DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

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Green Electricity Transition for Sustainability of Thailand

Chisanucha Bunnag

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Supervisor: Dr. Daniel Costola

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ABSTRACT

With rapid growth of electricity demand in Thailand, the power development plan that published by Thai Ministry of Energy targeted for 25 – 30% renewable electricity total supply by 2036. This plan particularly focusses on the green transition of Thai power sector and assure that the expanding demand can be supplied, which consists of security aspect, financial aspect, and environmental aspect. The aim of this dissertation is to investigate the feasibility of the development plan in terms of energy security, financial viability, and environmental sustainability by using EnergyPLAN as the simulation program. The program has the potential to generate hourly load profile that take into consideration energy resource availability and other variables. The distribution profile of current electricity demand had been investigated, as same as the solar, wind and hydro resource availabilities before the 3 future scenarios were simulated with different number and ratio installed capacity.

The results presented that solar PV plays a key part in green electricity transition of Thailand. To accomplish the minimum target to supply 25% of electricity demand by renewable energy, the country requires over 14,000-MW of solar systems and 7,000-MW of wind to accomplish that target. The capital cost is approximately 20,000 million USD, and 558 million USD/year is required as O&M cost. In addition, this can reduce 34% of carbon dioxide intensity.

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NOMENCLATURE

EGAT –Electricity Generation Authority of Thailand

EPPO – Energy Policy and Planning Organization of Thailand

FiT – Feed in Tariff

GW – Gigawatt

GWh – Gigawatt Hour

kW – Kilowatt

kWh – Kilowatt Hour

MEA – The Metropolitan Electricity Authority

MW – Megawatt

MWh - MWh

IRENA – International Renewable Energy Agency

IEA – International Energy Agency

LCOE – Levelised cost of Energy

PEA – The Provincial Electricity Authority

PDP – Thailand Power Development Plan

PV - Photovoltaic

1 INTRODUCTION

1.1 Problem definition

With global warming and climate change are one of the most controversial issues in century, many governments throughout the world are considering ways to transition to a more sustainable and environmentally friendly future. Since 12 December 2015, The Paris Agreement is a legally enforceable international climate change accord. It was approved by 196 Parties at COP 21 in Paris went into effect on 4 November 2016. To achieve its long-term temperature goal with limited increasing temperature below 2 Celsius degrees, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by this mid-century or 2050. This agreement requires nationally determined contributions that communicate actions to decrease their carbon emissions and their long-term strategies for development in technology, finance, and capacity building support. The energy transition is a pathway to transform global energy industry from fossil-based to zero-carbon. By the second part of this century, decarbonisation of the energy sector needs immediate global effort. While a global energy transition is beginning, further action is required to cut carbon emissions and ameliorate the consequences of climate change. To get through this transformation effectively, there is a solution which are mainly focused from various governments, increasing the renewable-based energy market shares in energy sector [1].

Between 1971 and 2019, the global total energy supply rose 2.6 times, from 230 EJ to 606 EJ, and its structure shifted dramatically. International Energy Agency (IEA) database presents the change in global total primary energy sources in 1971 and 2019, oil-based energy supply decreased from 44% to 31% while Coal has continuously ranked second in the global energy supply, accounted around 27%. Followed by Natural gas which rose from 16% in 1971 to 23% [2].

This situation also effects on Thai energy sector. In 2015, The Ministry of Energy has created the Thailand Integrated Energy Blueprint [3] which particularly focuses on 3 main scopes as follow:

(1) *Energy security* – energy need to be supplied to meet the future demand, in accordance with the rate of economic growth and population expansion with and urbanisation, and diversifying energy to suitable resources.
(2) *Economy* – fairly energy prices require reforming in the structure of fuel pricing in line with costs and an appropriate tax burden to level up national energy utilisation performance while promoting energy efficiency.
(3) *Ecology* – focuses in increasing domestic renewable energy generation, and energy production with high-performance technology to lessen environmental harms and impacts.

This plan shows that national peak energy consumption in 2015 was roughly 30 GW, and it is anticipated to rise to 51.5 GW by 2036. Annual power demand is predicted to increase by 70% between 2015 and 2036. Moreover, renewable energy share of market was set to be 25-30% of total energy supply [3].

Collected data from IEA present that electricity generation by renewable sources in Thailand was only 16%, and there was only slight growth in renewable-based power generation. Meanwhile, Electricity supply continues to expand at a rate of roughly 2% annum, changes in generating mix and more efficient fossil fuel plants have resulted in a plateau in CO_2 emissions from the power industry since 2013 [4].

However, variable renewable energy sources in Thailand produce more unexpected production, necessitating greater operational and market flexibility. Despite of that inflexibility, Assessment analysis from IEA (2018) shows that Thailand has potential to increase mixed electricity generating, and transmission infrastructure are flexible enough to handle a larger percentage of renewables. Furthermore, it is confined by restrictive fuel supply arrangements and inflexible power purchase agreements [5]. Decarbonising the electricity industry would thus necessitate changes in how the sector runs and is governed in general, as well as specialised measures to boost the percentage of variable renewable energy.

There is a need for investigating the feasibility of this plan. To accomplish the target of development plan with those 3 constrains while future demand is fluctuated increases, mathematical modeling-based energy planning will be utilised to justify the proper percentage of various of energy resources in country. The collected necessary information and simulation in hybrid energy will be focused based on financial constrain and environmental constrain.

1.2 Aim

Aim of this project is to study the feasibility of renewable power generating diversification in Thailand based on power development plan issued by Thai Government and whether resources assessment, economic, and policies. It is complemented by detailed objectives

- To take into account the current electricity demand and to calculate projected demand over based on the Thailand's power development plan (PDP) from 2015 – 2036 [3].
- To adequate the criteria of Thai electricity supply
- To identify the most robust hybrid energy under the constrains of this plan.

1.3 Overview of methodology

To accomplish these objectives of this project, the required steps need to be complete as follow:

- *Classify current electricity demand of target area (Thailand):* annual electricity demand will be investigated its pattern in period of time. Then, future demand will be estimated by mathematic model.
- *Identify electricity generation resources:* carry out non-renewable and renewable fuels with their capacity of existing power plants, to identify their efficiency. also investigate potential of each resource by characteristics for future installations.
- *Study cost of installations and operations*: Following the identifying energy resources, the costs of installation, operation and maintenance, and others of each technology will be collected to go to further steps.
- *Simulate the proper percentage of hybrid power generation in future by EnergyPLAN Software:* To demonstrate the efficient hybrid combination for power generation, EnergyPLAN software was chosen as the software for this

project since it can help with national-scaled hybrid combination design optimisation to meet the estimated future demand. Moreover, it can provide financial characteristics for feasibility study.

- *Result and Conclusion*: The discussion and comparing pros and cons of the study will be covered in this step. In addition, conclusion and suggestions for future works will be illustrated.

1.4 Structure of the dissertation

This dissertation is structured into 5 chapters, as follow:

- *Chapter 1* – to define the main problems of this study about the transition of Thai electricity sector and briefly introduce about current situations, the target of national power sector, and constrains. The aim and objectives also included in this chapter as well.

- *Chapter 2* – to cover the Literature Review regarding overview of Thailand, electricity sector Thailand for both demand side and supply side, renewable resources, and EnergyPLAN that would be used for simulations to archive the objectives of study.

- *Chapter 3* – to cover the investigation about electricity demand, solar profile, wind profile and hydro profile in Thailand that required as input data for the simulations. This chapter would also address the model and the setting of four separate situations. The scenarios had divided into two categories: Firstly, one based on the present demand-supply power profile in 2021, and the 3 others scenario on a projected power demand profile for the year 2036 with different installed capacity.

- *Chapter 4* – to present the results and main findings from the simulations that mentioned in previous chapter.

- *Chapter 5* – to conclude the dissertation and discuss about future work.

2 LITERATURE REVIEW

To archive above-mentioned aim of this project, there are 9 parts will be covered for this section within in-depth background knowledge as follow:

- Overview of Thailand
- Electricity Organisations and infrastructure of Thailand
- Electricity demand of Thailand
- Power generation of Thailand
- Thai Power Development Plan (2015-2036)
- Renewable resources of Thailand
- Energy policies of Thailand
- Nearby countries energy situations
- Energy Plan

2.1 Overview of Thailand

Kingdom of Thailand, or short-formed as Thailand, is the country that locate at centre of mainland Southeast Asian region. Continental co-ordinates of country are latitudes 20° 28’ N - 5° 36’ S and longitudes 105° 38’ E - 97° 22’ W. Ecosystems of Thailand are diversified, with high wooded areas on the northern border, bountiful rice fields in the central plains, vast coastline in the Gulf of Thailand (1,875 km) and the Andaman Sea (740 km), and rough beaches along the tiny southern peninsula with around 400 islands. Approximated land area is 541,000 m^2, while the marine economic zones span 72,200 m^2 in the Andaman Sea and 140,000 m^2 in the Gulf of Thailand. Thailand is divided into six regions which are Northern that contains 9 provinces, Northeastern that contains 20 provinces, Eastern that contains 7 provinces, Western that 5 provinces, Central that contains 21 provinces, and Southern that contains 14 provinces [6].

Figure 1 Map of Thailand

Climate of Thailand has a subtropical to tropical climate. Figure 2 illustrate the average monthly mean of rainfall (mm) and average temperature (°C) in Thailand, both of chart calculated by collected data from 1981 – 2010 by Thai Meteorological Department. As presented, temperature increased since end of February. After reached the peak of average temperature in April at 29.5 °C, then it sightly decreased and hit the lowest in December and January. Focusing on rainfall, Thailand has a rainy season around mid-year, number of rainfalls rapidly grow since May, reached the peak in October and reduced to less than 10 mm in November [7].

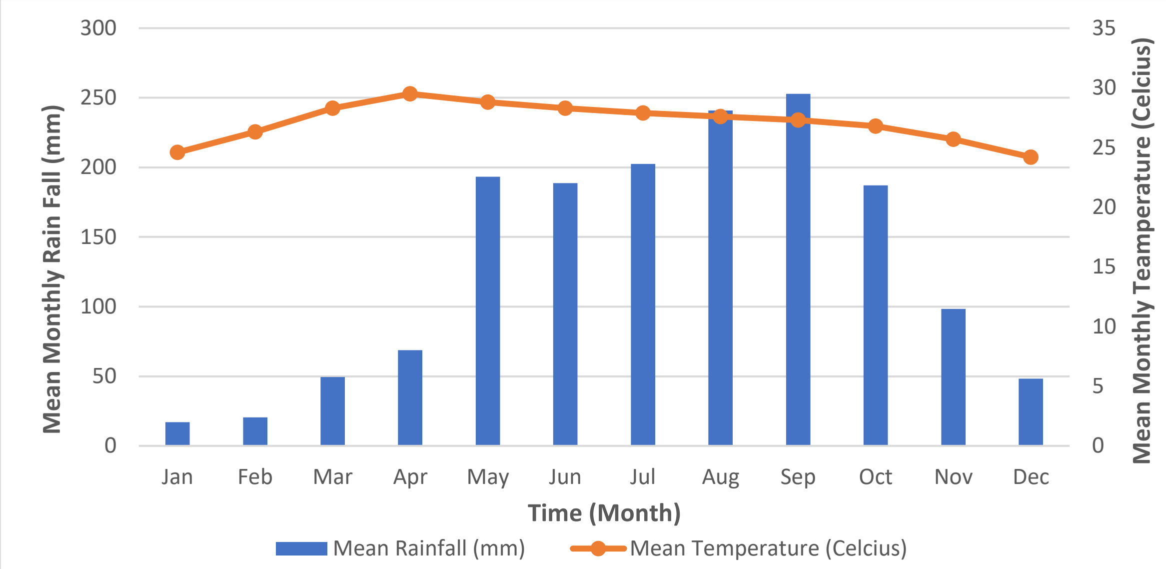


Figure 2 Average monthly rainfall (mm) and temperature (Celsius) in Thailand

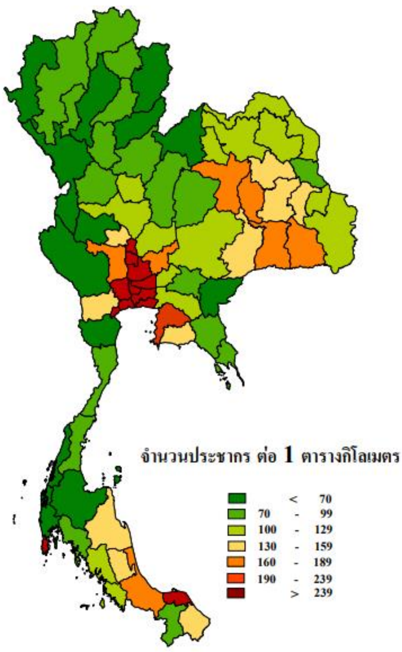


Figure 3 Thai population density (2014)

Thailand current population is accounted as 70,134,279 on 1 June 2022, which means population density is 137 people/m^2. The population density in country was presented in as following figure, data were collected and analysed by national statistical office Thailand (NSO) [8]. Accurate data are difficult to get because millions of Thai people commute from rural areas to cities and then return to participate with seasonal field labour. Bangkok and the nearby cities are contained the most population density, which lead to the most domestic power consumption as well [8] [9].

2.2 Electricity organisations and infrastructure of Thailand

The energy and electricity sector in Thailand is governed by the Ministry of Energy and involves multiple agencies: Department of Alternative Energy Development and Efficiency (DEDE), Department of Energy Business, Energy Policy and Planning Office (EPPO), Energy Regulatory Commission (ERC), Electricity Generating Authority of Thailand (EGAT), Metropolitan Electricity Authority (MEA), Provincial Electricity Authority (PEA), Petroleum Institute of Thailand (PTIT), and PTT Public Co., Ltd.

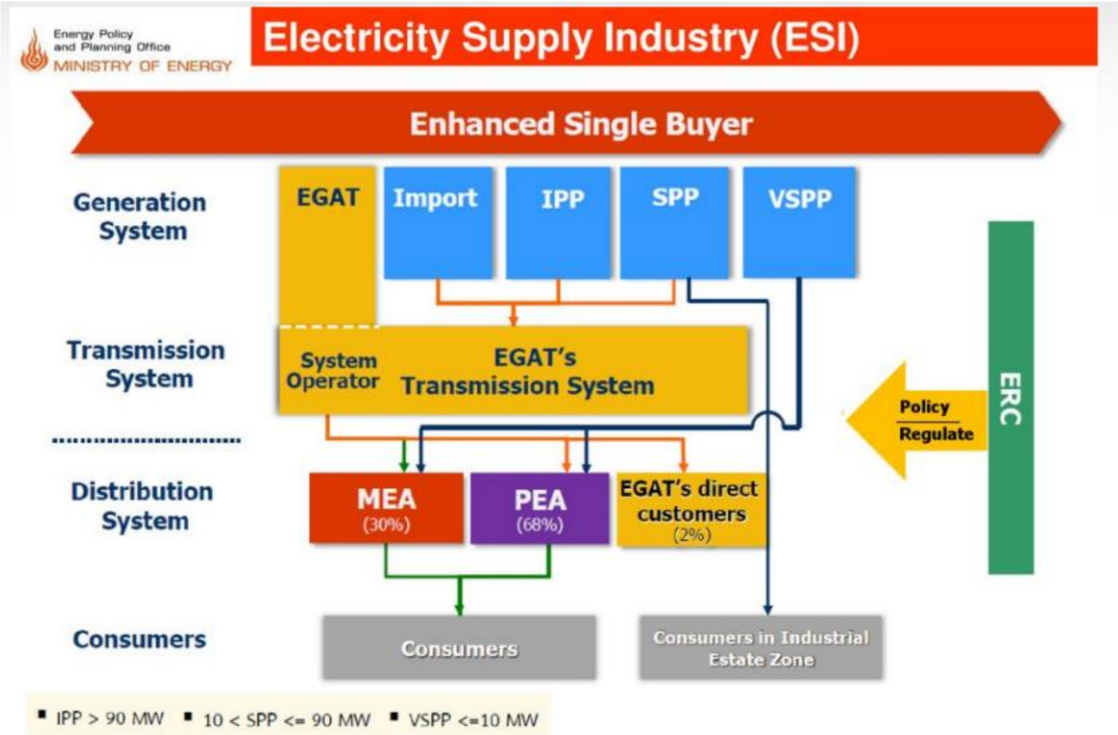


Figure 4 Electricity Industry

Figure 4 Electricity Industry presents that Thailand's power producing structure is organised around the improved single-buyer model, with state organisations serving as the sole purchasers and distributors of power via the national grid. Firstly, in generation level, a state-owned The Electricity Generation Authority of Thailand (EGAT) is both producer and purchaser, they operate and import majority of the country power supply capacity from private company and neighboring countries such as Loas, Malaysia and more. Grid-connected transmission line also owned by EGAT.

In Thailand, private electricity sector has been participated under purchase agreement with EGAT since the rapid electricity demand growth in early 1990s through bid solicitations. Thai private power producers are divided by the install capacity as follow:

(1) *Independent power Producers or IPPs* – over 90 MW install capacity. These power plants are mostly powered by natural gas and coal with the long-term agreement (25 years) with EGAT.

(2) *Small power producers or SPPs* – between 10 to 90 MW install capacity. SPPs primarily generate electricity from natural gas, coal, oil, and renewables. This type of power producers is classified into 2 categories. Firstly, firm SPPs, which have a 20-25-year contract to supply power to EGAT and are typically fueled by natural gas or coal. And non-firm SPPs, which have 5-year contracts (extendable in 5-year increments) and are typically fueled by renewables such as solar power, wind power, waste, and biomass.

