98

Table 18: Emission results of Base Model

Pollutants	Value (kg/yr)
Carbon Dioxide	8,377,840
Carbon Monoxide	43,342
Unburned Hydrocarbons	2,300
Particulate Matter	371
Sulfur Dioxide	20,479
Nitrogen Oxides	8,307

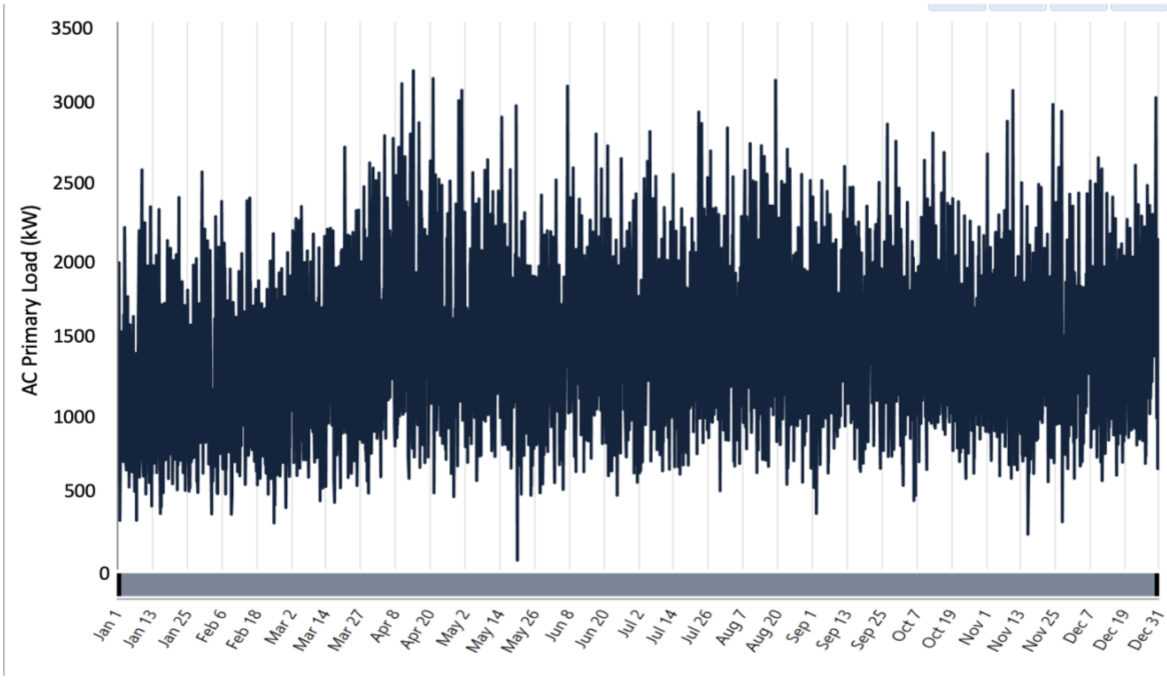

Figure 30: Projected electricity demand in Homer

4.1.2 Base Model Discussion

The primary power supply in the baseline model comprises five 1 MW diesel generators, and their operational schedule is determined through Homer optimization. According to the graph shown in Figure 30, the daily electricity demand reaches 33,075 kWh, with a peak of 3,190.35 kW. The power supply from diesel generators effectively meets the electricity demand with a low initial capital cost of GBP 76,470 per generator as shown in Table 17, without experiencing any capacity shortages over the course of the entire year.

In terms of COE, this particular model indicates a comparatively higher average value. This can be attributed to the current power system, which remains standalone from the grid, which leads to higher fuel costs for electricity generation in comparison to the distribution rate from the national grid. In Thailand, COE can be classified into various groups, such as residential, commercial, industrial, or by region. According to statistics of COE in Thailand from various generation sources recorded by EGAT in 2022, the average rate stands at 3.77 THB/kWh or around 0.084 GBP/kWh while the power generation from diesel generators was above the average at 8.45 THB/kWh or approximately 0.19 GBP/kWh [49]. Therefore, the COE value from the base model in Homer is 0.21 GBP/kWh, which is close to reality.

Furthermore, Table 16 indicates that the system could not be feasible over the long term. The total NPC is relatively high for GBP 32,837,830, which is nearly ten times of the initial capital cost. Notably, the fuel costs stated in Table 17 are substantial totalling GBP 29,814,656.59. Moreover, the system's heavy reliance on non-renewable sources results in a substantial annual production of pollutants especially CO_2 emissions at 8,377,840 kg/yr as shown in Table 18, which raises concerns regarding environmental sustainability and global warming. These highlight the need to investigate more economically viable and environmentally favourable energy solutions.

4.2 Scenario 1 and Discussion

This scenario combines the integration of a hybrid system of solar and li-ion battery storage with a national grid to supply power when the power production from solar PV is inadequate. The model includes both DC and AC components. with the solar PV functioning in DC mode to convert sunlight into direct current electricity to supply to the load as well as a li-ion battery to store excess power production from solar PV for supply during periods of high electric demand or when PV is not operated along with the electrical grid that is set on the AC side, while the converter is connected on both sides in order to transfer the power from DC and AC as shown in Figure 31.

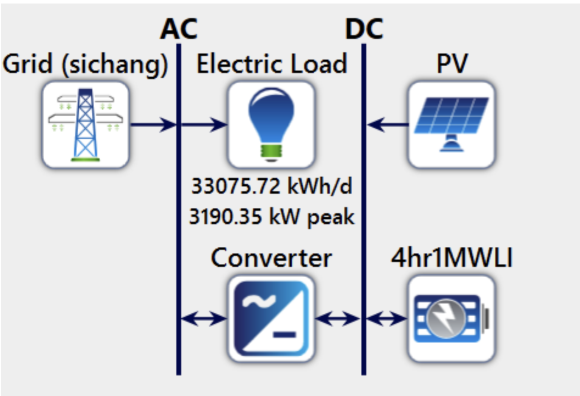

Figure 31: Schematic of Scenario 1

Table 19: Model Configuration of Scenario 1

Component	Quantity	Energy Production year (%/yr)
Generic Flat PV (1kW)	5,000	64.4
Grid (kW)	999,999	35.6
Converter (1kW)	1,496	-
Generic 4hr 1 MW Li-ion	3	-

4.2.1 Scenario 1 Result

Table 20: Performance of Scenario 1

Parameter	Value
Renewable Fraction (%)	60.0
COE (GBP/kWh)	0.07432
Total NPC (GBP)	11,469,010
Initial Capital Cost (GBP)	4,799,766.25
CO_2 Emission (kg/yr)	3,049,411
Annual Capacity Shortage (%/yr)	0
Unmet Electric Load (%/yr)	0
Excess Electricity (%/yr)	2.33

Table 21: Cost Summary of Scenario 1

Component	Capital (£)	Replacement (£)	O&M (£)	Salvage (£)	Total (£Million)
Generic Flat PV	3,280,000.00	0.00	1,278,335.62	0.00	4.56
Grid	0.00	0.00	4,749,353.02	0.00	4.75
Converter	493,556.25	102,971.89	0.00	-19,166.32	0.57
Generic 4hr 1 MW Li-ion	1,026,210.00	214,100.79	383,500.68	-39,850.92	1.58
System	4,799,766.25	317,072.68	6,411,189.32	-40,249.28	11.46

Table 22: Emission results of Scenario 1

Pollutants	Value (kg/yr)
Carbon Dioxide	3,049,411
Carbon Monoxide	0
Unburned Hydrocarbons	0
Particulate Matter	0
Sulfur Dioxide	13,221
Nitrogen Oxides	6,466