(3) *Very small power producers or VSPPs* – no greater than 10 MW install capacity. The majority of VSPPs that sell renewable energy are involved in engineering, design, procurement, and construction. Because these operators have the skills required to develop and manage renewable energy installations.

Meanwhile, for distribution is responded by 2 main organisations which are the Metropolitan Electricity Authority (MEA) that oversees distributing power throughout Bangkok and the provinces of Nonthaburi and Samutprakan, and distribution of the other provinces are controlled by the Provincial Electricity Authority (PEA). Apart from that, EGAT also has several direct customers prescribed by law, and supply to neighboring countries too.

Krungsri Research, one of the business units of Bank of Ayudhya Public Company Limited, released the study in April 2021 presents that long-term planning is necessary for expanding the power generation capacity, with average period before commissioning phase requires 5-7 years. To meet the future demand, transmission and distribution play the major roles, as well as the tariffs that have to be set for increasing investment for supply in national grid [10].

Figure 5 National Grid Network in Thailand (GENI, 2016)

At a frequency of 50 hertz, the standard voltage levels are 69 kV, 115 kV, 132 kV, 230 kV, 300 kV, and 500 kV. Thailand's grid network is linked to the distribution systems of the PEA and MEA in terms of transmission and distribution. Thailand's transmission infrastructure already covers most of of residential areas. Not only MEA and PEA that distribute electricity to retail customers throughout the nation, EGAT also exports energy to Lao People's Democratic Republic (PDR) power companies via 115 kV and 22 kV lines, and to Malaysia via 300 kV high voltage direct current (HVDC) lines [11].

Voltage level (kV)	**Line Length (Circuit-kilometers)**	**Number of Substations**	**Transformer Capacity (MVA)**
500	7,097	23	42,950
300	23	-	388
230	15,805	84	69,100
132	8	-	133.4
115	14,704	125	15,311
69	19	-	-
Total	**37,656**	**232**	**127,882**

Table 1 Summary of transmission system in Thailand. Sourced EGAT (2021)

According to the presented dataset, most of substations in Thailand are on 115 kV level, with over 55% of all. Between 2015 and 2019, EGAT intends to build approximately 2,300 circuit kilometres of transmission lines and over 25,000 MVA of transformer capacity, the company intends to greatly extend the 500 kV transmission network. Specifically, EGAT intends to focus on updating the region's ageing transmission lines and substations, as well as building new lines to connect renewable energy supplied by waste-to-energy power plants. In order to satisfy the region's expanding power consumption, EGAT wants to quadruple the present transmission system capacity in the south. Thailand is also working on several projects to upgrade and refurbish transmission lines and substations.

2.3 Electricity Demand in Thailand

Electricity demand in Thailand follows seasonal and daily patterns that are relatively predictable due to the moderate weather in country. On the contrary, other countries that have temperate climate such as United Kingdom, Japan, or China which their peak demand is rapidly increased in winter due to required heating demand, peak times in Thailand are often in hot summer when air conditioners are required to run continuously. Thus, the yearly peak of demand is generally between March and May, when temperatures are at their greatest, and the lowest load is usually between December and January, when temperatures are at their lowest.

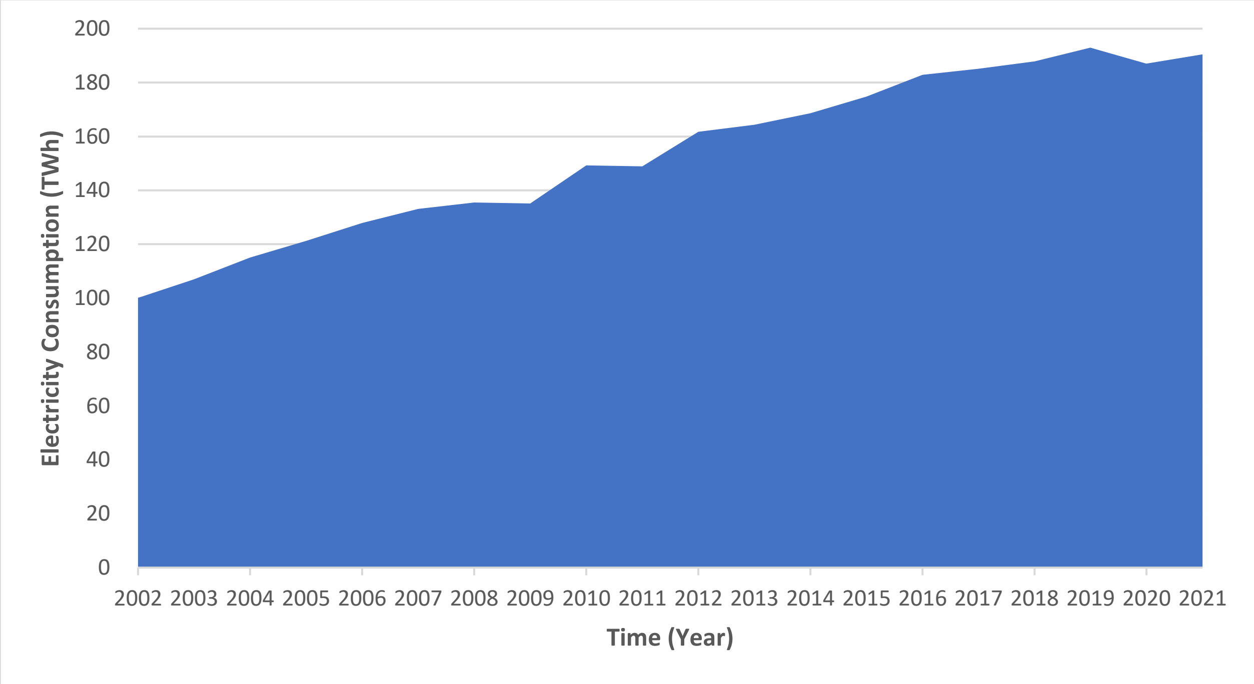


Figure 6 Electricity consumption in Thailand. Sources EPPO (2021)

Figure 6 provides electricity consumption for Whole country in TWh since 2002 until 2021, collected by Energy Policy and Planning Office (EPPO) [12]. As presented, national electricity demand trended continuously upwards during these two decades. In 2002, annual electricity consumption is approximately 100 TWh, and became 190.5 TWh in the next 20 years. Although there were sight decreasing in 2009, 2011 and 2020 but the average growth rate is 3.5% per year. Over 90% consumption climbs from 2002 to 2021 [13].

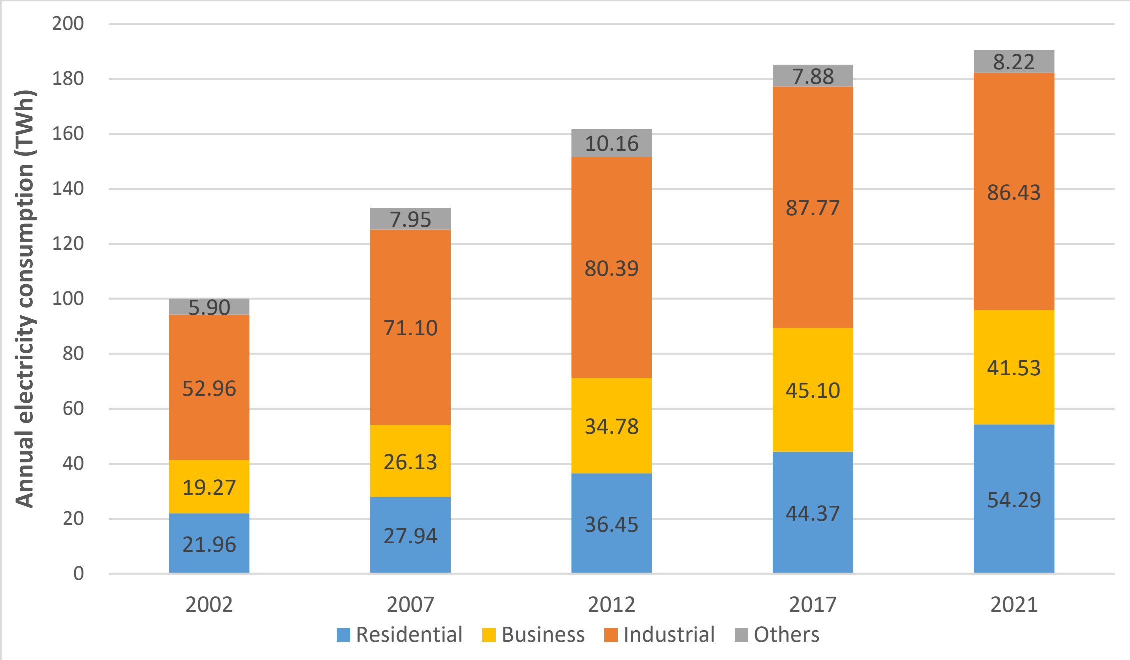


Figure 7 Annual electricity consumption in Thailand (Classified by sectors)

To breakdown the annual electricity demand at the same period as previous chart. Customers of Thai electricity are divided into 3 categories as residential sector, business sector, and industrial sector while other sectors which not included in those categories are presented in grey. Since 2002, the largest electricity was consumed by industrial sector around 53 TWh, accounts over half of all-year consumption. Followed by residential sector and business sector which are 22% and 19% respectively. Even though overall consumption for whole country is continuous increased, but the share of that is sightly change though the time. Industrial sector decreased from 53% to 46%. Meanwhile domestic business shares are increased to approximately 29% and 22% respectively [13].

One factor that significantly effects on electricity consumption is rising national gross domestic product or GDP. In general, electricity demand rises at a pace that is 0.9 - 1.1 times that of GDP growth. Figure 8 shows the correlation between electricity demand and economic growth from 1997 to 2020. The healthier economic growth, the more electricity was demanded, especially for major sources such as industrial and household. As example, when national economic growth was impacted by COVID-19 pandemic in 2022, the electricity demand was reduced as same as Thai annual GDP [10].

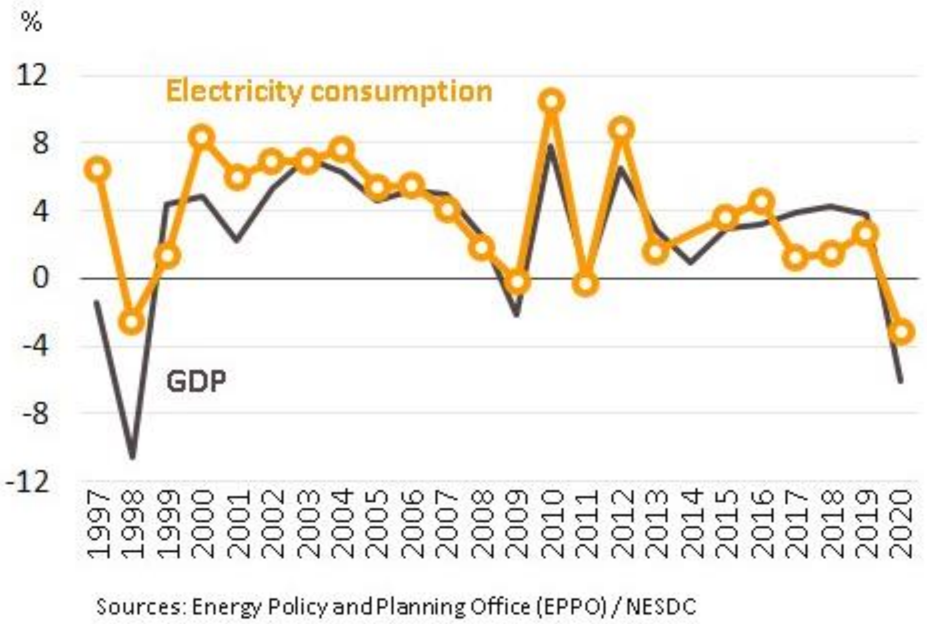


Figure 8 Correlation between electricity demand and economic growth

Furthermore, focusing on peak demand and load factor which shown in the above-mentioned graph, peak demand had sightly climbed since 2002 until 2015 from 17 GW to 26 GW, and then remained the same average level at 29.5 GW. However, load factor (LF) in each year has fluctuated a little around 75%, as a measurement of electrical energy usage efficiency, it expresses how much energy was used in a certain time in comparison to how much energy would have been utilised if the electricity had been left on during peak demand, which mean Thailand still need some improvement by reduce variance in power consumption [12] [13].

2.4 Power Generation in Thailand

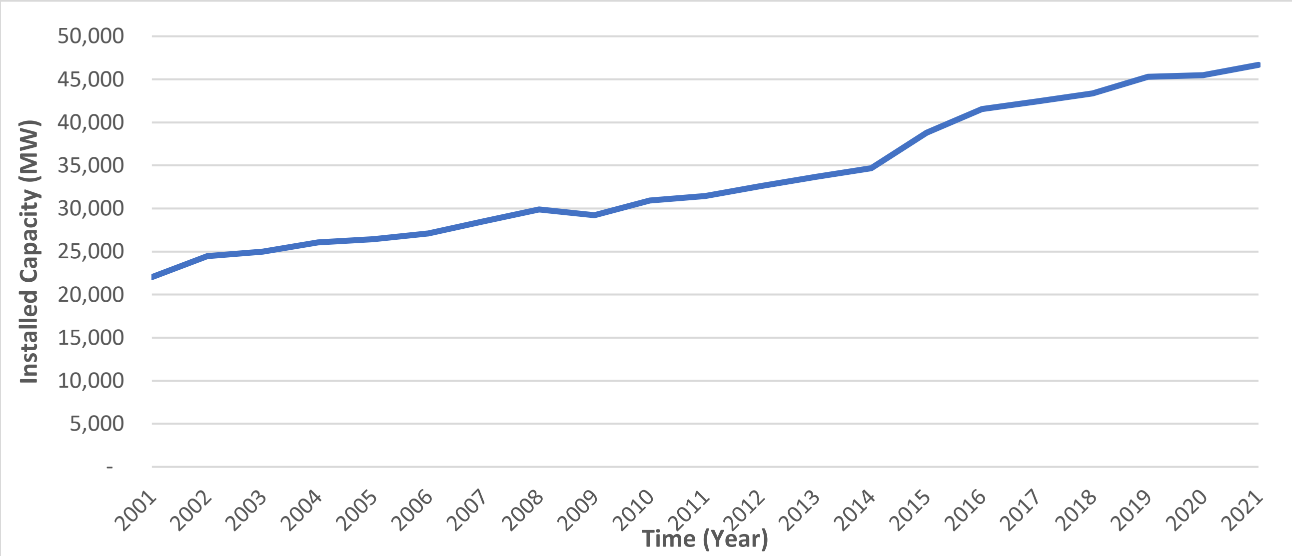


Figure 9 Installed capacity in Thailand

Over the past 20 years, private power producers have an important role in Thai electricity market. In 2020, total on-grid installed power generation capacity is 46,682 MW, although some of them are still in pre-operation phase, but total number has increased from the 2001 that had only 22,034 MW for supplying whole country. Electricity generation doubled in 20 years according to the growth in national power consumption that had mentioned in the previous section. To breaking down changing the owners of power capacity, the following bar chart is used for illustrating the market shares of electricity supply in Thailand [13].

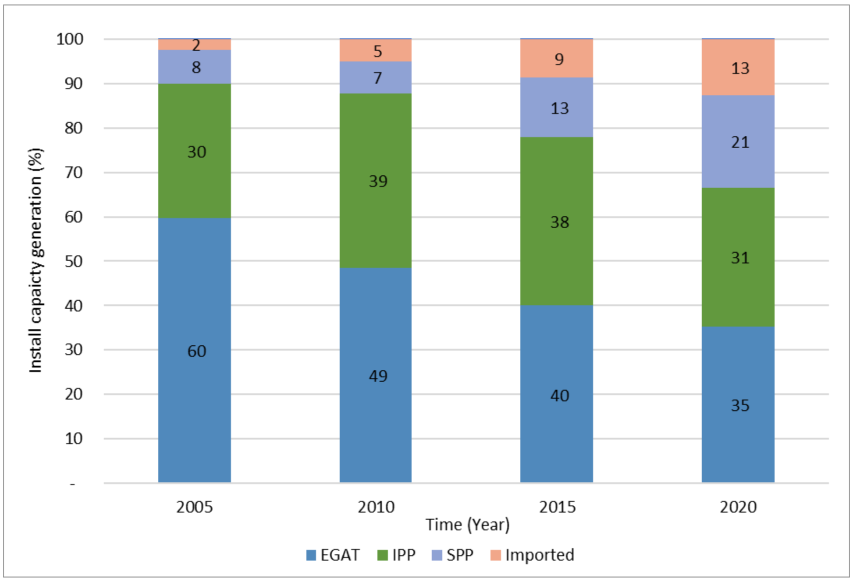


Figure 10 Percentage of Install capacity in Thailand (classified by producer)

Figure 10 illustrates percentage of on-grid install power generation capacity in Thailand from 2005 to 2020, there are different 4 sources in the electricity market share which are EGAT-owned power plants, IPP-owned, SPP-owned and imported power generation capacity. As shown, in 2005 EGAT had the largest electricity generation with over three-fifth of total market shares and decreased to 35% in the next 15 years. Meanwhile percentage of IPP-owned power plants had increased and reached the peak at around 40% of total capacity, then started to decrease and hit the same level on 2020. On the other hands, there are a growth in SPP market shares in the last two decades, from 8% to 21%. This number shows that small private producers have continuously plays the important key in power generation due to the supportive polices that will be clarified in the next sections [13].

However, the increasing percentage of imported power generation to supply in Thailand during this period shows that the power generation in country cannot supply the electricity consumption in whole country, which can lead to the electricity shortage in the future.

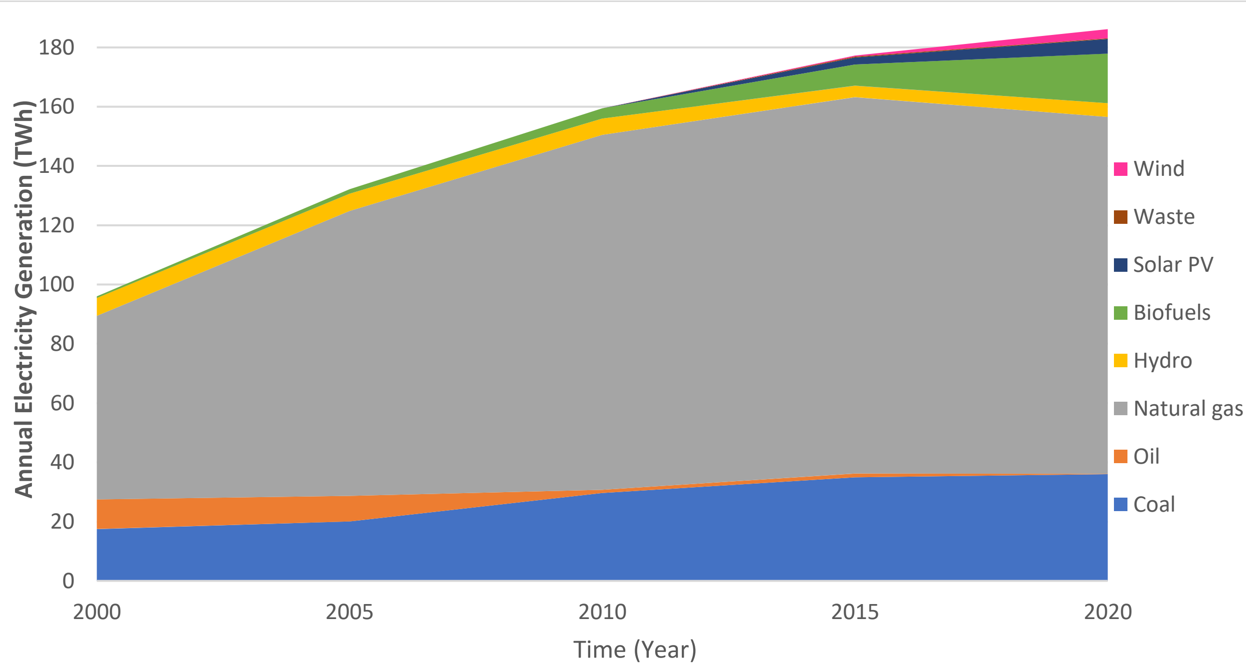


Figure 11 Annual Electricity generation in Thailand (Classified by fuel types)

In term of capacity breakdown of fuel types, the number of electricity power generated by different fuels from IEA databased was illustrated by above-mentioned chart. As a result, Thailand has clearly massive energy from non-renewable fuel such as oil, coal, and natural gas. The largest electricity was generated by natural gas, accounts as around 65% of total electricity consumption. Coal-based power ranks 2nd with around 19%, and only few amounts oil-based electricity. Meanwhile, electricity that generated by renewable-based such as wind, solar PV, biofuels, and hydro accounts only 16% of total electricity. The most green-power source is 9%, followed by solar PV and hydro, both were approximately 3% out of total electricity consumption. Wind-based power is the lowest among these fuel types [14].

Even though electricity planning considers fuel diversification, natural gas has emerged as the primary fuel for electricity generation in Thailand for decades due to its environmental appeal, low capital intensity, shorter gestation period, and higher efficiency of gas-based power plant technology [15]. Furthermore, popular opposition to coal-fired power plants and hydroelectric projects is now limiting their growth, leaving natural gas as the only viable choice. To point out the changing of each fuel types, natural gas had been continuously played a critical role in electricity generation since 2000s until reached its peak in 2015 with over 72% of annual electricity generation at that year and started sightly reduce after that. However, a large proportion of natural gas in power generation raises concerns about electricity supply security [16] and it was recently shown that the country has been sensitive to high gas dependency in its power generation over time. At that same time, Thai electricity sector had tried to reduce oil-based power generation, and little increased coal-based energy.

Meanwhile, diversity of renewable power generation in Thailand has been expanded. Although the stable electricity supply from hydro power plants remains at around 5,000 TWh annum, but Biofuels has become one of the most important roles for renewable electricity sector because Thailand is primarily reliant on imported oil and has an agricultural-based economy, and the government launched a program to encourage the production and usage of biodiesel in 2005 [17]. As same as solar power generation that rose since 2010 according to Feed-in-Tariff policy from the government and solar potential in country, especially in the northeast portion of the country. In 2015, the market share of wind power generation started to climb.

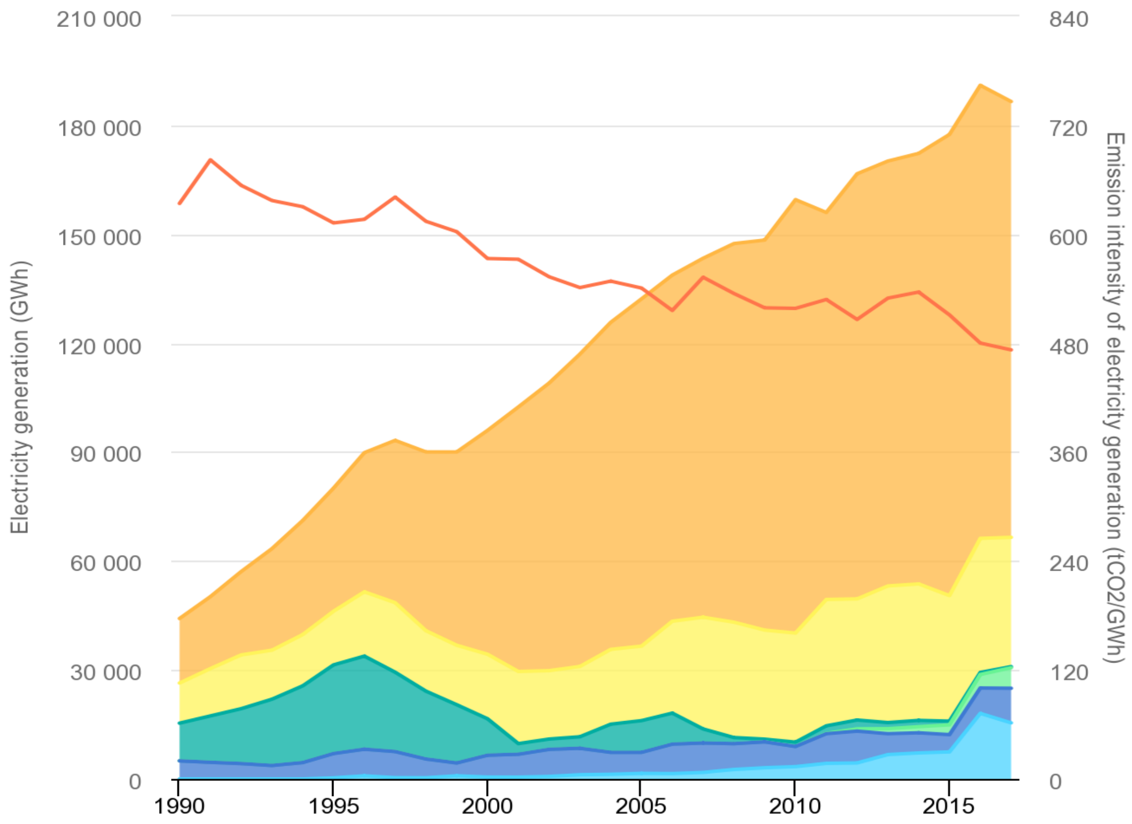


Figure 12 Electricity generation Energy (GWh) and Emission intensity in Thailand

Moreover, if take a closer look in Thai energy sector, this chart illustrates Electricity generation and related emissions in Thailand from 1990 - 2017. Electricity supply continues to expand, and changes in generating mix and more efficient fossil fuel plants have resulted in a plateau in CO_2 emissions from the power industry since 2013. According to improved technology and efficiency, have reduced the CO2 intensity of energy generation. It decreased by 12% from 2013 and reached 473 tCO_2/GWh in 2017, which was below the global average that accounted 485 tCO_2/GWh on that year [18].

With a faster adoption of variable renewable energy, such as solar PV and wind turbines, Thailand might further decouple GHG emissions from energy consumption and economic development. However, the nature of Thailand's power industry not only makes implementing a carbon pricing plan difficult, but it also makes developing renewables difficult.

2.5 Power Development Plan (PDP2015)

In 2014, Thailand's Ministry of Energy produced five plans for energy development and management in response to changes in national infrastructure and the ASEAN Economic Community's economic conditions, which includes:

- Thailand Power Development Plan: PDP
- Energy Efficient Development Plan: EEDP
- Alternative Energy Development Plan: AEDP
- Natural Gas Supply
- Petroleum Management Plan

The PDP2015 was developed in accordance with the National Economic and Social Development Board's social and economic development priorities (NESDB) [3]. The NESDB predicted 3.94 percent average increase in long-term Thai Gross Domestic Product (GDP). The convergence of the PDP2015 and the EEDP to promote energy efficiency is estimated to save 89,672 GWh by 2036. According to the AEDP, renewable energy, such as municipal waste, biomass, biogas, wind, and solar power generation, would be supported. Transmission and distribution system investments will allow for the development of renewable energy and smart grids.

Table 2 presents the requirement of estimated different fuels type in percentage, based on Alternative Energy Development Plan.

Fuel	Proportion in 2015	Proportion in 2036
Imported hydropower	7%	10-15%
Coal	20%	15-20%
Renewable energy	8%	25-30%
Natural gas	64%	30-40%
Nuclear	-	0-5%
Oil	1%	-

Table 2 Estimation of fuel requirements from PDP2015

Ministry of Energy set the long-term target for market share in power generation, increasing percentage of import hydropower, and renewable energy in country from 8% to 25-30%. Another fuel that Thai Minister of Energy concerned is reducing the proportion of natural gas according to whole country and will start construction phase of nuclear power plant. Moreover, The PDP2015 may be described using the assumptions and frameworks indicated above: In 2036, total capacity would be 70,335 MW, including existing capacity of 37,612 MW (as of December 2014), additional capacity of 57,459 MW, and retiring capacity of 24,736 MW between 2015 and 2036. [3]

Meanwhile, Thai government has supported alternative energy as described in Alternative Energy Development Plan: AEDP to promote a low-carbon society, and the Adder System has been developed to entice investors in alternative energy generation. This plan has been designed to implement a renewable energy system for the benefit of society, with a decrease in the use of fossil fuels and management of social impact concerns related to agriculture and solid waste. The objective is to boost biomass, biogas, and waste electricity generation. Figure 13 displays the estimate installed capacity by 2036.

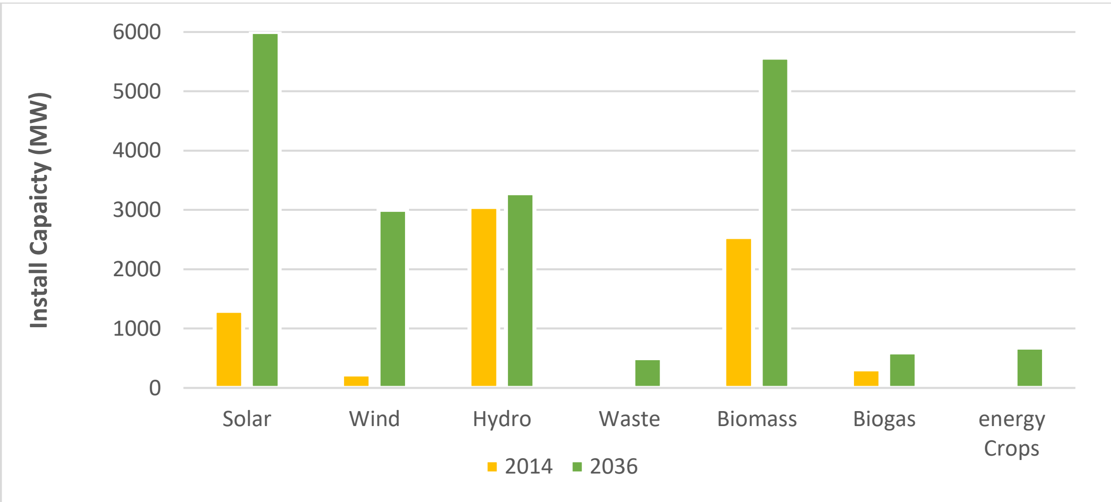


Figure 13 Renewable-based power plant Installed Capacity (DEDE, 2015)

This framework has been implemented to solve the aforementioned a few issues. Firstly, the Department of Alternative Energy Development and Efficiency (DEDE) is the body in charge of evaluating the potential of each renewable energy resource by area to determine the purchase amount and timeline. Secondly, considering transmission system availability by evaluating the present power demand and quantity of renewable energy power purchased by each high voltage substation to decrease transmission system losses and define purchase amount. Lastly, consider distribution system availability by calculating the existing power demand and quantity of renewable energy purchased by each 3-7 distribution substation in order to define purchase amount and prevent reverse power from the distribution system into the transmission system, which would cause power losses. As a result, electricity generation from renewable energy sources must be regulated by distribution operators to avoid such a situation (Ministry of Energy Thailand 2014).

In 2019, draft version revised of power development plan was released with some changes. Firstly, the target for total new install capacity increases 9% from the old one to 56,431 MW by 2037. Overall target installed capacity is unchanged, but there are revised in the percentage of each resource. New installed capacity of solar-based electricity will be slowed down due to the concerned of weakness in utility grid, while increase on purchasing of wind energy from neighboring countries, especially from Vietnam. Lastly, for small local community-based power generation would be more promoted.

2.6 Renewable Resources in Thailand

As above-mentioned section, Thai government has been promoted renewable energy resources to match the rapidly increasing demand and harmonise with the international policy about decarbonisation for climate change. With increased use of renewable energy and higher energy efficiency, imports of fossil fuels are predicted to fall, as are the risks of long-term energy spending on power importation. Furthermore, integrating these clean energy fuel types might give several benefits, including economic, social, and environmental benefits, as well as employment development.

2.6.1 Solar

Potential of energy generation by solar is depends on solar irradiation, which is measured as The Global Horizontal Irradiance (GHI). This indicator is a combination of Direct Normal Irradiation (DNI) and Diffuse Horizontal Irradiation (DHI), GHI is difference by its location and climate. Because Thailand is located near the equator and receives sunlight all year, and the solar potential is affected not only by irradiation but also by the northeast and southwest monsoons that pass across the nation [19].

Thailand has 37 pyranometer-equipped ground stations, 5 stations in the centre of Thailand, 12 in the north, 9 in the northeast, 3 in the west, and 9 in the south. Thai government has tasked the Energy Ministry's Department of Alternative Energy Development and Efficiency (DEDE) with evaluating, monitoring, encouraging, and supporting households and private enterprises in their use of solar energy [20]. **Figure 14** presents the data of average solar radiation in a year. It shows that the majority of the regions vary from light to dark orange, with a few lower or yellow parts. Daily average solar irradiation is 18.2 MJ/m^2-day, this equates to around 1,825 - 1,950 KWh/m^2 per day. Around 14.3% national area has 19–20 MJ/m^2 per day, and there is around 1% of Thailand has less than 16 MJ/m^2-day. The northeast has the highest average solar potential in the country [21]. It comprises the provinces of Nakhon Ratchasima, Buri Ram, Surin, Si Sa Ket, Roi Et, Yasothon, Ubon Ratchathani, and Udon Thani. The centre area, which includes the provinces of Suphan Buri, Chainat, Ayutthaya, and Lop Buri, has the greatest average of solar potential [19] [20].

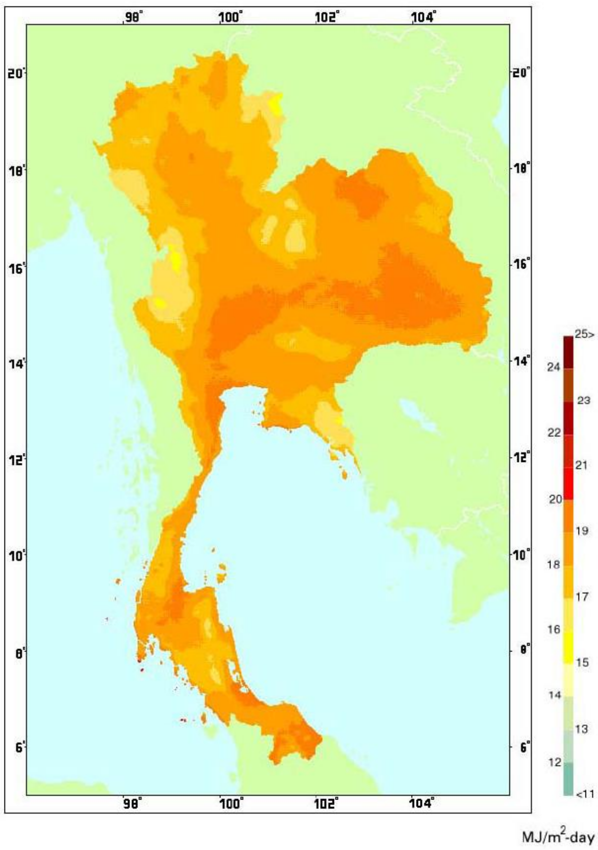


Figure 14 Solar Radiation of Thailand

2.6.2 Wind

According to the Department of Alternative Energy Development and Efficiency's (DEDE) current evaluation of wind potential, the average wind speed in Thailand is roughly 5 m/s measured at a height of 90 metres, as shown in Figure 15. The entire installed wind energy capacity is now 620 MW, most of them are under construction. However, this amount has the potential to increase to 13 GW in 21 regions around the country. Thailand has the ability to boost wind power capacity by up to 17 GW if contemporary low-speed technology wind turbines are employed, with conventional wind turbines still being used by one-third of this strategy. The strongest wind speeds are found in Thailand's western, northeast, and southern areas.