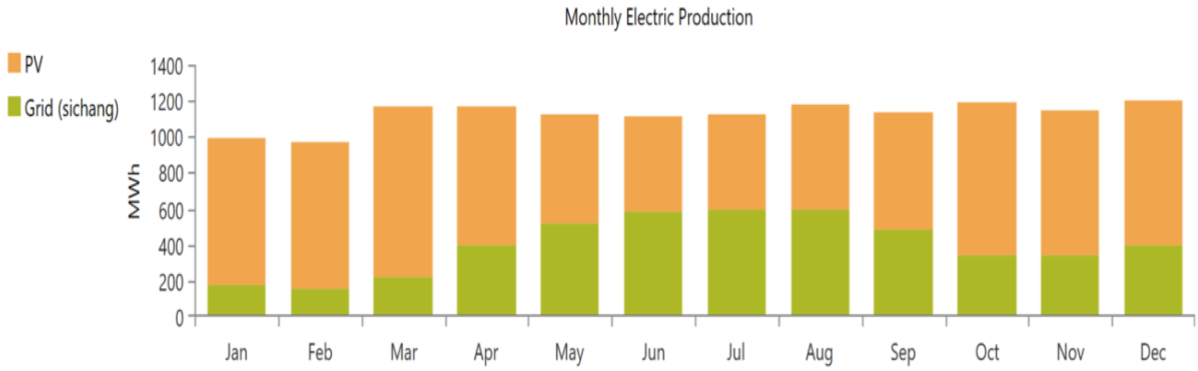

Figure 32: Monthly Electric Production of Scenario 1 by Homer

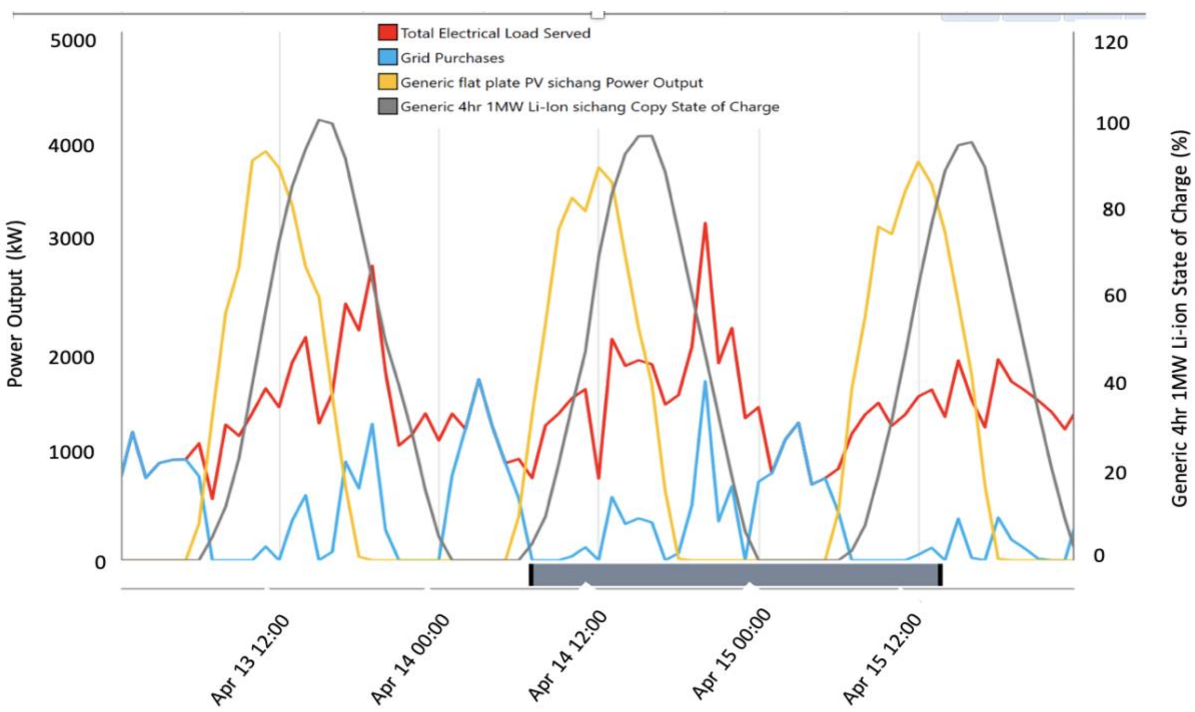

Figure 33: Characteristic of Scenario 1 power output in summer (April 13th-April 15th)

0

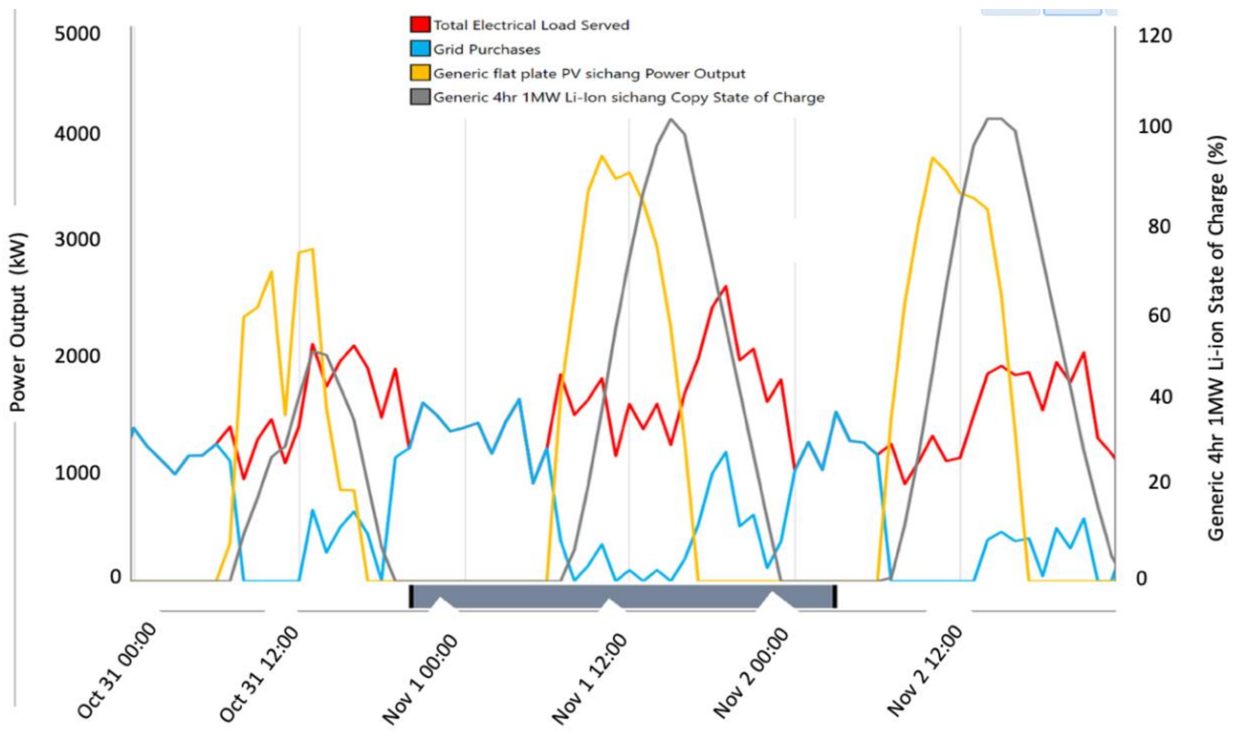

Figure 34: Characteristic of Scenario 1 power output in winter (October 31st -November 2nd)

4.2.2 Scenario 1 Discussion

In the first scenario, the most effective configuration for the implementation of solar energy includes a system of 5,000 solar PV with a power output of 1 kW each, along with a 1,496 kW converter, three lithium-ion batteries with capacity of 1 MW per each, and a connection to the electrical grid as presented in Table 19. Solar PV accounts for 64.4% of energy production, making it the primary source. The remaining 35.6% comes from the grid when solar PV generation is insufficient. Also, li-ion batteries function as energy storage systems, storing surplus solar energy generated during peak periods and supplying electricity during periods of low solar generation or high demand.

This scenario displays a power production performance that reaches a total renewable fraction of 60 %. The excess electricity in the system amounts to only 2.33% annually as shown in Table 20, which appears to be a relatively small proportion. This can be caused by the effective operation of battery storage and the grid's supply of electricity, maintaining proper control of the system's balance.

The COE of this model is lower than the base model at 0.07432GBP/kWh, which accounts for 64.6% of the original, and the total NPC is also significantly reduced to 11,469,010 GBP throughout the project year due to the removal of fuel costs, a cheaper replacement, and increased salvage value, as shown in Table 21. Furthermore, the initial capital cost is below the predetermined budget at 4,799,766.25 GBP.

Without diesel generator, there is a substantial decline in the amount of the emissions in comparison to the base model as shown in Table 22. The CO_2 emissions vastly decreased from 8,377,840 kg/yr to 3,049,411 kg/yr, corresponding to a reduction of approximately 63.6% as well as decrease in SO_2 from 20,479 kg/yr to 13,221 kg/yr and from 8,307 kg/yr to 6,466 kg/yr. Moreover, there is elimination of CO, UHC, and PM released.

Figure 32 represents the characteristics of the power generation output of each component by month. As a result, the solar PV expresses high efficiency throughout the year, particularly during the summer season when the region experiences abundant solar irradiance, whereas its efficiency reaches a minimum point in October, coinciding with the period of lowest solar irradiance, as previously discussed in Section 3.3.1. Hence, Figures 33 and 34 depict the power generation output that is specific to the summer and winter seasons, respectively.

The summer season has been selected as the period in which the highest level of demand is observed as shown in Figure 33. The graph indicates that solar PV typically commence generating electricity between 06:00-17:00 while 11:00-13:00 stands out as the most efficiency for solar PV production, with a peak output of 3,868.31 kW. Conversely, there is typically a notable increase in electricity demand during the evening hours, particularly from 17:00-22:00, when solar power generation is not work. Therefore, the implementation of battery storage is essential in order to mitigate and reduce reliance on grid electricity purchasing. The use of lithium-ion batteries has the potential to contribute to the provision of electrical energy during the time period of 17:00-01:00 along with the grid.

While the graph in Figure 34 illustrates the potential power output during the winter, the month with the smallest amount of solar PV production is the one that has been selected. The solar PV output and electricity demand display a similar pattern, although at a reduced level, in contrast to the summer season, when the solar PV has a maximum peak output of 2,993.20 kW.

4.3 Scenario 2 and Discussion

This scenario combines the hybrid system of wind energy with a national grid. The model consists only of an AC side wind turbine as the primary source, with the national grid as a backup power supply when the production from the wind power does not meet the electric demand as shown in Figure 35.