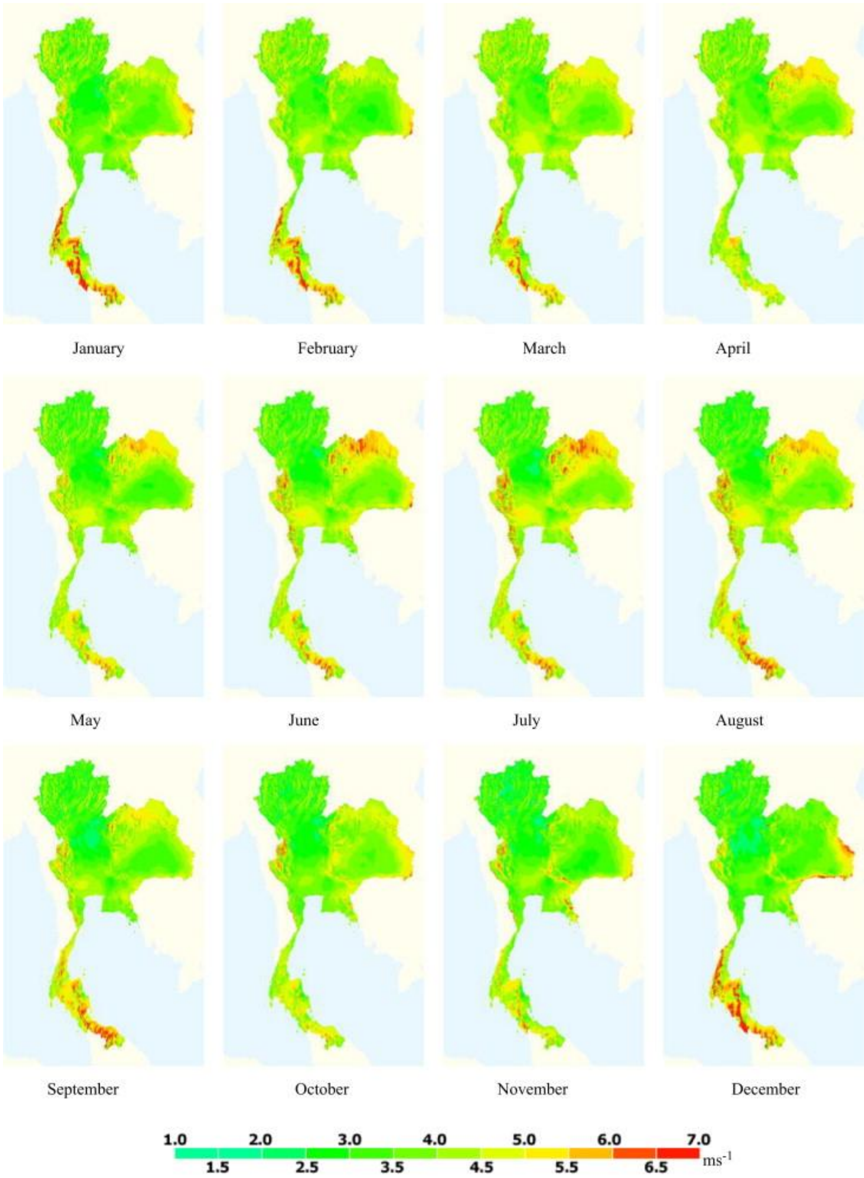


Figure 15 Monthly Wind Map of Thailand

However, even wind power plant construction was deemed extremely appropriate in the southern section of Chiang Mai province and the central portion of Nakhon Ratchasima province. But another approaches that need to be consider about wind potential is monthly climate, Areas with average wind speeds greater than 6 m/s are mostly found in southern mountain ranges. This is most likely due to the fact that January is the northeast monsoon season, with typical winds sweeping over the Gulf of Thailand [22]. To meet reduced wind obstruction and creating strong wind speeds in southern Thailand's northeast facing mountain slopes. The northeast monsoon normally continues until the middle of February, reducing average wind speeds in February compared to January [23].

Nevertheless, the amount of wind energy potential of Thailand was quite a low compared with the other countries due to the low wind speed in the country, especially Vietnam [22].

2.7 Energy Policy in Thailand

Like many other nations, the government of Thailand is focusing about boosting renewable energy. However, while renewable energy has been advocated to address the issue of global warming, power generation costs from some renewable energy resources are still greater than those of traditional energy resources such as coal, natural gas, and hydro.

In 2006, the Thai government announced the applied model of feed-in tariff (FIT), known as 'Adder'. To support the renewable power producer, especially VSPP and SPP. Premium rates will be applied to the selling price in specific period. Rate and period depending on the source of renewable energy. Thus, EGAT will purchase electricity from producers at the base price plus the wholesale fixed tariff and Adder and started in 2007 [24].

After years of using Adder model, growth rate of renewable energy is effectively increase. The National Energy Board recently adopted a feed-in tariffs (FiT) policy in 2013 to replace adder policy since adder is paid on top of the retail energy price, whereas FITs is a set wholesale price. The following diagram presents the simplified transitions of renewable power pricing policy. Firstly, Feed-in-Tariff was applied to solar PV rooftop since 2013 while other resources of power generation still had supported from Adder policy until 2015, Feed-in-Tariff was announced to the whole renewable energy sector with competitive bidding for private sectors. There are 4 approaches for determining Feed-in-Tariff rate, which are (1) The actual levelized cost of electricity generation, (2) utility avoided cost (3) fixed-price incentives unrelated to the actual levelized cost of electricity generation and (4) the outcome of an auction or bidding process [25].

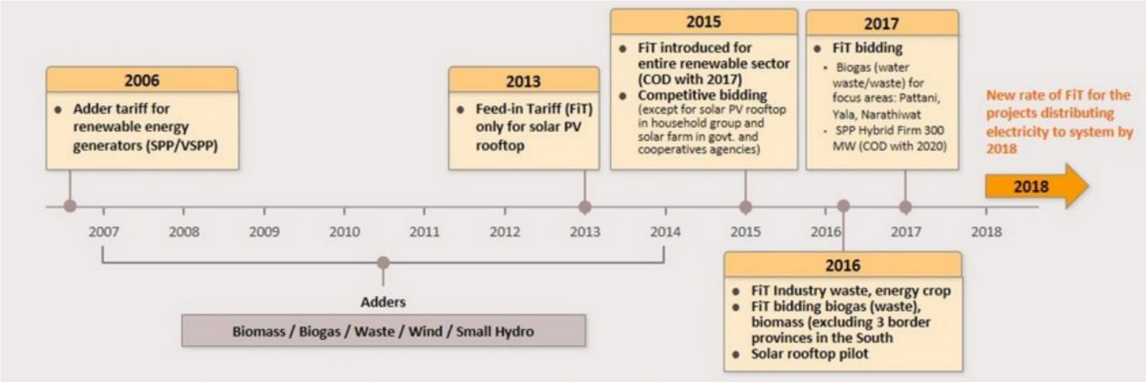


Figure 16 Pricing Development in Thailand (Since 2006)

Type of Renewable Resources	FiT (THB/kWh)	FiT (USD/kWh)	Period of Support (years)
Biomass			
Capacity < 1 MW	5.38	0.1544	20
Capacity 1-3 MW	4.86	0.1395	20
Capacity > 3 MW	4.27	0.1226	20
Biogas			
Biogas from waste	3.76	0.1079	20
Biogas from energy crop	5.39	0.1547	20
Wind	6.06	0.1739	20
Solar			
Solar Farm	5.66	0.1625	25
Solar Rooftop (Residential)	6.85	0.1966	25
Solar Rooftop (Non-residential)			
Capacity 10-250 kW	6.40	0.1837	25
Capacity 250 – 1000 kW	6.01	0.1725	25
Hydropower	4.90	0.1406	20
SPP hybrid firm	3.69	0.1059	20

Table 3 FiT rate and period in Thailand (EPPO, 2021).

The FiT rate in USD/kWh were calculate by using exchange rate 34.84 THB/USD on 16 Jun 2022 [26]. As presented in Table 3, the supported longest period is 25 years for solar energy systems, both solar PV rooftop and solar farm. The highest rate is solar rooftop in residential sector, which shows that Thai government supports self-generation in non-business sector. On the other hand, Feed in Tariff of biomass and biomass are lower than other resources due to the growth in renewable power generation was satisfied already [10]. There is a study presented that it was discovered that policy measures promoting renewable energy technology through the use of FiT have a lower impact on overall power production costs when compared to the adder scheme. Electric users will benefit from cheaper electricity bills [10] [25].

2.8 Regional Power Generation Current Status

In June 2022, IEA released the annual energy outlook of Southeast Asian that presents the key findings about current status and constrains about overall energy management in overall region and each country. The energy situation in Southeast Asia differs greatly every nation, based on resource endowments, economic structure, and legislation [27]. This following chart present total energy supply in different and market shares by country.

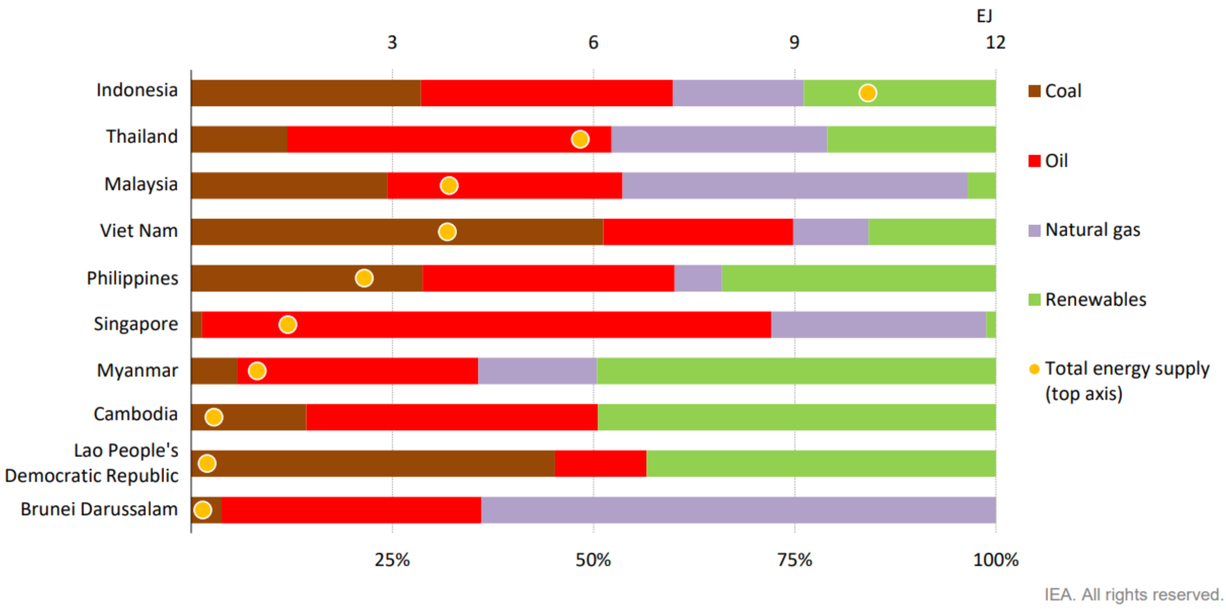


Figure 17 Total energy supply by fuel, by country in Southeast Asia

More than 90% of the increase in energy consumption was accounted for by fossil fuels between 2000 and 2020. Particularly, natural gas use increased by more than 80% and now accounts for almost 20% of overall energy consumption, especially in electricity generation, follow by oil and coal consumption are increasing 40% and 26% respectively. In the meantime, the energy supplied by current renewable types of energy more than quadrupled. Although solar PV and wind energy have grown fast in recent years, modern bioenergy, geothermal energy, and hydropower continue to account for more than 98% of all modern renewable energy in Southeast Asia today [27].

Some Southeast Asian countries have increased their respective objectives. Vietnam has set a target of increasing renewable power to 21 percent of total installed capacity by 2030, in order to achieve a 43 percent decrease in coal capacity by 2030 [28]. Indonesia has established a goal of using 23 percent renewable energy by 2025 and 31 percent by 2050, changed its energy strategy and revised its power purchase agreements in 2017 [29].

For energy economic in Southeast Asian country, as the cost of generation is affected by a variety of factors. Sensitivities to the installation cost, operation and maintenance cost (O&M), debt percentage, depreciation schedule, and discount rate were investigated in by National Renewable Energy Laboratory of U.S. [30]. The levelised cost of energy or LCOEs exhibited the greatest sensitivity to installation costs and discount rates.

Country	**Average solar photovoltaic Levelised cost of energy (USD/MWh)**		
	Relaxed Scenario	**Moderate Scenario**	**Restricted Scenario**
Brnuei	118.2	117.9	117.6
Burma	80.3	79.1	79.8
Cambodia	87.5	87.4	87.7
Indonesia	166.5	164.8	165.3
Lao PDR	111.1	110.5	110.7
Malaysia	108.0	107.5	107.5
Philippines	118.5	116.8	117.6
Singapore	123.0	123.1	122.7
Thailand	85.1	84.9	85.3
Vietnam	87.1	86.6	87.5

Table 4 Solar photovoltaic Levelised cost of energy in Southeast Asian

The average solar photovoltaic levelised cost of energy are presented in

[30]. It shows that Vietnam, Burma, Thailand, and Cambodia have the lowest LCOE values in the area, with minimum LCOEs of roughly $64, $70, $80, and $82 USD/MWh, respectively. The reduced LCOE results are due to places with potential solar energy resource quality, as well as the estimated economic (inflation and tax rates) and techno-economic (installation and O&M costs) assumptions for each nation.

Country	**Average Wind Levelised cost of energy (USD/MWh)**		
	Relaxed Scenario	**Moderate Scenario**	**Restricted Scenario**
Brunei	140.4	140.1	129.9
Burma	111.6	111.4	112.0
Cambodia	146.5	146.6	145.4
Indonesia	146.1	145.9	148.6
Lao PDR	186.3	186.0	187.0
Malaysia	134.3	135.0	136.1
Philippines	126.3	127.6	127.1
Singapore	150.0	153.6	151.3
Thailand	145.0	145.1	144.7
Vietnam	91.8	91.6	93.0

Table 5 wind Levelised cost of energy in Southeast Asian

On the other hand, Table 5 contains the different wind levelised cost of energy of countries in Southeast Asia. As areas are successively excluded from development within the scenarios considered, the consistent average LCOE reflects a reasonably stable resource quality across each country. The Lao PDR has the highest average LCOE for wind in the area, at $186 USD/MWh, followed by Singapore, Cambodia, and Thailand. While Vietnam has the lowest, at around $92 USD/MWh. This study also pointed out that despite high installed costs of wind system in Thailand, this country still can increase the wind installed capacity unlike some others such as Singapore that has limited grid-connection problem or Burnie that has limited landscape for wind power [30].

IRENA presents that LCOE of renewable power generation systems in Asia. In 2021, the levelised cost of power from solar PV declined by 13% per year while wind fell by 15% per year. Meanwhile, wind-based power generation system has reduced over 63% from 2010 to 2021, and 88% in solar system in the same period [31].

2.9 EnergyPLAN Software

In present day, a variety of computer tools enable users to simulate and analyse energy systems at the national and regional levels in order to assist in the design of transition paths, especially for generation expansion planning from fossil fuel sources to renewable power sources [32] To choose the most suitable software for modelling the situations, the aim and objectives should be considered carefully.

Optimization, simulation, and equilibrium models are the three most widely used methodological approaches to energy system modelling. Endogenous system design optimization is one of the optimization tools; simulation tools simulate exogenously designed energy systems; and equilibrium tools contain a bigger econometric model of the society [33]. For this dissertation, simulation model is the most suitable due to its uncertainties and fluctuations in inputs for low-carbon energy systems which identified significant impact on the performance in systems [32].

EnergyPLAN is an example of a well-known freeware simulation programme. This is one of the most widely used techniques for assessing energy systems with high renewable energy resources for both in academic and further purposes. Since started to develop this tool in early 2000s, its main purpose is to form a basis for acquaint of potential development pathways for national or regional system. With the supplement from Geographical Information System (GIS), the analysis of demand and supply of energy will be assessed in this tool, includes the electrical, heating, cooling, manufacturing, and transportation sectors [34].

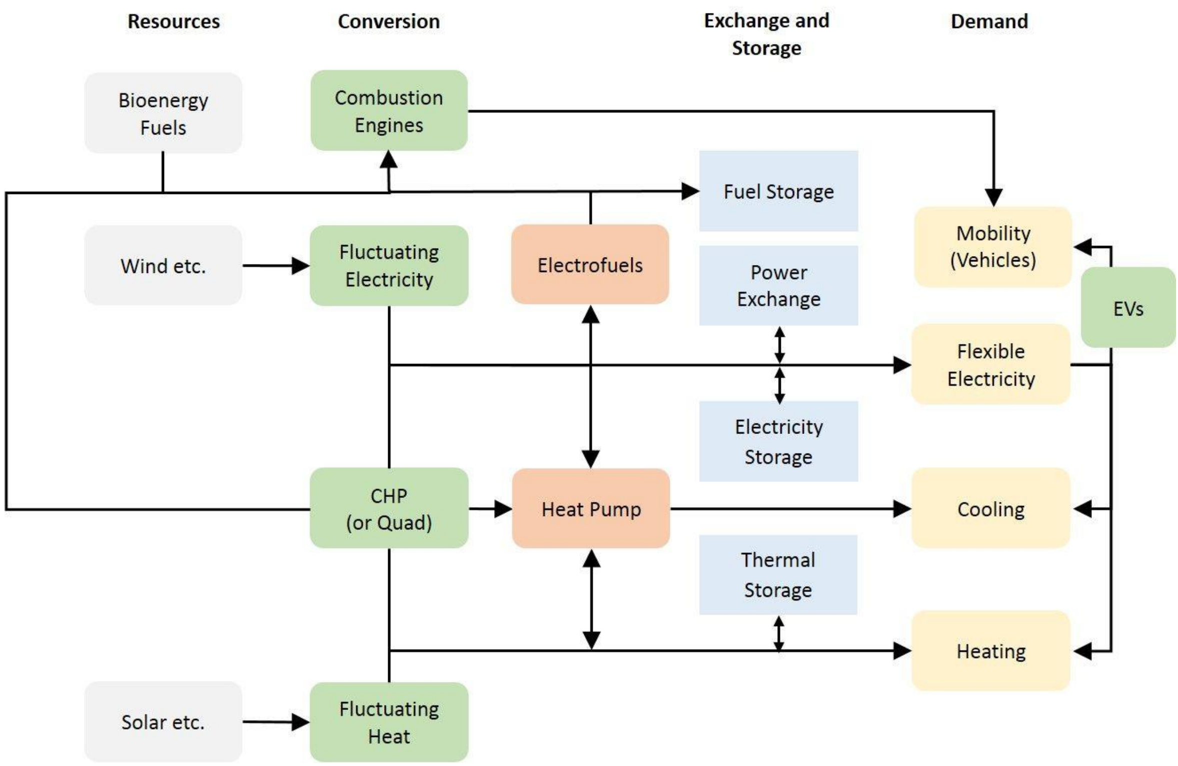


Figure 18 example of EnergyPLAN user interface

The input structure of EnergyPLAN includes the aspects of energy system such as energy demand, energy production units (non-renewable and renewable resources), technical limitations, and costs. After simulation, EnergyPLAN generates outputs such as energy balances and consequent yearly productions, fuel consumption, electricity import/export, and overall expenses including money from electricity exchange. With a temporal resolution of one hour, findings may also be displayed at this level. The results may be exported and imported into a spreadsheet for additional analysis or demonstration using the export function [34]. Furthermore, the findings are given in monthly and yearly overviews of production and demand within major technological units, as well as imports and exports of power. Number of emissions, money movements with an external power market, and fuel usage are also included in the result as well.

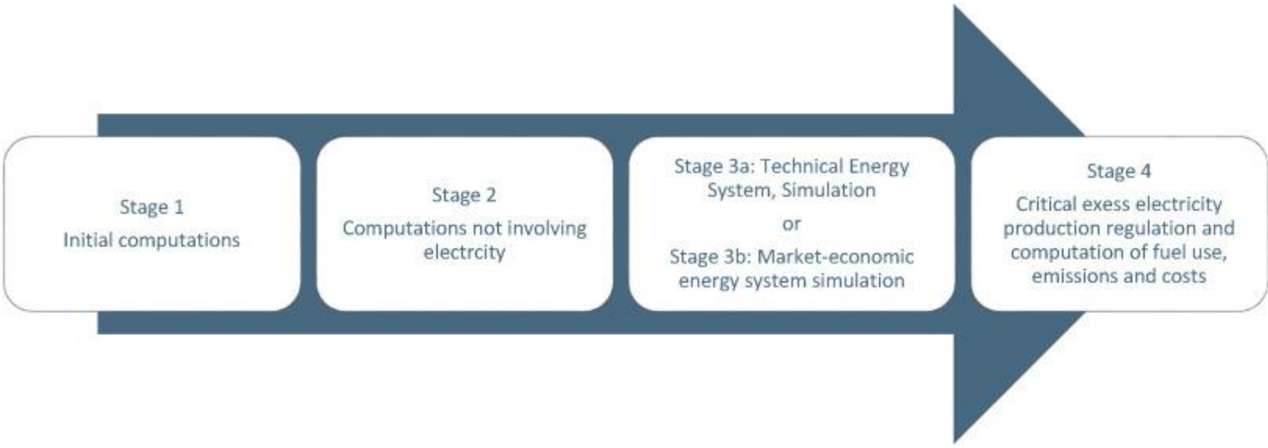


Figure 19 Overall structure of the energy system simulation procedures

Figure 19 illustrates how the energy system be simulated, the initial inputs need to be cover in the first stage, then EnergyPLAN will complete a variety of preliminary calculations that do not include electricity balancing, such as the quantity of power provided by each unit or the hourly heat demand in systems. Afterwards, there are 2 strategies that user can specify which are technical simulation and market-economic simulation. For technical simulation, the results will identify solution that minimise consumed fuels. Meanwhile, market-economic simulation results will be based on the maximised economical business profit in each unit. Lastly, EnergyPLAN will conclude both simulation methodologies by calculating the system consequences in terms of total energy systems costs and carbon emissions. Both simulation strategies can be readily performed and compared because the entire simulation procedure [34].

3 MATERIALS and METHODS

3.1 Object

There are 3 situations will be simulated by EnergyPLAN software in this project. Firstly, the situation of case 0 or baselined case in which details of annual demand and supply of electricity in Thailand since 2021. The input data and setting will be mentioned in the next section.

This thesis considers two more important scenarios in order to analyse the future power generation idea of energy sustainability for Thailand. The future scenarios (Case 1, Case 2 and Case 3) will be based on three scenarios to determine the optimal wind and/or solar energy system configuration(s) to achieve the target of renewable energy penetration in the grid for the projected energy demand for 2036.

3.2 Model and Distributed Profiles

These simulations are based on the model of software named *Smart Energy System*; this is analysis tool 16.2 version which released in April 2021 . The smart grid for power balancing is presented in this model, RES are transformed into other types of energy carriers besides electricity in this scenario using various power-to-x technologies such as heat, hydrogen, e-gases, and electro fuels. EnergyPLAN may also simulate renewable energy systems by incorporating various energy conservation and efficiency enhancements, such as cogeneration of heat and power (CHP) fuel cells [33].

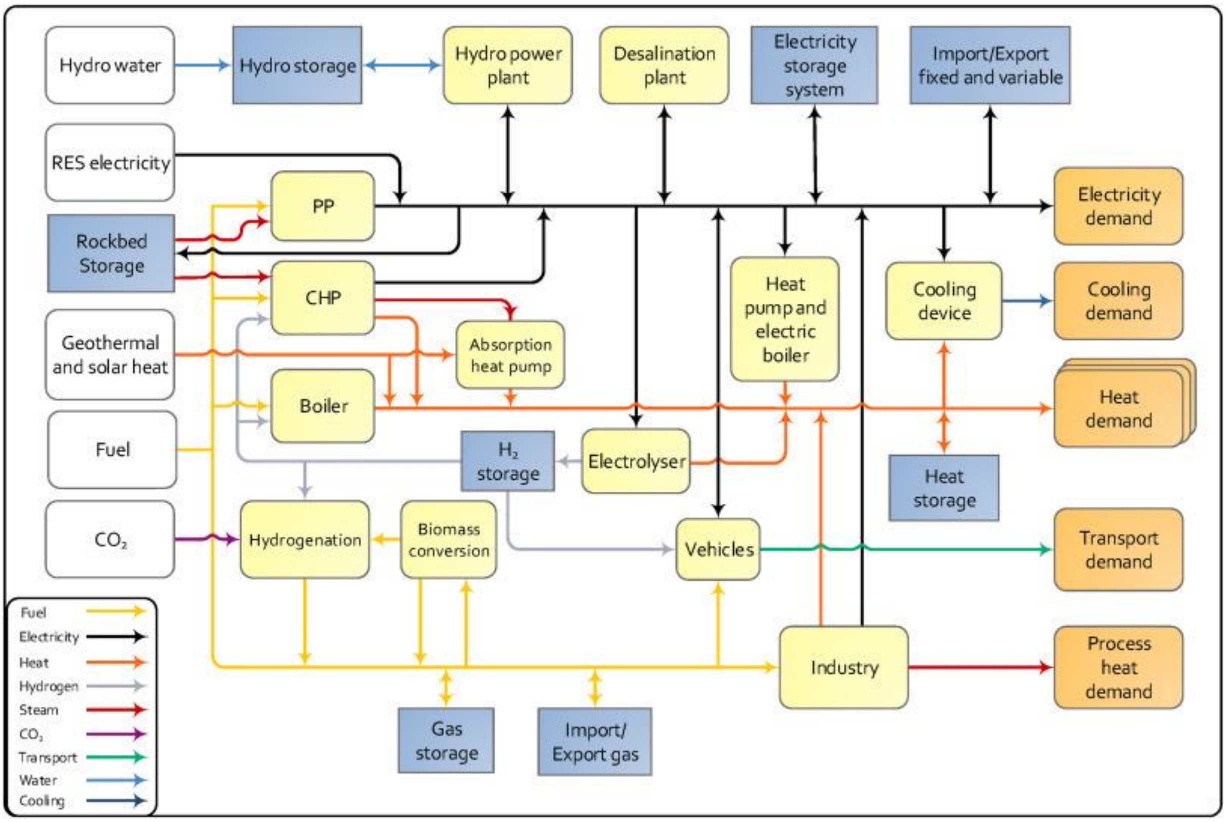


Figure 20 The flow model in EnergyPLAN

This model presents the smart grid and its several units, both fossil-based power generations and renewable power generations are included in this model with the specific inputs for simulations. Only electricity demand is focused on these scenarios according to Thailand have rare heating demand and cooling demand, most of them has covered by using electricity for heating and cooling, which summarised in electricity demand that collected by EGAT already.

For variable renewable power generation, the resources of energy will be simulated by the open-sourced data which includes the essential statistic that needed for simulation such as weather, sun-hours, wind speeds and in one year-round, the data were collected since 2004 to 2018 by Climate One Building organization [35] . These data were used as the structure of distribution profile of wind energy production, solar energy production, and hydro energy production.

To define any new distributions, the hourly data have to simplified into 8,784 values in a text file (.txt). The whole year hourly values presented from midnight January to midnight December. In this project, the databased were manipulated and converted from .clm file to excel files, and then converted to text files that can be used as proper inputs in the software [33].

3.2.1 Electricity Demand Distributed Profiles

Electricity demand or load profile is described as the pattern of electricity usage in specific period, mostly presented in power unit. For this software, the electricity demand distributed profile need to be covered hourly value in a year.

Raw data of demand load based on Thailand power system flexibility study from IEA, 2021 [36]. Hourly electricity demand in week is presented as following graph.

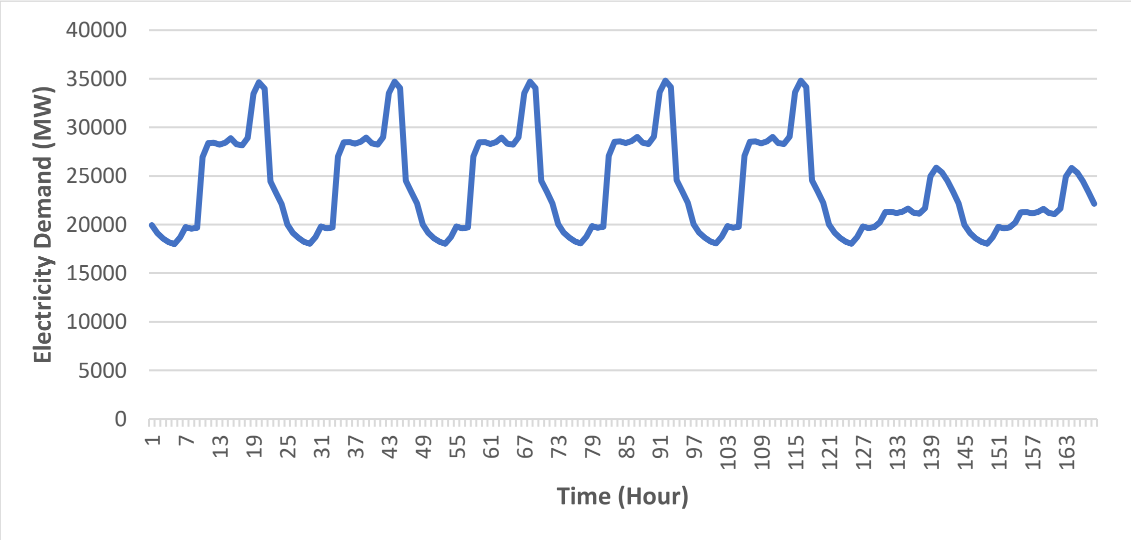


Figure 21 National Electricity Demand in a week (IEA, 2021)

This graph illustrates hourly electricity demand in whole country during a week. As presented, average energy weekday is 24,990 MW, calculated as around 3,000 GWh per day, weekday electricity demand stables during the nighttime and rapidly increases at 9 A.M. and then stays around 28,000 MW until 17.00 P.M., then shows the significantly growth again at from 18.00 P.M. to approximately 33,000 MW and remain for 3 hours before its decreasing. Meanwhile, load pattern of weekend is as same as weekday, but the demand of electricity is around 80% compared to weekday. The average energy demand is around 21,207 MW, leads to daily energy demand is 1,017 GWh.

However, to illustrate whole year electricity demand distributions, the difference of national load profile in annual should be considered as well. Average values of each month were calculated by this following.

$$Monthly\ Demand\ (\%) = \frac{Average\ Monthly\ Demand\ (MW)}{Average\ Annual\ Demand\ (MW)} x100$$

By using this equation, percentage of electricity demand comparing to whole year average electricity demand were determined based on EGAT website 10-year statical data of power sector, collected from 2011 to 2021 [37]. The simplified monthly electricity demand from January to December are presented in the following chart.

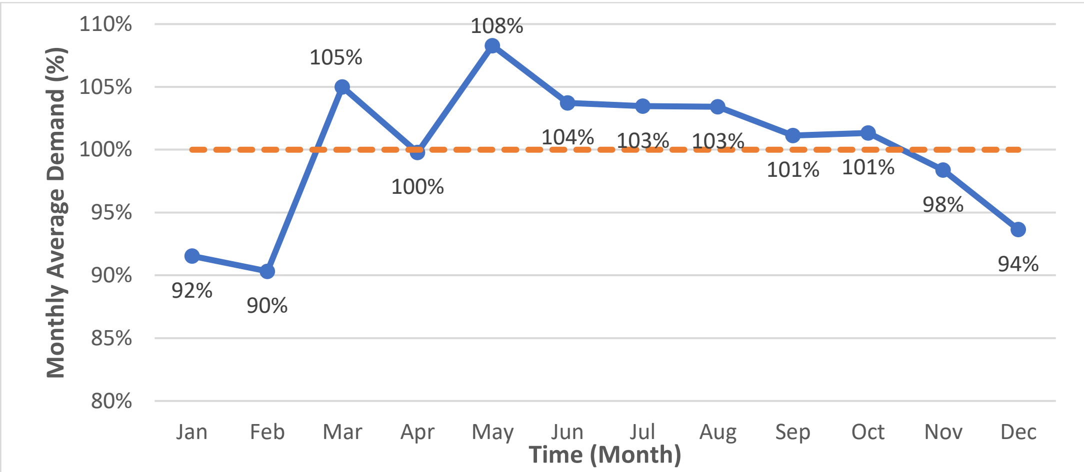


Figure 22 Monthly Average Demand (%) in Thailand (2011 - 2021)

According to the 10-year average monthly demand that presented in percent compared to each year electricity average demand (100%), national load profile shows that Thailand requires higher electricity demand around mid-year. The electricity demand reached the peak in May at 108% of annual average electricity demand, after had significant increasing in March, which is the first summer month. Then, the power demand started to decrease and remained at around 103% until October, which is the last month of rainy season. Winter is the lowest electricity demand season during the whole year, accounted lower than annual average electricity demand.

3.2.2 Solar Distributed Profile

To manipulate the solar production distributed profile, the dataset of a province in each region of Thailand were used to calculate the average irradiance, contributed by 6 provinces which are Chiang Mai (North), Khon Kaen (North-East), Bangkok (Central), Cha Choeng Sao (East), Nakhon Si Thammarat (South), and Prachuap Khiri Khan (West).