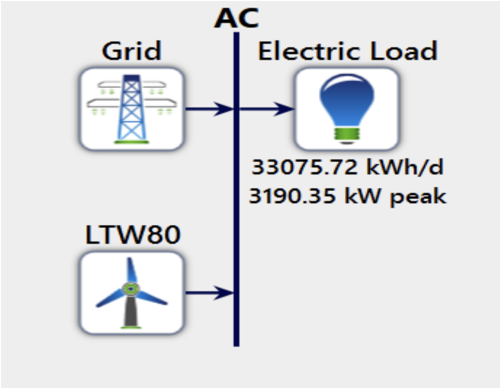

Figure 35: Schematic of Scenario 2

Table 23: Model Configuration of Scenario 2

Component	**Quantity**	**Energy Production year (%/yr)**
Leitwind 80 1000 kW	3	66.5
Grid (kW)	999,999	33.5

4.3.1 Scenario 2 Result

Table 24: Performance of Scenario 2

Parameter	**Value**
Renewable Fraction (%)	56.9
COE (GBP/kWh)	0.05948
Total NPC (GBP)	9,179,226
Initial Capital Cost (GBP)	3,440,100
CO_2 Emission (kg/yr)	3,287,316
Annual Capacity Shortage (%/yr)	0
Unmet Electric Load (%/yr)	0
Excess Electricity (%/yr)	22.3

Table 25: Cost Summary of Scenario 2

Component	**Capital (£)**	**Replacement (£)**	**O&M (£)**	**Salvage (£)**	**Total (£Million)**
Grid	0.00	0.00	5,119,882.43	0.00	5.11
Leitwind 80 1000 kW	3,440,100.00	536,319.72	383,500.68	-300,576.97	4.06
System	3,440,100.00	536,319.72	5,503,383.11	-300,576.97	9.17

Table 26: Emission results of Scenario 2

Pollutants	Value (kg/yr)
Carbon Dioxide	3,287,316
Carbon Monoxide	0
Unburned Hydrocarbons	0
Particulate Matter	0
Sulfur Dioxide	14,252
Nitrogen Oxides	6,970

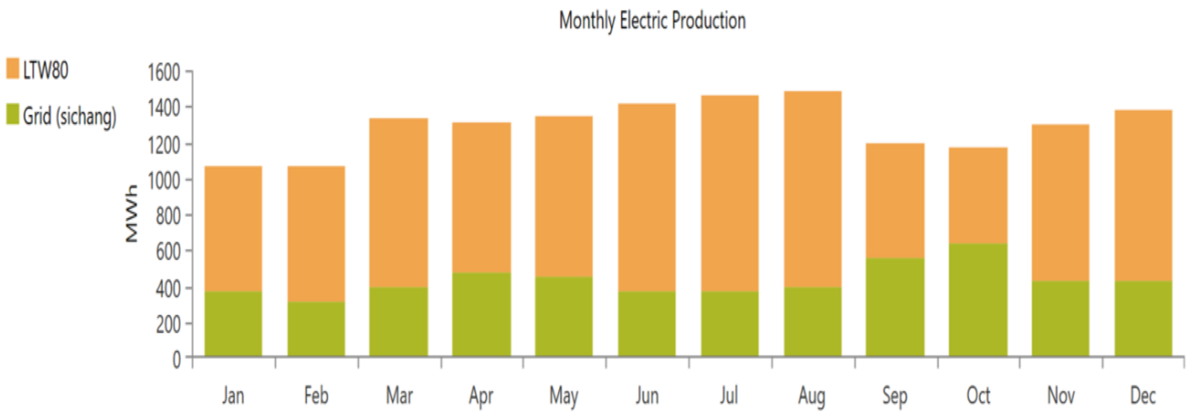

Figure 36: Monthly Electric Production of Scenario 2 by Homer

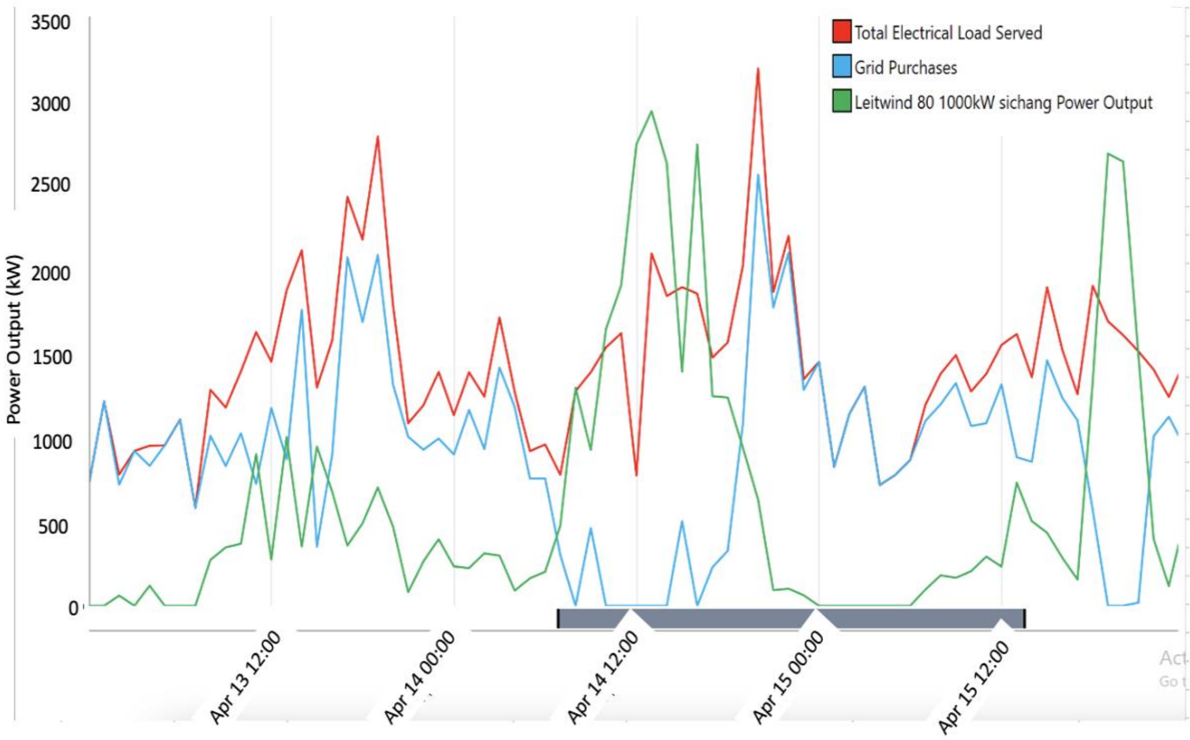

Figure 37: Characteristic of Scenario 2 power output in summer (April 13th-April 15th)

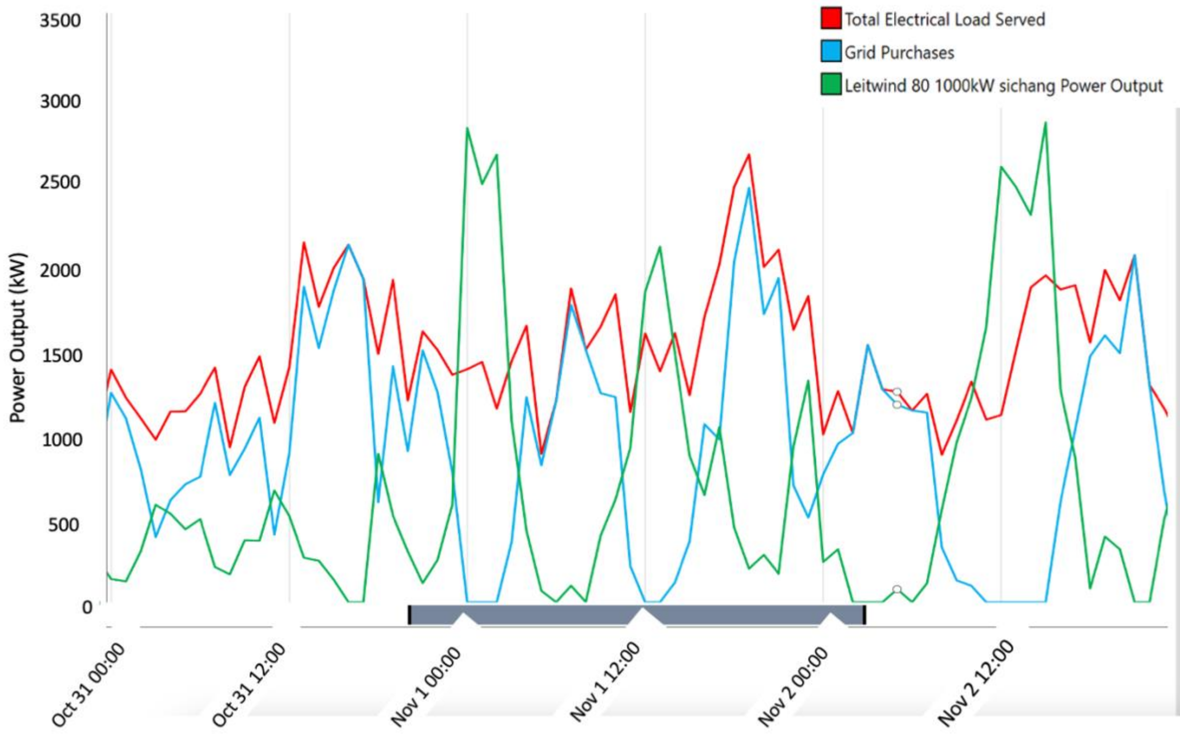

Figure 38: Characteristic of Scenario 2 power output in winter (October 31st -November 2nd)

4.3.2 Scenario 2 Discussion

In the second scenario, the optimal arrangement for the implementation of wind energy includes a configuration that consists of three wind turbines, each with a power output of 1 MW. These turbines are designed to work together with the electrical grid. Wind power is responsible for a significant proportion of energy production, constituting 66.5% of the total output and thus serving as the primary source. The remaining 33.5% of electricity is sourced from the grid in situations when the generation from wind power is inadequate as shown in Table 23.