Each Dataset from Climate One Building organisation have 2 columns of different types of solar irradiance; diffuse solar on the horizontal (W/m^2) and direct normal solar intensity (W/m^2). Each of them presents in average hourly values from 1st January midnight to 31st December midnight. Equation 1 is used to calculate the average effective solar irradiance for simulations.

$$I_{gh} = I_{dn}\sin(\beta_s) + I_{fh}$$

While I_{gh} is global horizontal irradiance (W/m^2)

I_{dn} is direct horizontal irradiance (W/m^2)

β_s is solar angle

I_{fh} is diffuse horizontal irradiance (W/m^2)

In this project, solar angle was assumed as 15^O, due to the general inclination angle is 15 degrees south in Thailand [19] [21].

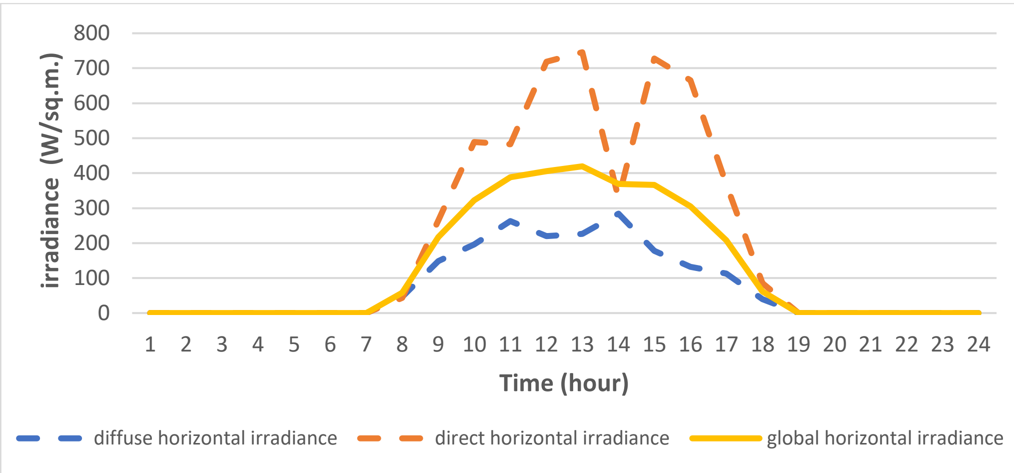


Figure 23 average irradiance distribution profile in Thailand

By the above-mentioned equation, the value of average diffuse horizontal irradiance (W/sq.m.) and direct horizontal the distribution (W/sq.m.) were presented in Figure 23, with the calculated global horizontal irradiance in a day. Average sun time in Thailand is 8 hours per day, approximately from 9 A.M. to 17.00 P.M., depends on seasonal. However, to be used as input data in EnergyPLAN software, the profile of average solar global horizontal during the year has to be contained in text file. To analysis the monthly solar resources, hourly solar irradiance that measured in a specific area were used to find summary in a day. Thus, average of effective daily irradiance is 3,477.50 W/sq.m per day.

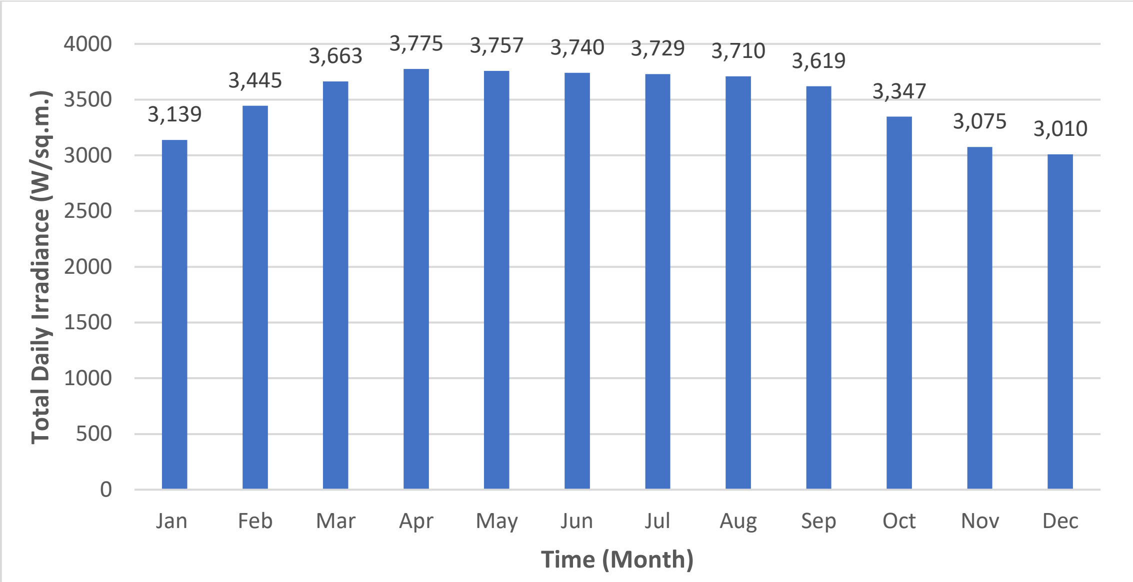


Figure 24 Monthly Average Daily Irradiance in Thailand

3.2.3 Wind Distributed Profile

As same as to convert distributed profile of solar energy to simulate, wind distributed profile in hourly values also calculated by using average of prevailing wind speed (Tenths m/s) that provided in the open-access source from 6 main provinces each region; Chiang Mai (North), Khon Kaen (North-East), Bangkok (Central), Cha Choeng Sao (East), Nakhon Si Thammarat (South), and Prachuap Khiri Khan (West). Hourly value of wind speed from 1st January midnight to 31st December midnight were included in the text file after averaged those data by using excel.

Comparing to solar energy, even though most of the global statistics illustrate that wind is more efficient source of energy than solar, but wind potential of Thailand is different.

Average wind speed in Thailand is not as high as Vietnam that is nearby country. Even though in raining season.

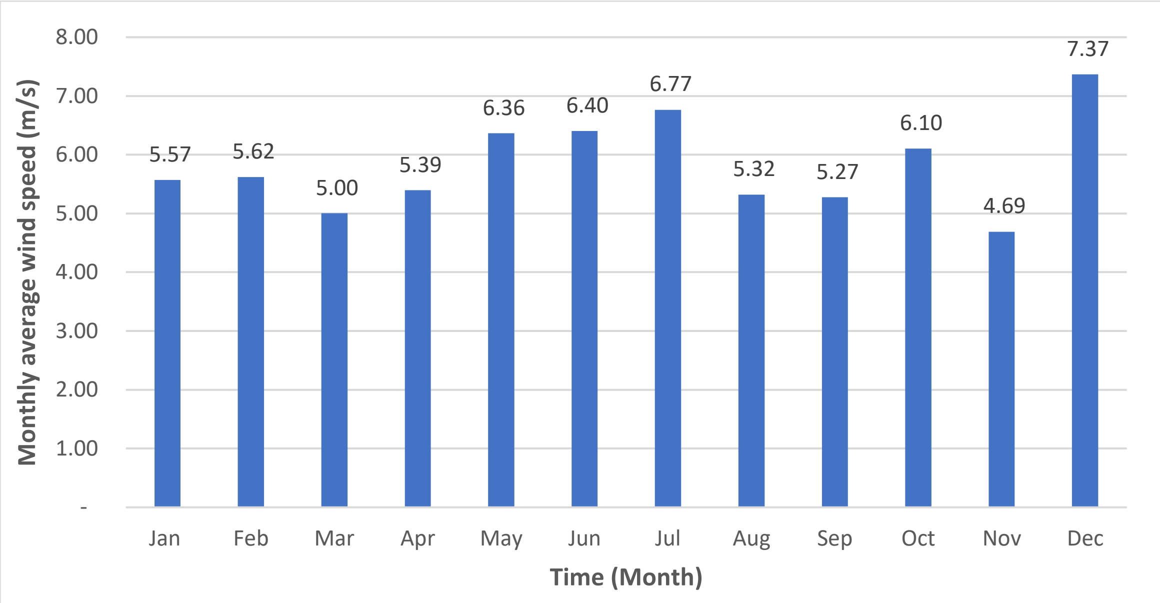


Figure 25 Monthly average wind speed (m/s)

3.2.4 Hydro Distributed Profile

As mentioned in Literature Review, hydroelectric power accounts as the most renewable electricity power generation in Thailand over wind-based and solar-based power. However, Thailand government decided to slightly slow down the number of hydro power plant installations, especially the large-scale plants, with consideration of environmental impacts because most of them are hydroelectric dams. Meanwhile the small-scale dams or run-of-river hydroelectricity still rising in the modest rate.

Even hydro power plants in Thailand have both run of river type and pumped storage type, but the distribution profile of hydroelectricity is covered only the run of river type. This type of dams is a kind of hydroelectric power dam with no water storage provided. Consequently, the distribution will be only seasonal in these following simulations.

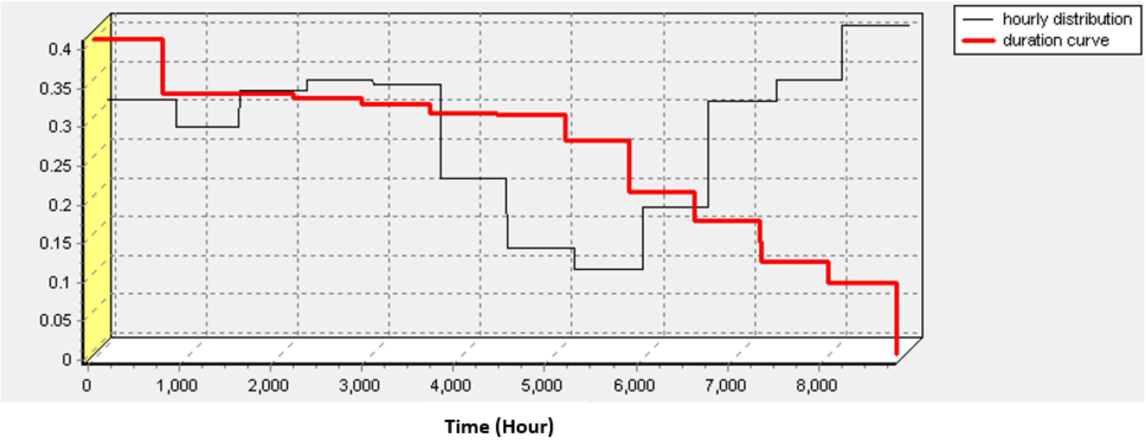


Figure 26 Hydro distributed profile

Error! Reference source not found. presents the distribution profile of hydroelectricity in Thailand during the year. Unlike other distribution profiles that mentioned before, hydroelectricity is unfluctuating with only one value represents the whole month value. This distribution was generated by ExecuteTool which is add-on software provided by the same company with EnergyPLAN [33].

3.2.5 Technical specification and Financial Data

To analyse the financial constraint as mentioned in previous chapter, the required data about capital cost, operation & maintenance cost, and some specification about Solar Photovoltaic and wind system are declared as follow:

Specification	Value
Model of PV panel	JKM520-540M-72HL4-V
Efficiency (%)	20.94%
PV panel Capacity (W)	540
Lifespan (years)	20
Capital Cost ($/kW)	857
O&M Cost ($/kW/year)	14.1
Interest Rate (%/year)	3%

Table 6 Specification of Photovoltaic System

In this study, the solar panel that used as a model is monocrystalline module from Jinko Solar, which is one of widely used in Thailand.

While numerous industries and financial institutions have invested and competed in this industry. In 2021, the global capacity weighted average total installed cost of utility-scale projects was $857/kW. It has decreased dramatically from an average cost of roughly

4,400 $/kW in 2010. Furthermore, competitive pressures and technological developments have contributed to system designs that are optimised to lower O&M costs. The capacity weighted average utility-scale O&M cost for projects in the IRENA Renewable Cost Database was $14.1/kW per year, declined around 48 percent from 2010. These are the projected total 'all-in' O&M expenses, which include items like insurance and asset management [31].

Specification	Value
Model	XANT M-24
Hub height (m)	38
Lifespan (years)	20
Capacity (kW)	95
Capital Cost ($/kW)	1,325
O&M Cost ($/kW/year)	56
Interest Rate (%/year)	3%

Table 7 Specification of Wind System

The wind turbine model that used for calculated in this dissertation is XANT M-24. This turbine is of moderate size, with a hub height of 38 metres. Furthermore, since the cut-in speed is less power curve than other types of turbines, this turbine is appropriate for low wind speed areas such as most areas of Thailand [38].

The global average total installed cost of wind energy projects dropped by 74% between 1984 and 2021, from $5,136/kW to $1,325/kW. Wind turbine pricing and balance-of-plant cost reductions drove this fall [27]. O&M expenses for wind generation often account for up to 30% of the LCOE for this technology. However, technological advancements, more competition among service providers, and improved operator and service provider expertise are driving down O&M costs. Increased attempts by turbine OEMs to win service contracts are supporting this trend, since such agreements may generate larger profit margins than those from turbine delivery alone. The annual cost of operation and maintenance is $56/kW per year [31].

3.2.6 Carbon Emission

Fuel Type	**CO_2 (kg/GJ)**
Natural Gas	56.7
Oil	74
Coal	95

Remark: Sourced EnergyPLAN documentation (2019)

Table 8 Carbon emission factors per unit

Regarding to EnergyPLAN documentation, the number of carbon emission content in different fossil fuels. These factors are described as the total carbon dioxide which emitted per unit of consumed fuels [33]. As presented in

, coal has the maximum carbon dioxide among mainly used fossil fuels in country, while natural gas contains the smallest emission.

All these required distribution profiles were organised and manipulated into the required form as text files included 8,784 rows and a single column. Then, the simulations of different scenarios will be cover in the next section.

3.3 Input Data and Setting Simulations

According to objectives of this dissertation, simulations that related to green transition of Thailand in the next 15 years have 4 scenarios. Firstly, the first scenario is to simulate the current situation (2021) as the baseline for the further situations. For the simulations of future electricity situations in Thailand, there are 3 scenarios will be studied with difference assumptions about growth rate of electricity demand. In this and subsequent cases will be focused on electricity, disregard for thermal demand and supply system since most of the heat supply system in Thailand is generated by electricity energy. The different main inputs of each scenario will be covered in this section.

3.3.1 Baseline (current scenario)

This scenario is the baseline scenario and it revolved around a simplified grid model in Thailand. Setting is based on electricity generation and supply information until the end of 2021. At the end of this year, total renewable power plants accounts over 17% of all electricity generation capacity (ref). Meanwhile, in terms of non-renewable power generation technology, combined cycle and condensation thermal power plants accounted for almost 76% of the total. The rest of them came from other such as electricity from waste, biodiesel, or others.

Data input of electricity demand were collected from EGAT [ref]. Sources in government do not include data regarding safety factors for reserved margin. These factors are assumed to be equal to 10% of electricity demand, refers to the connection code in Thailand (2019), published by EGAT [39].

The details of input data apart from distributed profile is presented in the Table 9:

Demand	Electricity (TWh/year)
Electricity	190.47[1]
Safety margin [2]	19.05
Export	20.95[1]
Total	230.46

Remark: [1] sourced : EGAT (2021)
[2] Safety margin for electricity ensuring that the national maximum electricity is used. This value was assumed as 10% of national electricity. Sourced: Thai Connection Code (2019)

Table 9 Demand data of baseline scenario

Regarding to details of electricity install capacity, only power generation capacity that had started to operate was set into the baseline simulation.

Technology	Installed Capacity (MW)	Efficiency	Correction Factor
Non-renewable	28,583 [1]	45% [2]	-
Wind	224 [1]	-	70%[3]
Photo Voltaic	1,298 [1]	-	85% [3]
Hydro	3,048 [1]	-	60% [4]

Remark: [1] Sourced : EGAT (2021)
[2] Sourced: EnergyPLAN documentation version 15 (2019)
[3] Sourced: IEA (2017)
[4] Sourced: Thai Power development plan (2010)

Table 10 Installed Capacity data of baseline scenario

This simulation will not only examine if the grid in simulation will match the real information in Thailand, but it will also assess the validity of the renewable profile produced for the analysis.

3.3.2 Future Scenario (Case 1)

This future scenario will simulate the next 15 year or electricity sector of Thailand in 2036, based on electricity demand at the lower growth rate, which is 3.5% per year [ref]. Thus, national electricity demand assumed as Equation 2 Future electricity demand:

$$E_n = E_0 \ x \ (1 + i)^n$$

While E_n is Energy demand in n-year (TWh/year)

E_0 is Energy demand in baseline year (TWh/year)

i is Energy demand increasing rate (%)

n is number of years from 2021 or baseline situation

In this case, while E_0 is accounted as 190.49 TWh/year, n is 15 years, and energy demand growth rate is 3.5%. Consequently, projected energy demand of Thailand in 2036 for this case counted as 319.10 TWh/year, this value is to the one that revealed in Thailand Power Development Plan at 326.20 TWh/year, or 3.67% increasing energy demand. Decreasing projected electricity demand was caused by economic slowdown [10].

Regard to power development plan, exported electricity demand was projected to be 15% annum by 2036, increasing from the baseline scenario approximately 4%.

Demand	**Electricity (TWh/year)**
National Electricity	319.10[1]
Safety margin	31.91[2]
Export	49.46[3]
Total	400.47

Remark: [1] Calculated by This future scenario will simulate the next 15 year or electricity sector of Thailand in 2036, based on electricity demand at the lower growth rate, which is 3.5% per year [ref]. Thus, national electricity demand assumed as Equation 2.

[2] Safety margin for electricity ensuring that the national maximum electricity is used. This value was assumed as 10% of national electricity. Sourced: Thai Connection Code (2019).
[3] Sourced: Power Development Plan (2015).