This scenario demonstrates a power production performance that achieves a total renewable fraction of 56.6%. The excess electricity in the system is regarded as significant at 22.3% per year as presented in Table since it has no battery storage in the system and there is overpower production from renewable resources during some periods of the day.

In terms of COE, this model has a lowest value of 0.05948 GBP/kWh compared to the base model and other scenarios. This reduction represents 71.7% of the original value. Similarly, the amount of total NPC also lowest which substantially decreased to 9,179,226 due to the removal of fuel costs, a reduction in components, and a significantly greater salvage value as shown in Table 25, and the initial capital cost is lower than the set budget, amounting to 3,440,100 GBP.

Regarding the number of emissions in Table 26, the CO_2 emissions dropped from 8,377,840 kg/yr to 3,287,316 kg/yr, which accounted for a 61.8% decrease, along with SO_2 from 20,479 kg/yr to 14,252 kg/yr and NO_x from 8,307 kg/yr to 6,970 kg/yr. Moreover, there is elimination of CO, UHC, and PM released.

Figure 36 shows the power generation output characteristics of each component by month. Wind power shows a high level of efficiency throughout the year. It particularly produces a high output power during the rainy season in June–August, when the region experiences abundant wind speed, whereas its efficiency reaches a minimum point in October, just like solar energy. Therefore, Figures 37 and 38 illustrate the power generation output specific to the summer and winter seasons, respectively.

The graph from Figure 37 and 38 indicates that wind power has a more fluctuation when compared to solar PV since there is no specific interval time for the peak output, making it more difficult to predict. It can generate high power during the day or night depending on the wind speed, as shown on April 14th in summer and November 2nd in winter, when the maximum output of wind power appears during the day. While April 15th in summer and November 1st in winter appear during the night, unlike solar, which the power can normally produce during the sunlight hours, Consequently, the maximum power output from a wind turbine is recorded at 2,957.32 kW in summer and 2,848.26 kW in winter.

4.4 Scenario 3 and Discussion

This scenario is an off-grid hybrid renewable system that combines solar and wind power with Li-ion batteries and a diesel generator as a backup power supply when the power production from renewable sources and stored energy from batteries do not meet an electric load. The model includes both DC and AC sides, with the solar PV functioning in DC mode as well as a Li-ion battery to store and exceed power production from solar and wind energy. Wind power and diesel generators are on one AC side, while the converter is connected on both sides in order to transfer the power from DC and AC as presented in Figure 39.

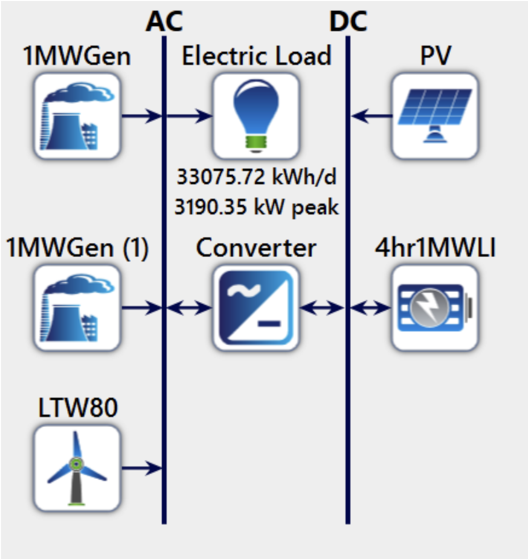

Figure 39: Schematic of Scenario 3

Table 27: Model Configuration of Scenario 3

Component	Quantity	Energy Production year (%/yr)
1 MW Diesel Generator	2	43.5
Generic Flat PV (1 kW)	3,000	30.8
Converter (1kW)	1,994	-
Leitwind 80 1000 kW	1	25.7
Generic 4hr 1 MW Li-ion	3	-

4.4.1 Scenario 3 Result

Table 28: Performance of Scenario 3

Parameter	Value
Renewable Fraction (%)	51.8
COE (GBP/kWh)	0.1405
Total NPC (GBP)	21,682,770
Initial Capital Cost (GBP)	4,951,886
CO_2 Emission (kg/yr)	3,950,684
Annual Capacity Shortage (%/yr)	0.0435
Unmet Electric Load (%/yr)	0.0159
Excess Electricity (%/yr)	2.21

Table 29: Cost Summary of Scenario 3

Component	Capital (£)	Replacement (£)	O&M (£)	Fuel (£)	Salvage (£)	Total (£Million)
1 MW Diesel Generator (1)	76,470.00	36,508.49	217,061.39	10,031,991.86	-1,514.48	10.81
1 MW Diesel Generator (2)	76,470.00	36,508.49	217,061.39	4,027,512.69	-1,514.48	4.36
Generic 4hr 1MW Li-ion	1,026,210.00	216,240.97	148,990.02	0.00	-39,850.92	1.35
Generic Flat PV	1,968,000.0	214,100.79	767,001.37	0.00	0.00	2.73
Leitwind 80 1000 kW	1,146,700	178,773.24	431,438.27	0.00	-100,192.32	1.66
Converter	658,075.00	137,295.85	0.00	0.00	-25,555.10	0.77
System	4,951,925.00	699,632.39	2,142,937.91	14,059,504.54	-171,193.84	21.68

Table 30: Emission results of Scenario 3

Pollutants	Value (kg/yr)
Carbon Dioxide	3,950,684
Carbon Monoxide	20,439
Unburned Hydrocarbons	1,085
Particulate Matter	175
Sulfur Dioxide	9,659
Nitrogen Oxides	3,917

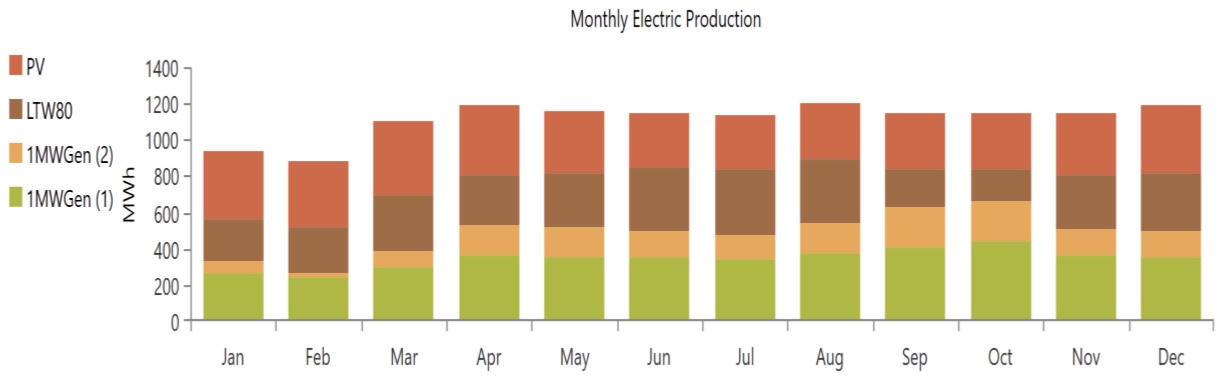

Figure 40: Monthly Electric Production of Scenario 3 by Homer

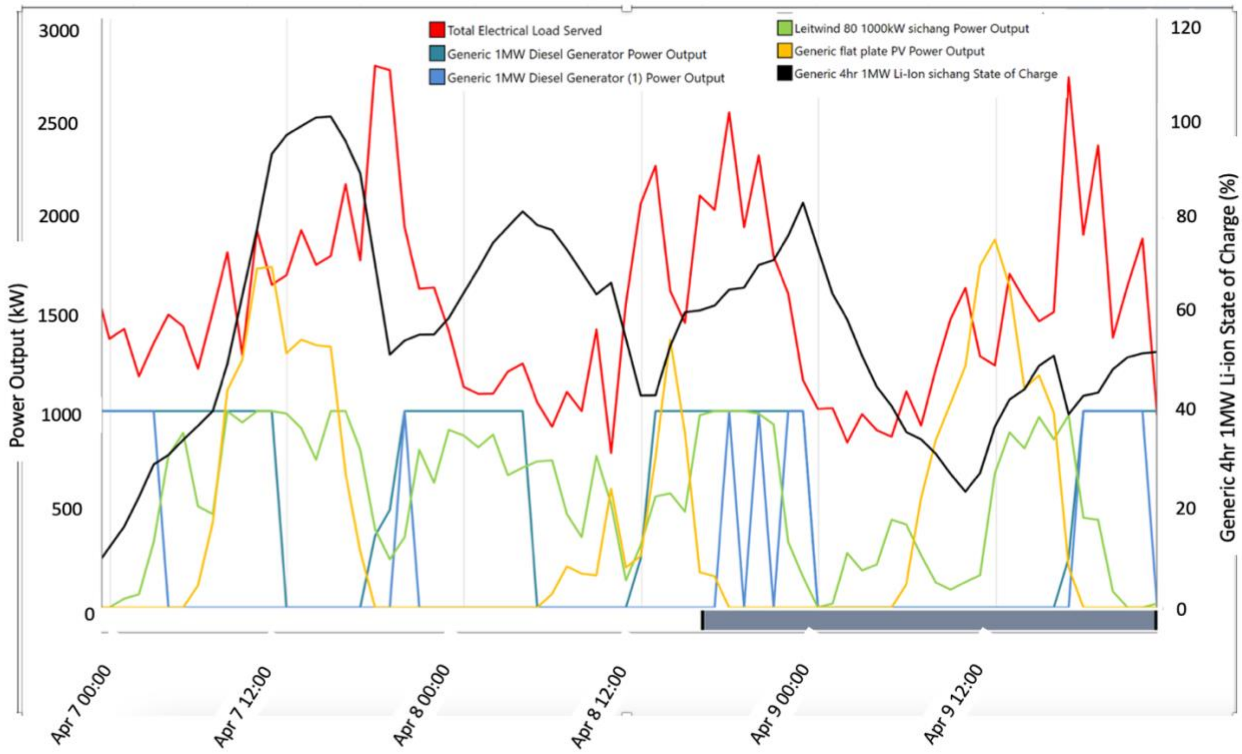

Figure 41: Characteristic of Scenario 3 power output in summer (April 7th-April 9th)

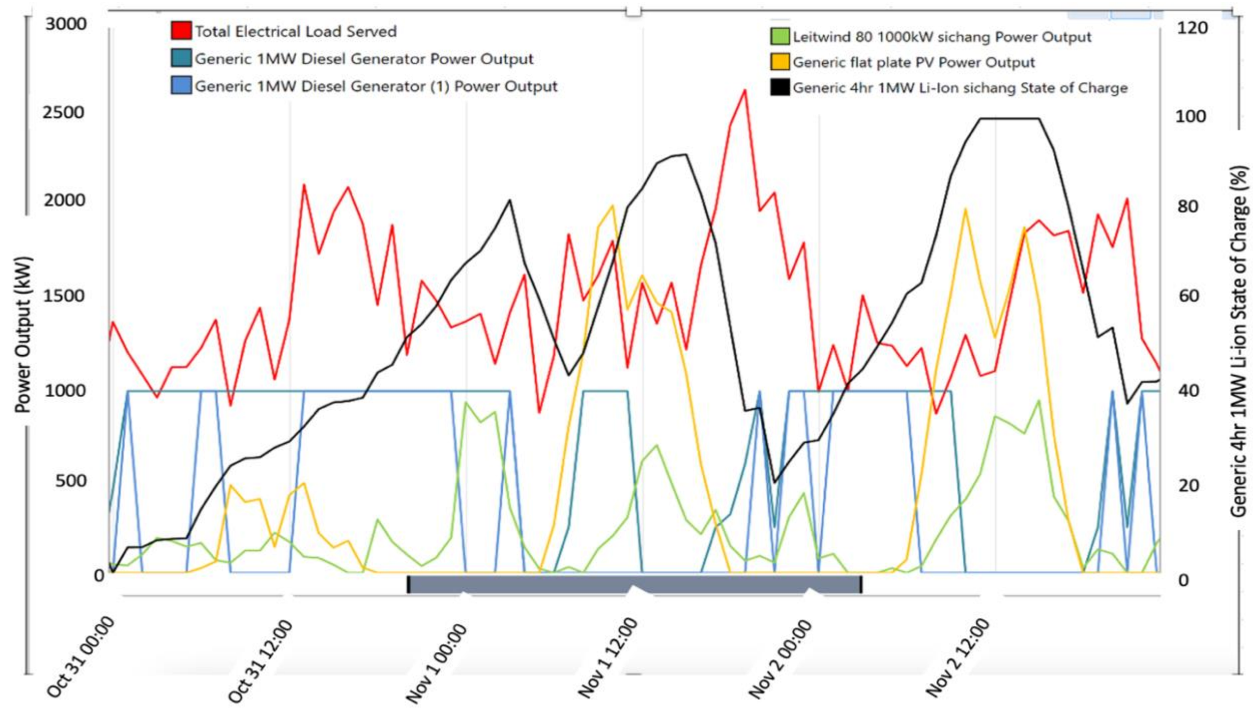

Figure 42: Characteristic of Scenario 3 power output in winter (October 31st -November 2nd)

4.4.2 Scenario 3 Discussion

In the third scenario, the optimal configuration for installing an off-grid hybrid solar and wind energy system consists of 3,000 PV panels, each with a power output of 1 kW, along with 1 MW wind turbine, a 1,994 kW converter, three lithium-ion batteries with capacity of 1 MW per each, and 2 MW diesel generators as a supply source in case the production from renewable outputs is deficit as presented in Table 27. However, the main generation sources in this scenario still come from diesel generators with 43.5 % per year from total energy production, followed by solar PV at 30.8 % per year and wind power at 25.7 % per year respectively. Also, li-ion batteries function as energy storage systems, storing surplus solar and wind energy generated during peak periods and supplying electricity during periods of low generation from renewable sources or high demand.

The COE of this model is lower than the base model at 0.1405 GBP/kWh, which represents 33.1% of the original, but it is the highest when compared with other scenarios, as well as the total NPC of 21,682,770 GBP throughout the project year due to the fuel cost included in this system, with a higher replacement cost but increased salvage value, as shown in Table 29. While the initial capital is below the predetermined budget at 4,951,925 GBP.

According to Table 28, this scenario indicates a power production performance that reaches the lowest total renewable fraction when compared with other scenarios at 51.8%. The system's excess electricity is only 2.21% per year due to the effectiveness of battery storage, maintaining control of the system's balance. However, there are some unmet electric loads at 0.0159 percent per year, which occur when electrical demand exceeds the capacity of the power supply.

The COE of this model is lower than the base model at 0.1405 GBP/kWh, which represents 33.1% of the original, but it is the highest when compared with other scenarios, as well as the total NPC of 21,682,770 GBP throughout the project year due to the fuel cost included in this system, with a higher replacement cost but increased salvage value, as shown in Table 29. While the initial capital is below the predetermined budget at 4,951,925 GBP.

In terms of emissions, there is a reduction in CO_2 emissions, which decreased by 52.9% from 8,377,840 kg/yr to 3,950,684kg/yr, but it is considered the highest CO_2 emission when compared with other scenarios, while the amount of SO_2 and NO_x emission in this scenario were the highest reductions, from 20,479 kg/yr to 9,659 kg/yr and 8,307 kg/yr to 3,917 kg/yr respectively. However, there are still CO, UHC, and PM released as illustrated in Table 30.

Figure 40 illustrates the monthly power generation output characteristics of each individual component. From the graph, the total power generation from renewable sources is slightly greater in the year except in some months, when the power output from wind and solar is significantly less than that from diesel generators, especially in September and October. Therefore, Figures 41 and 42 represent the power generation output specific to the summer and winter periods, respectively.

In the summer season, it has been observed that solar PV has a greater power output when compared to wind power during the daytime hours spanning from 06:00 to 17:00. During nighttime hours, wind power can be utilized in conjunction with li-ion batteries to supply the electrical demand, thereby reducing the reliance on a diesel generator and minimizing fuel costs, as shown in Figure 41. The solar PV displays a peak power output of 1,873.16 kW, while the wind power achieves a maximum output of 1000 kW. During the winter season, the power output derived from both solar and wind sources is below average. For instance, the maximum power output generated by solar PV on October 31st during peak daytime hours was measured to be 494.35 kW. Also, the maximum power output for a wind turbine is 737 kW. Thus, it can be argued that this scenario has relatively lower stability in comparison to other scenarios due to its highly unpredictable renewable output, elevated cost, lowest amount of CO_2 emissions reduction, and occur some flaws in the system, such as capacity shortages and unmet electric loads during the year.

4.5 Scenario 4 and Discussion

This scenario combines the hybrid renewable system of solar and wind power with a national grid as a backup power supply when the power production from renewable sources does not meet an electric load. The model includes both DC and AC sides, with the solar PV functioning on the DC side while wind power and the national grid are on the AC side, and the converter is connected on both sides in order to transfer the power from DC and AC as presented in Figure 43.