Table 11 Demand Data of Future Scenario (Case 1)

For total installed capacity, power generation was projected to have new capacity of 57,459 MW and retiring capacity of 24,736 MW between 2015 and 2036 . Install capacity of each classified technology are presented in Table 12. Thai government planned to increase Photo Voltaic around 6 times, and wind-based install capacity to approximately 3,000 MW. Meanwhile, hydro power generation remains the same level due to consideration of environmental issues.

Regarding to efficiency improvement of different technologies, for non-renewable power generation was projected to have overall efficiency as 60% in the next 15 years [3]. Meanwhile the correction factors of renewable technologies were assumed to increase 5% in this this scenario.

Technology	Installed Capacity (MW)	Efficiency	Correction Factor
Non-renewable	50,701[1]	60%[2]	-
Wind	3,002[1]	-	75%[3]
Photo Voltaic	6,000[1]	-	85%[3]
Hydro	3,282[1]	-	65%[4]

Remark: [1] Sourced : Power Development Plan (2015)
[2] Sourced: EnergyPLAN documentation version 15 (2019)
[3] Sourced: IEA (2017)
[4] Sourced: IEA (2019)

Table 12 Install Capacity of Future Scenario (Case 1)

3.3.3 Future Scenario (Case 2)

As second case of future scenario, all of input data of demand-side remains the same as the first case at around 400 TWh/year.

Demand	Electricity (TWh/year)
National Electricity	319.10[1]
Safety margin	31.91[2]
Export	49.46[3]
Total	400.47

Remark: [1] Calculated by This future scenario will simulate the next 15 year or electricity sector of Thailand in 2036, based on electricity demand at the lower growth rate, which is 3.5% per year [ref]. Thus, national electricity demand assumed as Equation 2.

[2] Safety margin for electricity ensuring that the national maximum electricity is used. This value was assumed as 10% of national electricity. Sourced: Thai Connection Code (2019).

[3] Sourced: Power Development Plan (2015).

Table 13 Demand Data of Future Scenario (Case 2)

Table 14 presents the overview of installed capacity in Thailand of this case. Despite of efficiency and correction factors that were set as same as the first case of Future scenario, installed capacity of wind-based electricity and Photo Voltaic system were double, calculated as 6,000 MW and 12,000 MW, respectively.

Technology	Installed Capacity (MW)	Efficiency	Correction Factor
Non-renewable	50,701[1]	60%[2]	-
Wind	6,000[5]	-	75%[3]
Photo Voltaic	12,000[5]	-	85%[3]
Hydro	3,282[1]	-	65%[4]

Remark: [1] Sourced : Power Development Plan (2015)
[2] Sourced: EnergyPLAN documentation version 15 (2019)
[3] Sourced: IEA (2017)
[4] Sourced: IEA (2019)
[5] Assumed installed capacity

Table 14 Install Capacity of Future Scenario (Case 2)

3.3.4 *Future Scenario (Case 3)*

Details of demand-sided electricity input data are the same as Case 1 and Case 2.

Demand	Electricity (TWh/year)
National Electricity	319.10[1]
Safety margin	31.91[2]
Export	49.46[3]
Total	400.47

Remark: [1] Calculated by This future scenario will simulate the next 15 year or electricity sector of Thailand in 2036, based on electricity demand at the lower growth rate, which is 3.5% per year [ref]. Thus, national electricity demand assumed as Equation 2.

[2] Safety margin for electricity ensuring that the national maximum electricity is used. This value was assumed as 10% of national electricity. Sourced: Thai Connection Code (2019).

[3] Sourced: Power Development Plan (2015).

Table 15 Demand Data of Future Scenario (Case 3)

Total installed capacity of non-renewable and hydro power generation remains as same as 50,701 MW and 3,282 MW. In addition, installed capacity of wind energy added to be 7,000 MW and increased solar power generation capacity to 14,000 MW as presented in Table 16.

Technology	Installed Capacity (MW)	Efficiency	Correction Factor
Combined cycle	50,701[1]	60%[2]	-
Wind	7,000[5]	-	75%[3]
Photo Voltaic	14,000[5]	-	85%[3]
Hydro	3,282[1]	-	65%[4]

Remark: [1] Sourced: Power Development Plan (2015)
[2] Sourced: EnergyPLAN documentation version 15 (2019)
[3] Sourced: IEA (2017)
[4] Sourced: IEA (2019)
[5] Assumed installed capacity

Table 16 Install Capacity of Future Scenario (Case 3)

3.4 Uncertainty analysis in simulations

Considering three main causes of uncertainty as insufficient amount of raw data, cosine correction and repeatability of measurement [40]. In this study, although the simulations and calculations were set as above-mentioned section, uncertainty exists concerning the accuracy of the results due to some limitation of input data as follow:

- Due to the massive number of renewable plants, the information required to calculate correctly requires precision and accuracy as each project's parameters that effect on its electricity profiles vary from location, equipment, maintenance, and details of installation such as height, temperature, and tile angles.
- Distribution profiles of electricity demand and renewable resources in baseline scenario and the future scenario have the same pattern. Neglected the changing of distributions between 15 years.
- The carbon emissions that simulated by software was calculated from the fuel-related factors. Neglected the non-direct carbon releasing activities such as operations, transportation, etc.
- The interest rate of country remains as 3% per year. Neglected the economically instability.

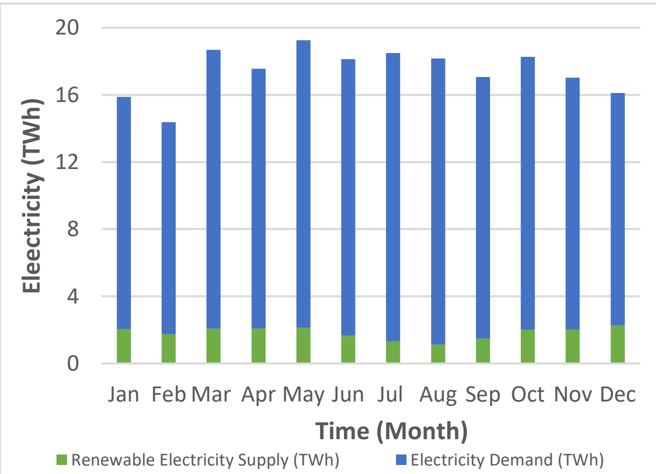
4 RESULTS

In this chapter, the results of simulations that mentioned in previous section will be described as follow:

4.1 Baseline Scenario

According to the setting of this scenario, after plug in all the inputs and distributed profiles on EnergyPLAN, the main result of this case is presented as follow:

National electricity demand of Thailand counts approximately 210 TWh annum and has peak electricity demand as 37,530 MW. Although the summarised renewable-based electricity generation accounts around 17% of total installed capacity in Thailand, but only 9.54% of electricity unit were supplied by renewable energy due to the limitations of resources and technologies. Therefore, Thai electricity sector needs to rely on non-renewable sources, which is electricity generated on fossil fuel such as natural gas, coal, oil and more.



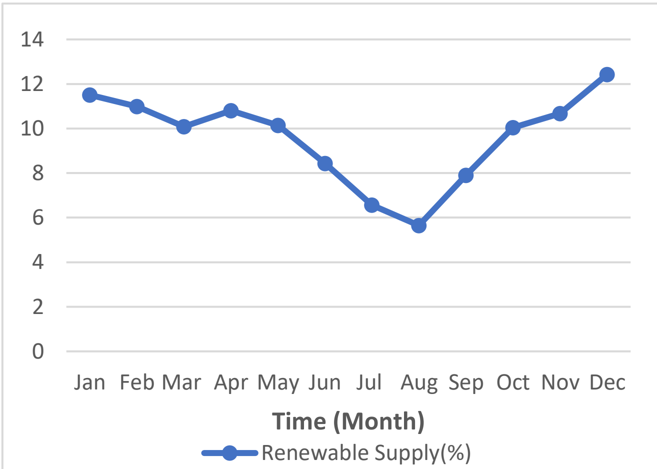


Figure 27 Monthly electricity demand and renewable electricity supply from baseline scenario

Figure 28 Monthly renewable power supply (%) from baseline scenario

As the information from Figure 27 and Figure 28, monthly electricity details about both electricity energy show that number of electricity that generated by renewable sources depends on seasons and climate, Thailand can supply green electricity most in December. It starts a slightly decreasing at beginning of the year until hit the lowest point in August at 1.19 TWh per month, or 5.65% of total electricity usage in the month, which is the month that has heaviest rain of all year. Then, share of supplied renewable electricity grows again.

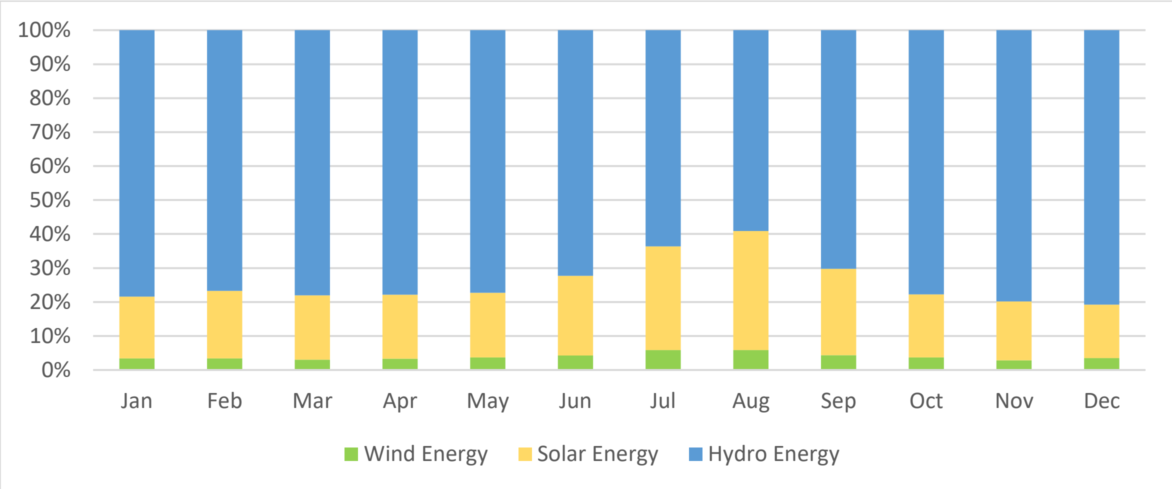


Figure 29 Shares of different renewable electricity supply from baseline Scenario

To explore more details in generated energy by different renewable resources as presented in Figure 29. it presents percentage of electricity units from wind, solar and hydro energy which have install capacity as 224 MW, 1,298 MW and 3,048 MW, respectively. Therefore, the most renewable that can supply electricity in 2021 is Hydro energy, as 16.65 TWh annum, with estimated capacity factor as 0.62 which is the highest among all focused resources. Following by solar-based electricity at accounts over 4.5 TWh per year, and the lowest electricity generated resources is wind, which is estimated less than 1 TWh per year. Capacity factor of solar is 0.4, which is still in global range from 0.2 – 0.5 [40]. And capacity of wind energy is 0.4.

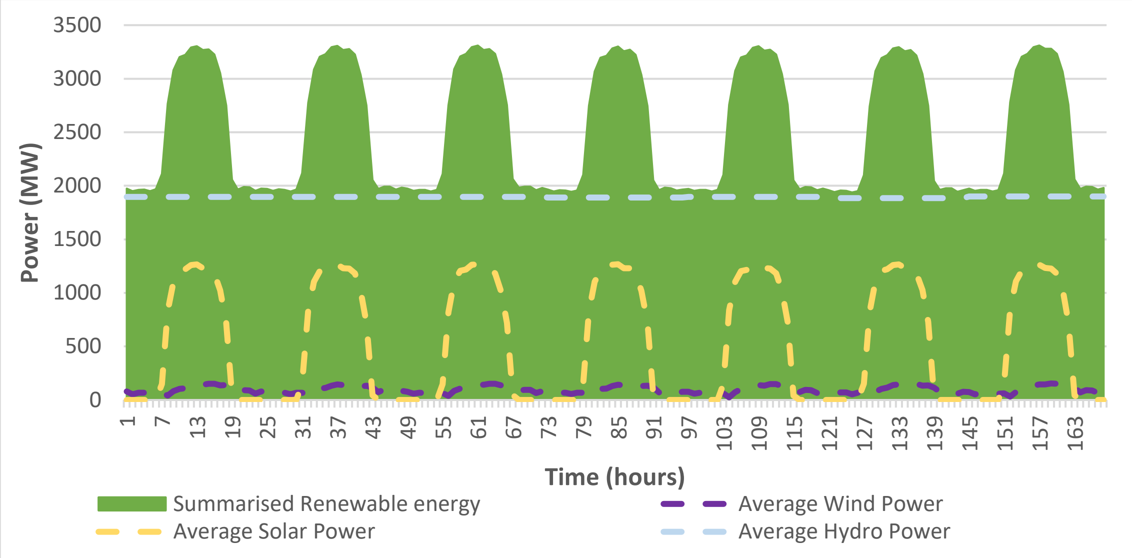


Figure 30 Characteristic of Renewable energy (Baseline Scenario)

Power characteristics of generated renewable electricity in a week is presented in Figure 30, based on EnergyPLAN software. Despite of hydroelectricity which is stable around 2,000 MW during the time, it clearly shows that even though but for the 2nd largest green electricity was produced by PV system at daytime, or average only 8 hours a day, as same as wind energy that has lower stability compares to hydroelectricity. Thus, Thailand has a lack of continuously renewable electricity to match the demand, renewable electricity is rapidly generated around 9 P.M., reached the peak at noon with around 3,300 MW. After that, it started to decrease until has only hydroelectricity and a few of wind-based electricity. This following chart presents the net electricity demand that need to be supplied by non-renewable fuels.

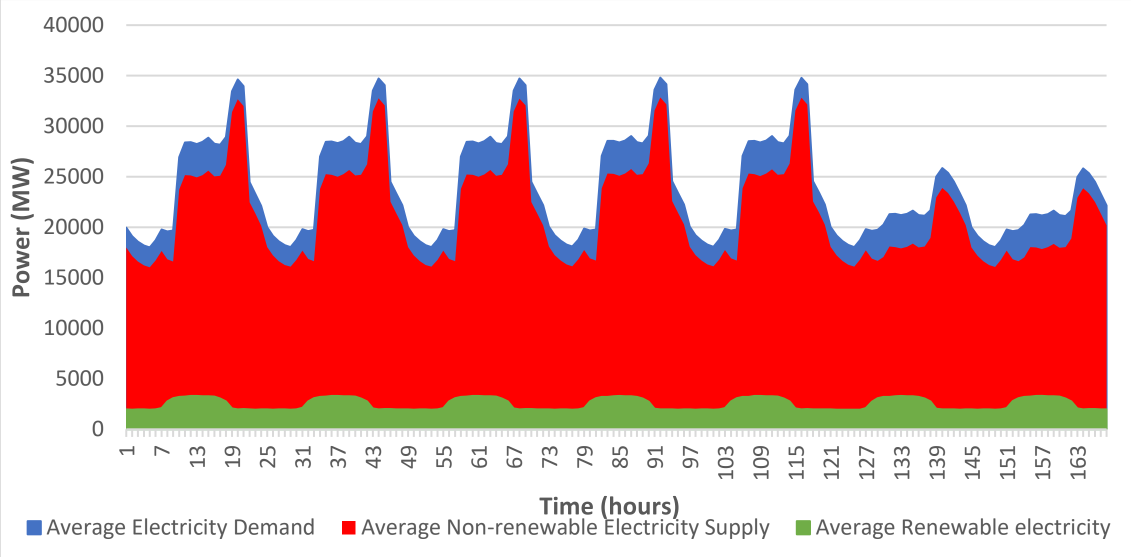


Figure 31 National Power Characteristic of Thailand (Baseline)

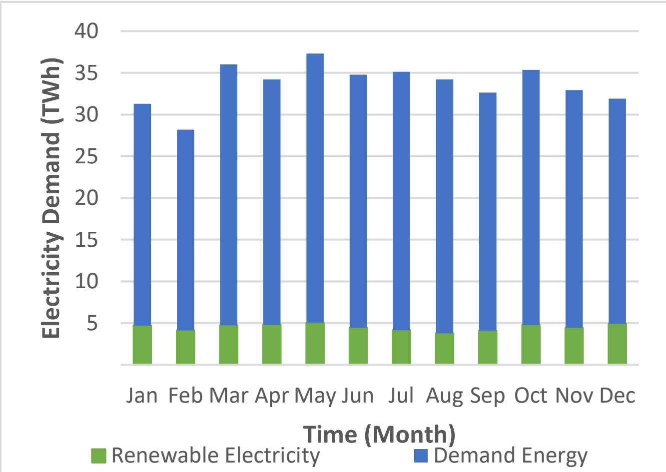
Average electricity profiles are illustrated in this chart, included electricity demand, generated electricity by renewable and non-renewable sources. It clearly shows that Thailand power system is still depends on fossil fuel, especially for the peak time (19.00 – 22.00 P.M.) of weekdays. Despite of lower electricity demand during weekend, renewable electricity production system still not enough.

In addition, the simulated result shows that over 90% of electricity must be supplied by non-renewable fuels, accounted as 207.23 TWh annum. Most of them was generated by natural gas, generated over 106,334 thousand tonnes of carbon dioxide. Following by 70,307 thousand tonnes CO_2 that released from 34,614 TJ of consumed coal. Only 1.2% of this emission generated by oil because it was the smallest consumed fuel for power generation. Average carbon intensity is 0.4616 kgCO_2/kWh.