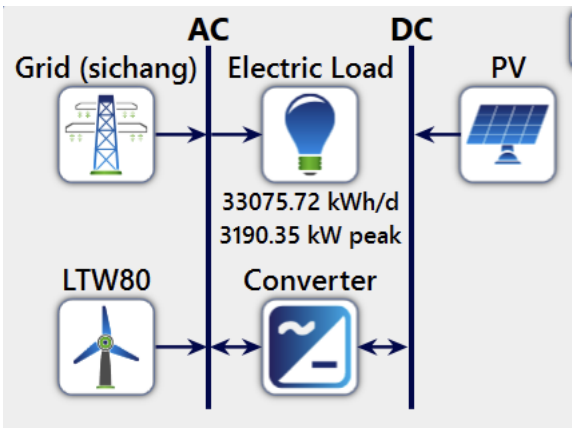

Figure 43: Schematic of Scenario 4

Table 31: Model Configuration of Scenario 4

Component	Quantity	Energy Production year (%/yr)
Generic Flat PV (1 KW)	3,000	31.3
Converter (1kW)	1,172	-
Leitwind 80 1000 kW	2	41.2
Grid (kW)	999,999	27.5

4.5.1 Scenario 4 Result

Table 32: Performance of Scenario 4

Parameter	Value
Renewable Fraction (%)	61.8
COE (GBP/kWh)	0.06762
Total NPC (GBP)	10,435,090
Initial Capital Cost (GBP)	4,648,019.06
CO_2Emission (kg/yr)	2,916,014
Annual Capacity Shortage (%/yr)	0
Unmet Electric Load (%/yr)	0
Excess Electricity (%/yr)	26.7

Table 33: Cost Summary of Scenario 4

Component	Capital (£)	Replacement (£)	O&M (£)	Salvage (£)	Total (£Million)
Generic flat plate PV	1,968,000.00	0.00	767,001.37	0.00	2.73
Grid	0.00	0.00	4,541,591.52	0.00	4.54
Leitwind 80 1000kW	2,293,400.00	357,546.48	255,667.12	-200,384.65	2.70
Converter	386,619.06	80,661.31	0.00	-15,013.62	0.46
System	4,648,019.06	438,207.79	5,564,260.01	-215,398.27	10.43

Table 34: Emission results of Scenario 4

Pollutants	Value (kg/yr)
Carbon Dioxide	2,916,014
Carbon Monoxide	0
Unburned Hydrocarbons	0
Particulate Matter	0
Sulfur Dioxide	12,642
Nitrogen Oxides	6,183

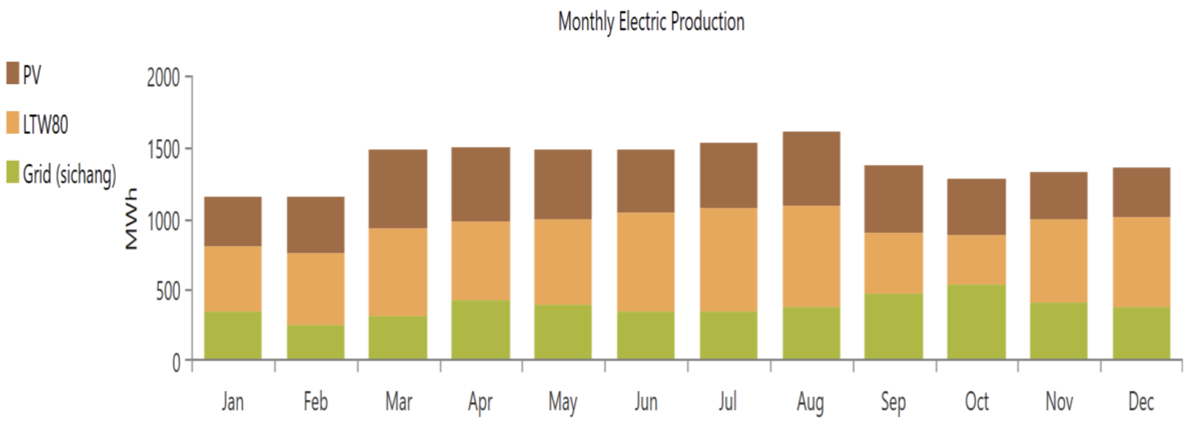

Figure 44: Monthly Electric Production of Scenario 4 by Homer

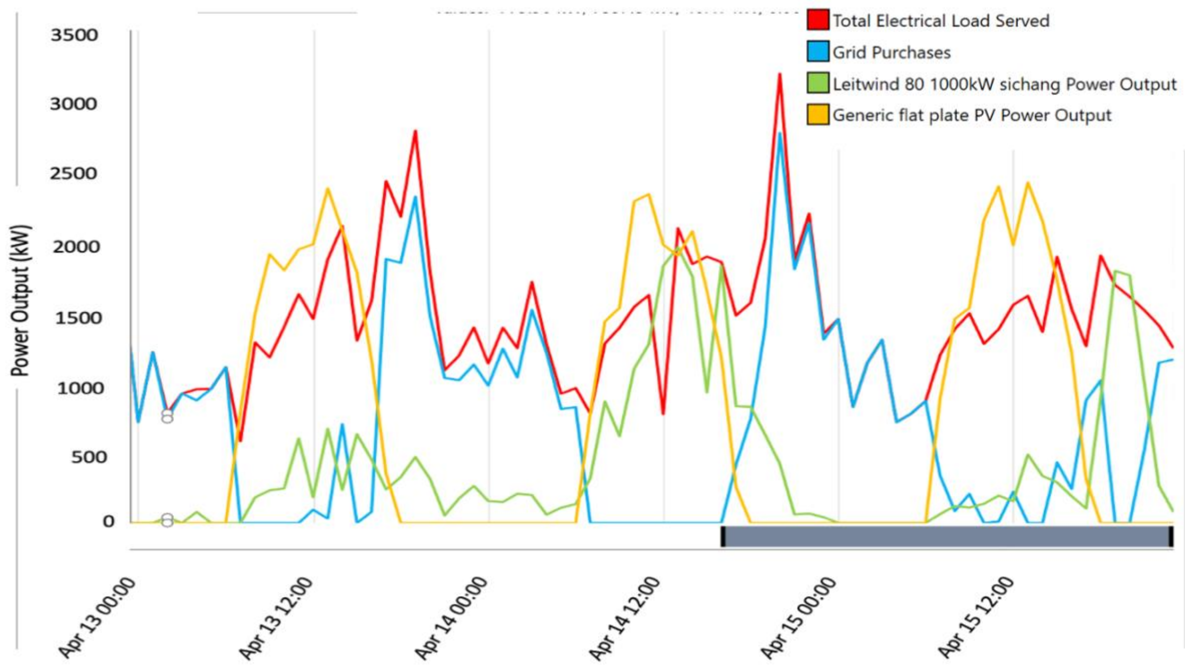

Figure 45: Characteristic of Scenario 4 power output in summer (April 7th-April 9th)

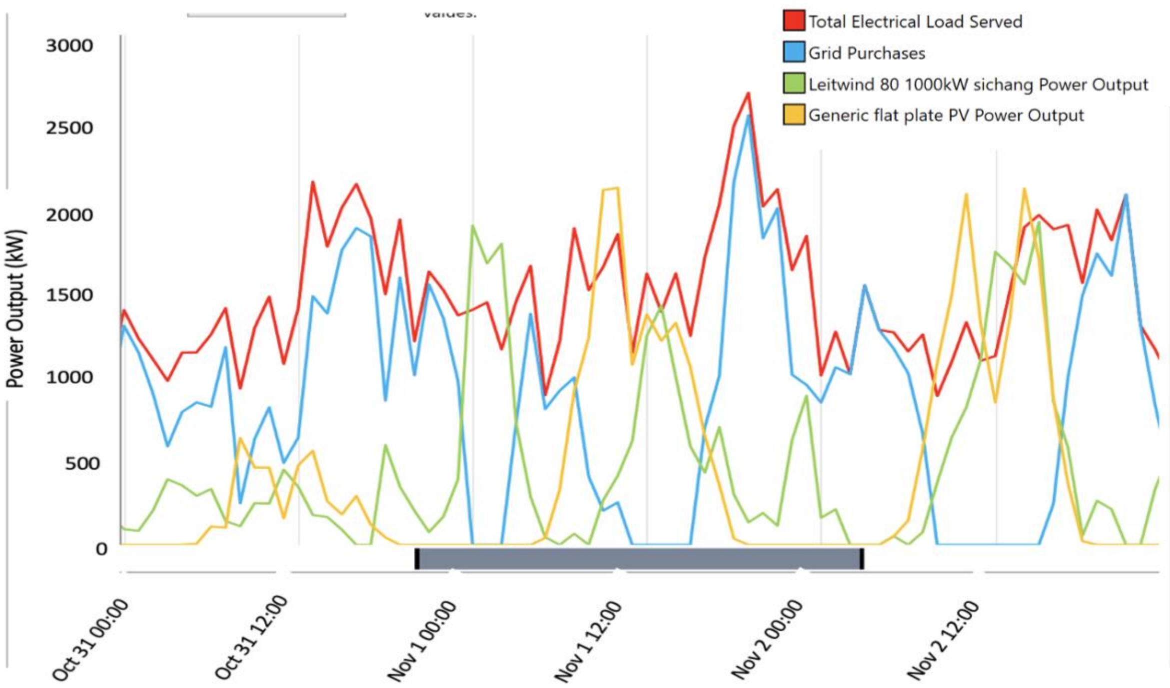

Figure 46: Characteristic of Scenario 4 power output in winter (October 31st -November 2nd)

4.5.2 Scenario 4 Discussion

In the fourth scenario, the optimal configuration for installing a hybrid solar and wind energy system consists of 3000 PV panels, each with a power output of 1 kW, along with two wind turbines, each generating 1 MW of power, a 1,172 kW converter, and a connection to the electrical grid, as presented in Table 31. Wind power accounts for 41.2% of the total energy production, with solar PV contributing 31.3%. The remaining 27.5% comes from the grid to compensate for inadequate output from solar PV and wind power during high electricity consumption.

This scenario indicates a power production performance that reaches a total renewable fraction of 61.8%, but the system's excess electricity is 26.7% per year as shown in Table 32 since it has no battery storage in the system and there is overpower production from renewable resources during some periods of the day.

The COE of this model is lower than the base model at 0.06762 GBP/kWh, which represents 67.8% of the original, and the total NPC is also significantly reduced to 10,435,090 GBP throughout the project year due to the elimination of fuel costs, a cheaper replacement, and increased salvage value as shown in Table 33, as well as the initial capital cost, which is also below the predetermined budget at 4,648,099.06 GBP.

In terms of emissions in Table 34, there is a significant reduction in CO_2 emissions when compared to the base model. The emissions decreased by 65.2% from 8,377,840 kg/yr to 2,916,014 kg/yr, along with SO_2 from 20,479 kg/yr to 12,642 kg/yr and NO_x from 8,307 kg/yr to 6,183 kg/yr. Moreover, there is an elimination of CO, UHC, and PM. Therefore, this scenario is considered to have the lowest emissions compared to others.

Figure 44 illustrates the monthly power generation output characteristics of each individual component. Wind power generally displays a greater level of output compared to solar PV energy throughout the year, except in September and October. Therefore, Figures 45 and 46 represent the power generation output specific to the summer and winter periods, respectively.

In the summer season, it is observed that solar PV illustrates a higher power output compared to wind power during daylight hours. During nighttime hours, wind power can contribute to supplying an electric demand in order to reduce the amount of electricity purchased from the grid, as shown in Figure 45. The maximum output of solar PV is recorded at 2,457.93 kW and 2,000 kW for wind power output throughout the day and night. Similarly, during the winter season, wind power exhibited variability during the peak output timeframe, whereas solar PV generated less power output, down to 2,100.23 kW at maximum, as shown in Figure 46.

4.6 Comparison and Discussion

Table 35: Base Model and Scenario 1-4 results comparison

	Base Model	**Scenario 1 (PV+Battery+Grid)**	**Scenario 2 (Wind+Grid)**	**Scenario 3 (Diesel Gen + PV + Wind + Battery)**	**Scenario 4 (PV+Wind+ Grid)**
Renew Fraction (%)	0	60.0	56.9	51.8	61.8
COE (GBP/kWh)	0.21	0.07432	0.05948	0.1405	0.06762
Total NPC (Million GBP)	32.83	11.46	9.18	21.68	10.43
Initial Capital Cost (Million GBP)	0.38	4.79	3.44	4.95	4.68
CO_2 Emission (million kg/yr)	8.33	3.04	3.28	3.95	2.91
Excess Electricity (%/yr)	0.0018	2.33	22.3	2.21	26.7

Table 35 provides an extensive summary of Scenarios 1–4 in addition to the base model, in order to evaluate and compare the most feasible options for a hybrid renewable energy system on Sichang Island. This evaluation is carried out based on the criteria of economic feasibility, environmental impact assessment, and increase of renewable energy production. The table clearly indicates that Scenario 3 has the highest values for COE, total NPC, initial capital cost, CO_2 emission, lowest renewable fraction, as well as operational issues such as capacity shortage and unmet electric load, which were previously discussed in Section 4.4.2. Therefore, Scenario 3 could be omitted from the list of the most feasible options.

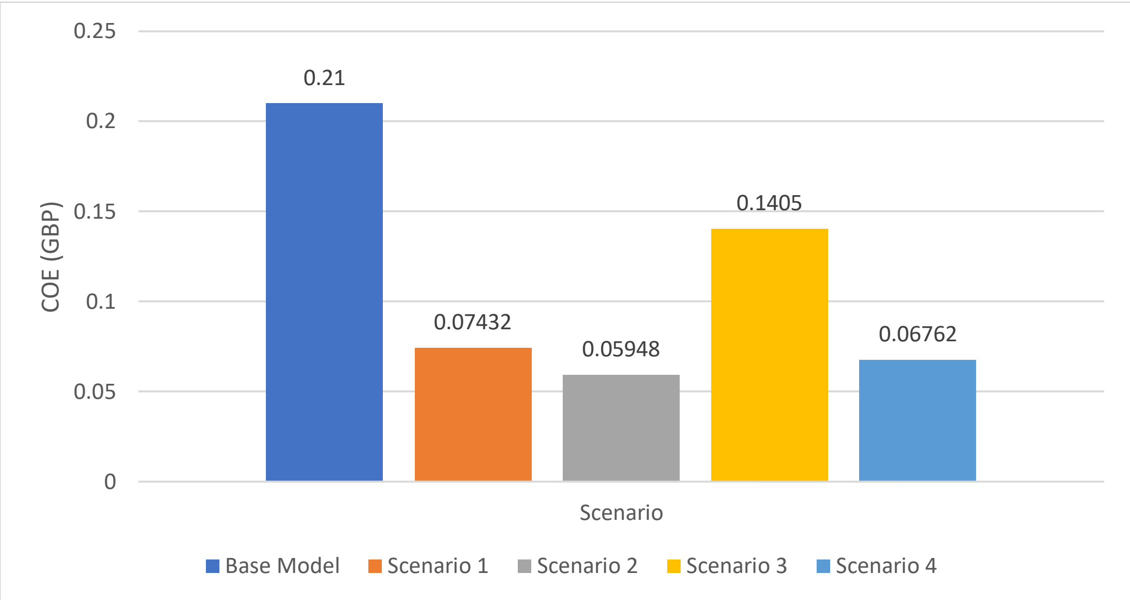

Figure 47: Base Model and Scenario 1-4 COE comparison

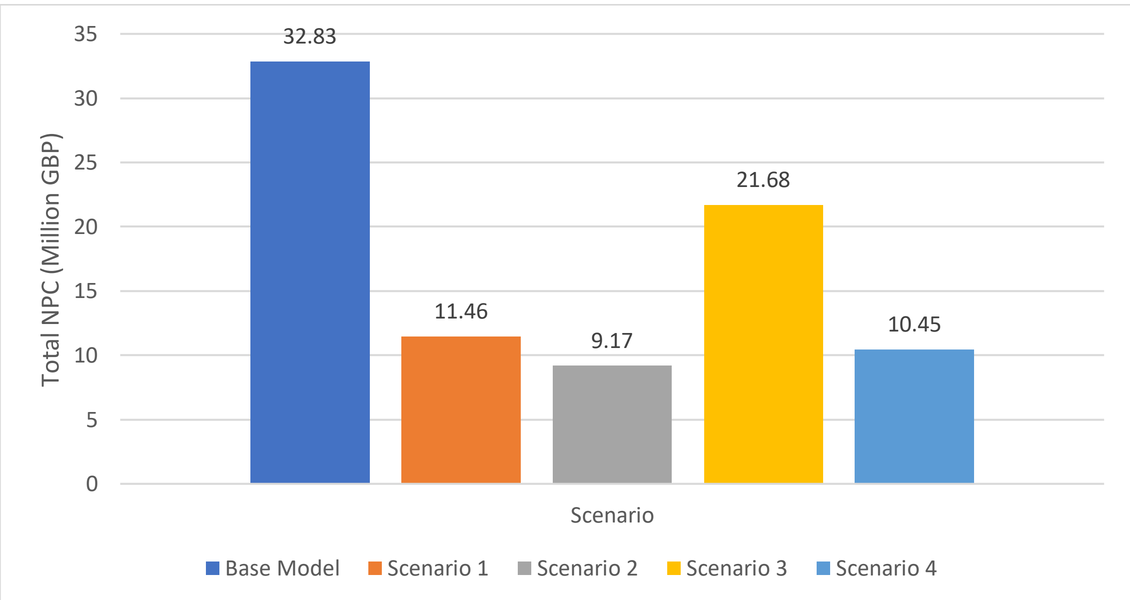

Figure 48: Base Model and Scenario 1-4 Total NPC comparison

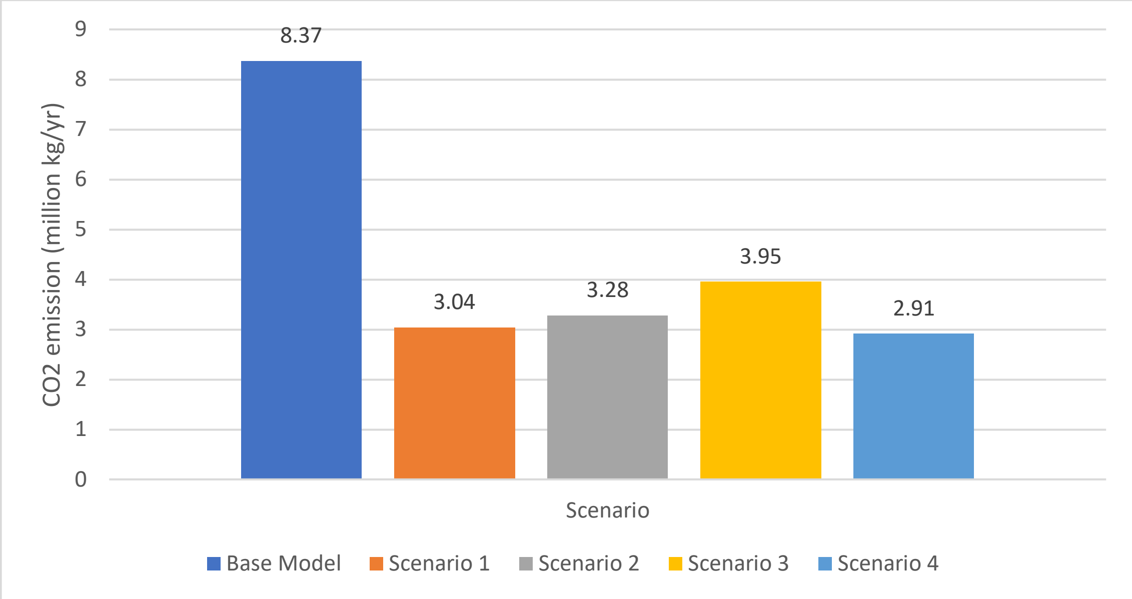

Figure 49: Base Model and Scenario 1-4 CO_2 emission comparison

The cost analysis is presented through the charts depicted in Figures 47 and 48, providing a comparison of the COE and total NPC for each scenario. The analysis revealed that Scenario 2 expresses the lowest COE and total NPC due to having fewer components than Scenarios 1 and 4. Nevertheless, wind energy has more fluctuation compared to solar energy due to the intermittent nature of wind speed, which can vary greatly at different times of the day or night. Furthermore, in comparison to the environmental impact assessment presented in Figure 49, Scenario 2 has the second highest levels of CO_2 emissions, but the total renewable fraction is also lower than Scenarios 1 and 4, and this model has the second highest excess energy. Therefore, Scenario 2 is not considered an optimal choice.

Since Scenarios 2 and 3 are not the optimal choices for implementation, the remaining two models between Scenarios 1 and 4 will be evaluated to determine which one represents the most feasible system. Both models reveal similar outcomes with regard to their financial aspects and environmental impacts. In Scenario 4, there is a slightly better result in terms of economic factors and the amount of CO_2 emissions released. However, the significant difference between these models is the amount of excess electricity. Scenario 4 has a maximum excess electricity at 26.7%, while Scenario 1 has only 2.19% due to the battery storage installed in the Scenario 1 model that could help maintain the balance of the system and obtains more consumption from renewable sources generation. However, due to the possibility of a growth rate of electricity consumption over the year as described in Figure 6 in Section 2.1, the amount of excess electricity can be gradually decreased by the increasing electricity consumption, along with grid sales are not included in the simulation as stated in Section 3.6, so it can be a way to manage excess electricity by selling it back to the grid, generate an income, and enhance the flexibility of the system, which could enhance the performance of Scenario 4 in the future.

Overall, under the condition of a hybrid renewable system in this project to advocate power production from renewable energy at least 35% refers to the PDP 2018 policy in Thailand, which was discussed in Section 2.2, as well as evaluating the economic aspect and minimising CO_2 emissions. Therefore, it is determined that Scenario 4 is currently the most viable decision to be implemented in this project.

5 Site Recommendation for the Most Feasible Scenario

Figure 50: Recommendation site

This section will recommend a possible site on Sichang Island for the installation of the hybrid renewable system in the Scenario 4, assuming that the green space from Google Earth in Figure 50 is available for installation, with the exception of the conserved forested area at the top of the map.

Solar panel can be adaptable to install in both on the rooftop or solar farm installation on ground, which the direction facing south with axis 15° is most potential angle in Thailand [50]. This orientation is preferred due to the country's location near the equator, where the sun is predominantly in the southern hemisphere. By aligning the solar panels towards the south, they can capture the maximum amount of sunlight throughout the day, optimizing their energy generation potential. Hence, the location for solar power plant would be suggest on available land space on a yellow line as shown in Figure 50 with the measured area approximately 63,000 m^2. Regarding to the location for wind turbine, in order to maximize wind speed, it is recommended to select a suitable location for wind turbines in nearby coastal areas. Hence, the area along an orange line could be considered an appropriate area, which covers up to 12,000 m^2.

6 Final Remarks

6.1 Conclusions

To conclude this research journey, due to the fact that energy consumption in Thailand appears to have grown gradually over the years, with an average increasing rate of 5.47% per year over the past 20 years, However, the primary power generation source in Thailand currently comes from natural gas, which is classified as a fossil fuel source and has a negative impact in terms of emissions as well as a high production cost. Therefore, Thailand's government presently intends to boost power generation from renewable resources under the PDP 2018 policy, which sets to achieve 35% of total power generation from renewable sources in order to support cleaner production as a pathway to energy security and carbon neutrality by 2037. For this reason, the aims of this study are to investigate the viability of a hybrid renewable energy system design and promote the power generation that comes from renewable sources. The criteria for evaluating the outcome also involve financial analysis and an assessment of the environmental impact by using Homer software as a simulation tool.

Sichang Island, an island located in the eastern region of Thailand, was selected as a case study location due to the damage to submarine cables that connect to the mainland's power plant to distribute electricity from the grid to the island. Diesel generator has been the sole power supply instead, which is classified as a fossil fuel resource. Thus, this could result in high emissions released as well as NPC of the system, which could not be beneficial in the long term. As a result, renewable energy can be a solution, and the Thai government is already planning a project to install a hybrid renewable energy system with the submarine cable on Sichang Island that connects to the mainland's substation.

Although Homer has the ability to provide the financial, emission, and technical results of various hybrid energy systems, the changes in the cost of the components or energy price during the project's lifetime, as well as the potential of renewable resources, are the limitations of the software. In addition, there are some input variables that are unable to receive an accurate value, which can cause a slight discrepancy in the result, such as the capital cost of the component of the system that referred to that capacity size from another research journal to achieve the most precise outcomes as much as possible.

The result of this project is divided into 4 scenarios of hybrid renewable systems with various proportions and input components in each scenario between solar and wind energy operate with the grid or diesel generator along with li-ion batteries and compare the outcome under the amount of renewable output, economics and emissions analysis. The following list will summarize the key overviews of the result:

- Wind power generates a greater power output compared to solar PV at equivalent capacity.
- Wind is more unpredictable than solar, as the result shows that the daily peak power output can occur at different times of the day or night, while solar has a clearer timeframe between the daytime and reaches its peak during a midday.
- Both solar and wind power generation vastly reduce emissions and eliminate some pollutants, including PM and UHC.
- Scenario 1 (Solar PV + Li-ion batteries + Grid) and Scenario 4 (Solar PV + Wind Turbine + Grid) are the most two feasible options in terms of renewable power fraction, economics, and emissions aspects. While there is a difference in the amount of excess electricity between the two scenarios, which scenario 4 generated a significantly greater amount than Scenario 1.

In terms of selecting on the most appropriate model, Scenario 4 is considered the optimal choice for a hybrid renewable energy system as it expressed the overall best outcome. Although Scenario 2 offers a better economic outcome, with slightly lower costs in terms of COE and NPC, Scenario 4 goes above and beyond in terms of renewable fraction, accounting for 61.8% of total power production as well as minimal CO_2 emissions. Finally, it is important to recognise that this study may be subject to particular limitations arising from the constraints of the software and input parameters, as previously mentioned. The following section will suggest a possible direction for future research that could improve the quality and extent of this project.

6.2 Future Works

Since there are timing limitations, constraints in software capabilities, and the lack of some particular input data for the simulation, it is possible that some of the results of this research could demonstrate discrepancies. However, the following sections will outline potential approaches that could have an opportunity to improve the accuracy and comprehensiveness of the outcome of this project in the future as follows:

1) Sensitivity analysis – this study encompasses several fixed parameters, including renewable resources such as solar irradiance and wind speed, as well as cost variables such as component costs, fuel prices, and electricity

distribution rates. Therefore, a sensitivity analysis of these factors would reveal the configuration and results of the hybrid system.

2) Precise parameters – certain input values in this study were calculated from assumptions, as described in Section 3.7. Also, the financial results could be improved for greater realism as the inflation rate and the value-added tax (VAT) on electricity are not accounted for in this study.
3) Energy demand mitigation – to investigate cooling system requirements for both residential and general users in order to identify methods for reducing demand, which can decrease electricity usage and minimize the size of hybrid systems.
4) Energy sales to the grid –to take advantage of excess energy production, grid sales based on the FiT rate that is already stated in Section 2.3 could be further considered in order to generate potential revenue and encourage the increased use of renewable energy.
5) Alternate energy storage technologies – li-ion batteries have only been implemented in this study, as there is a limit to battery models in Homer, along with li-ion batteries, which are considered the most widely adopted battery technology due to their performance, which is described in Section 2.5. However, it should be determined to further study other energy storage technologies, for example, flow batteries, which have some advantages over li-ion such as a longer lifespan and a lower cost.

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