Consequently, renewable electricity generation market has a huge space for new installation projects and improvement for technologies to achieve the greener power generation, without ignoring the electricity demand that continuously gain through time.

4.2 Future Scenario (Case 1)

For the first case of future scenarios that simulated by directly referring installed capacity based on Power Development Plan of Thailand (2015). 12,284-MW installed capacity in the country can supply approximately 54 TWh per year by 2036. Despite of significant expansion in PV and wind power generation system, the simulation result shows that Thailand cannot accomplish the target 25-30% renewable electricity supply.



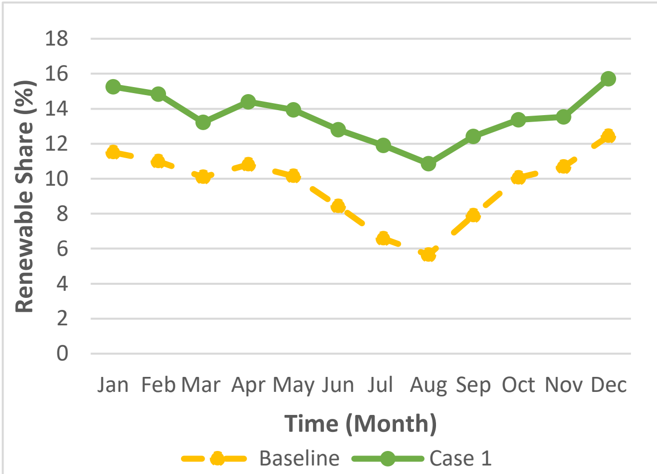


Figure 32 Monthly electricity demand and renewable electricity supply (Future scenario – Case1)

Figure 33 Monthly renewable power supply (%) from Case 1

As presented in Figure 32 and Figure 33, monthly renewable energy generation averaged around 4.5 TWh per month. August is the lowest generated electricity numbers with only 3.48 TWh, while the total supplied units rise during the winter season, as same as the current trend.

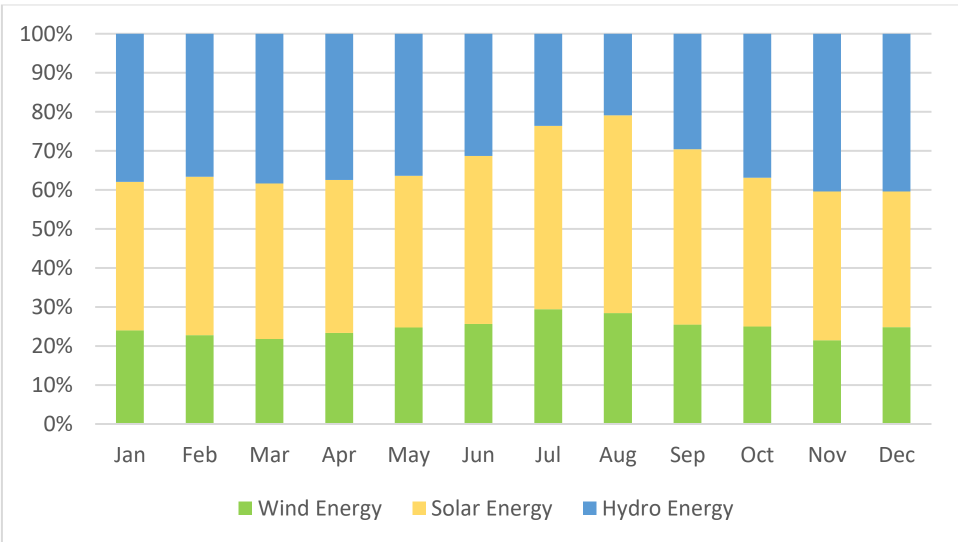


Figure 34 Shares of different renewable electricity supply (Future Scenario - Case 1)

Figure 34 illustrates the simulated shares of hydroelectricity, solar-based electricity, and wind-based electricity from January – December 2036. Average generated power from hydro, solar, and wind are 1.56 TWh, 1.84 TWh and 1.11 TWh, respectively. As presented, there are no massive difference between the produced power.

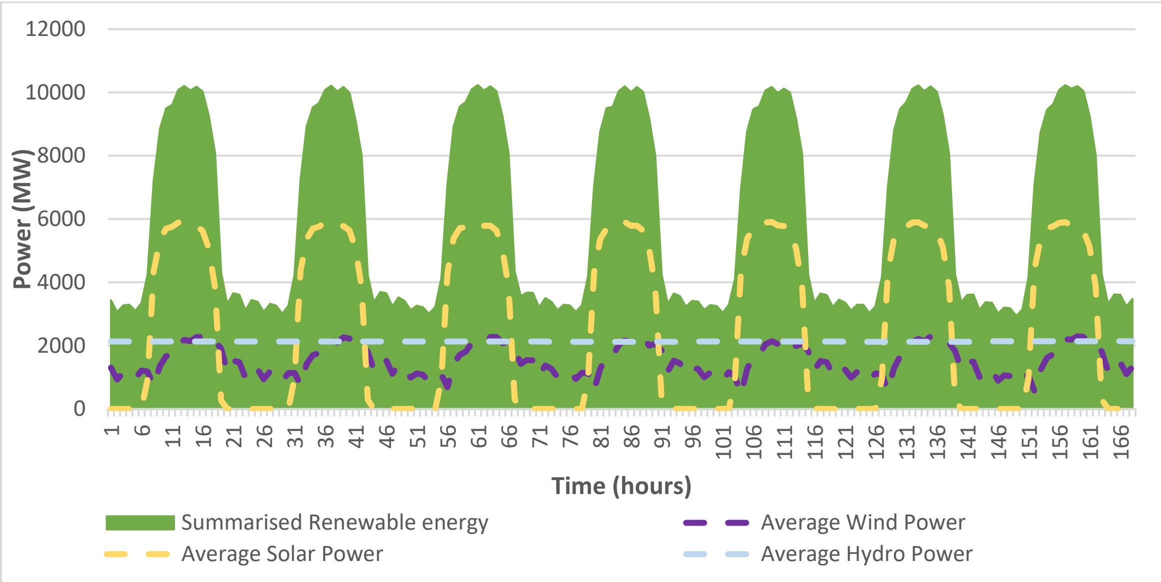


Figure 35 Characteristic of Renewable energy (Future Scenario - Case 1)

Due to the shares of solar installed capacity has potentially grown, pattern of net renewable power has become the same trend of solar power profile as shown in Figure 35 and Figure 36. Power supply reached the peak at noon, around 10,500 MW. This leads to different load profile between daytime and nighttime from the renewable resources. When electricity demand increased and renewable electricity production also decreased, this required more electricity supply from fossil fuel power plant during that time.

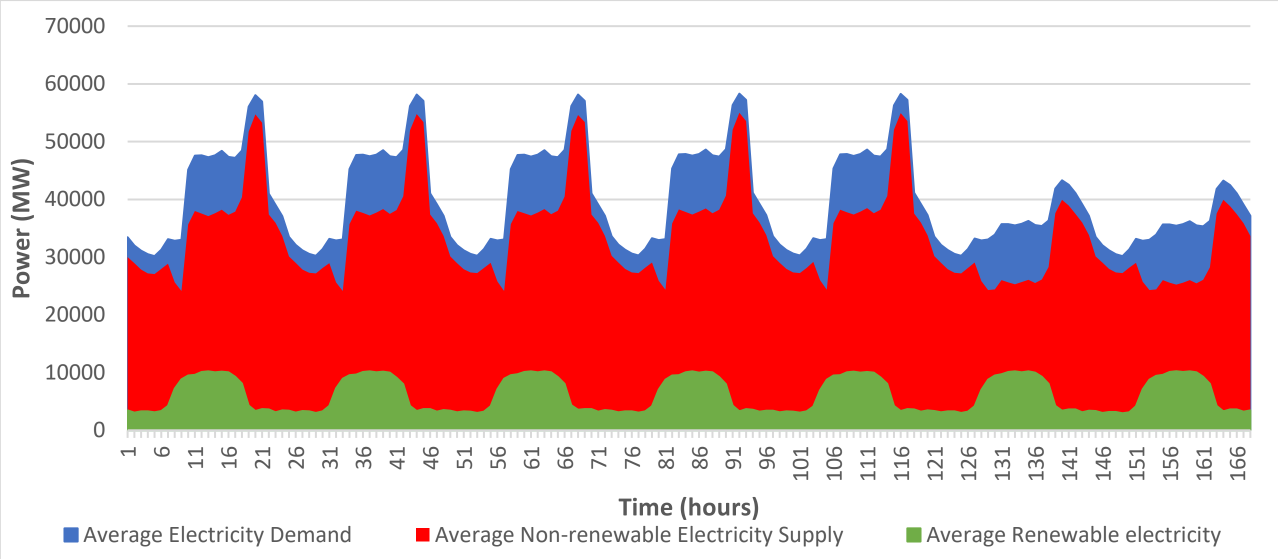


Figure 36 National Power Characteristic of Thailand (Future Scenario - Case 1)

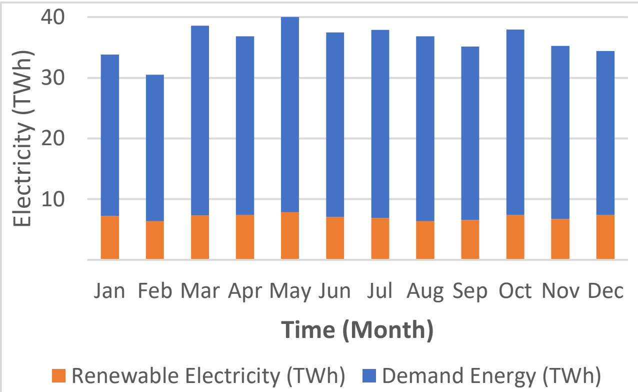
With this expansion of wind and solar power generation in nation, Thailand has to supplied 29,242 Turbines, and over 8.7 million solar PV panels. This costed around 7,710 million USD for capital cost and cost for O&M over 211 million USD per year. As a result, the LOCE for wind energy and solar energy in 2036 were expected to be 39.42 USD/MWh and 19.97 USD/MWh, respectively. There are 72% and 77% decreases from 2021, respectively.

Results of Case 1 provided that the installed capacity suggested by PDP2015 would not achieve the 30% renewable energy goal. Over 346.48 TWh has to be supplied by natural gas and coal. This leads to the carbon emission over 140,670 thousand tonnes CO_2 in 2036. However, even total among rises, but carbon intensity is 0.3515 kgCO2/kWh. It reduced during the baseline scenario over 24%.

To deal with dealing with rising electricity demand in accordance with the national economic and social, fuel diversification is the main key of energy security. As a result, Thailand the purchase of fossil fuel from neighboring nations such as Lao PDR, Myanmar, Cambodia, and Malaysia by the international supply line, especially for natural gas and Coal. This causes the harder situation to reduce the dependency of power sector in Thailand [3].

4.3 Future Scenario (Case 2)

To simulate this case, doubled installed capacity of wind and solar were added as the data input with the same electricity demand, this leads to total renewable power generation system turned to 21,282 MW. Over 56% of the are Photo Voltaic system, followed by wind turbine and hydro power generations. However, despite of massive growth, renewable electricity supply still not enough to accomplish the minimum target of Power development plan by 15 years.



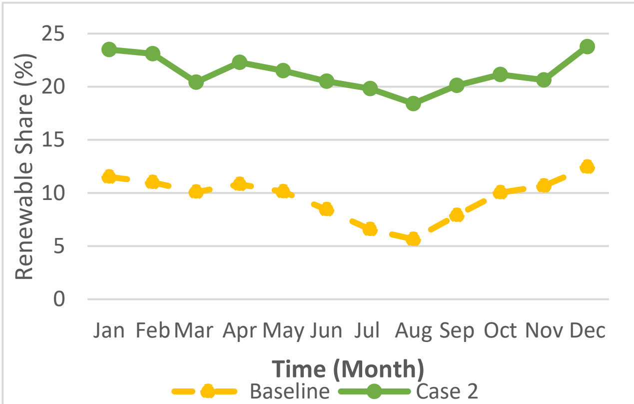


Figure 37 Monthly electricity demand and renewable electricity supply (Future scenario – Case2)

Figure 38 Monthly renewable power supply (%) from Case 2

With this installed capacity in 2036, the renewable power system has potential to produce around 85 TWh, or 21.20% out of national electricity demand during the year. Figure 38 and**Error! Reference source not found.**Figure 39 show the details about how much electricity demand can be supplied by green electricity. Average monthly renewable power generation accounted 7.07 TWh, almost 6 times from the baseline scenario.

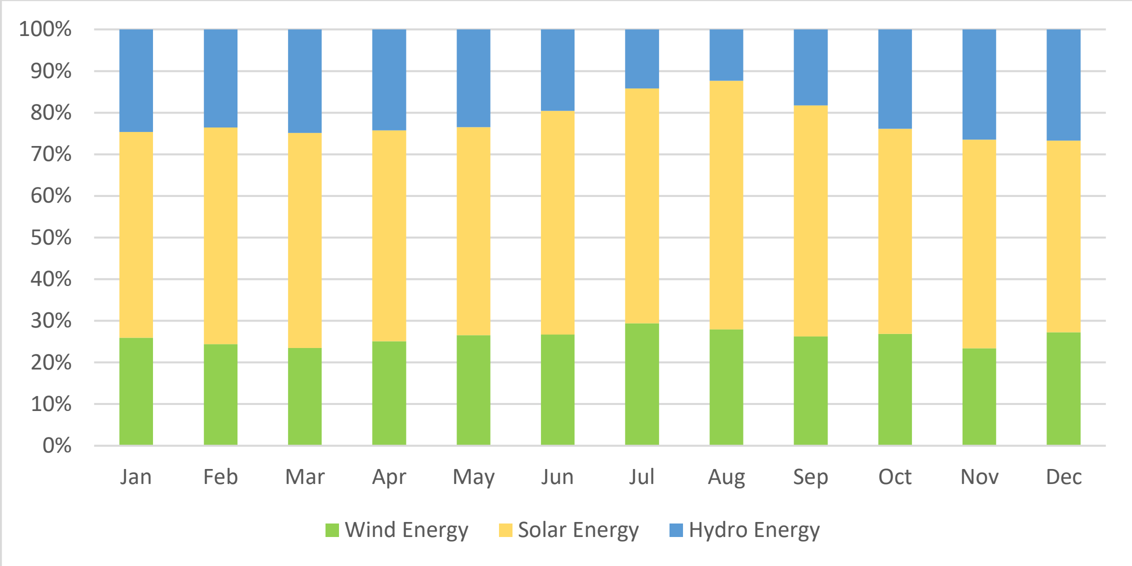


Figure 39 Shares of different renewable electricity supply (Future Scenario - Case 2)

The shares of monthly generation are presented on Figure 39**.** With this proportion of installed capacity, hydroelectricity became the lowest market shares amount three of different types of technology with 22.6%. Following by wind power that produced around 22.16 TWh, calculated as 25%. While over half of total renewable-based power come from the solar system, accounted as 44.03 TWh a year or 52%.

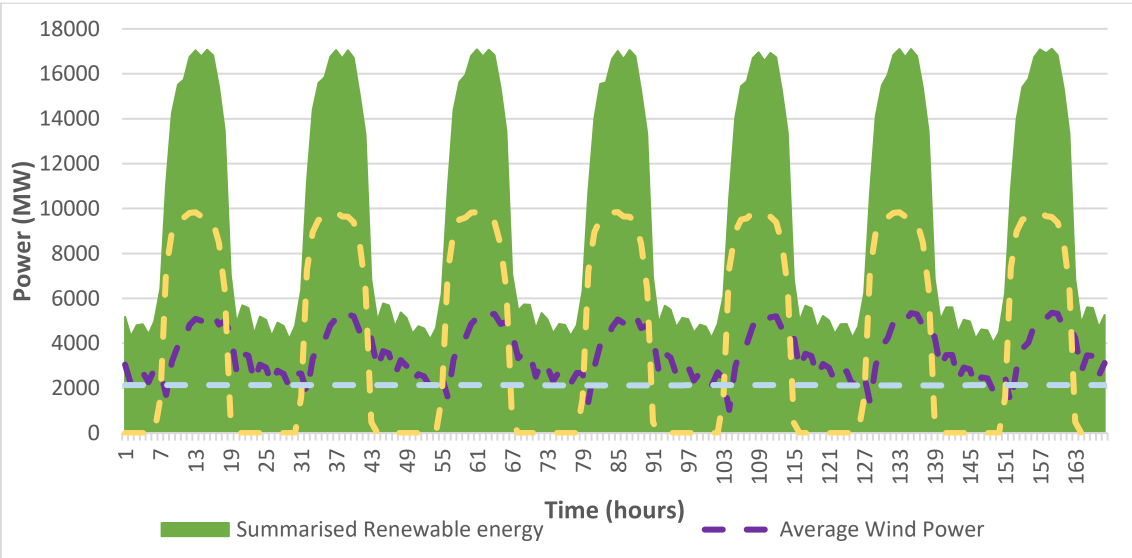


Figure 40 Characteristic of Renewable energy (Future Scenario - Case 2)

The characteristics of renewable electricity production are illustrated in Figure 40, and the net power generations from different resources are shown in Figure 41. Although the peak power from renewable fuels is approximately 17,500 MW at noon. At the same time, the highest electricity demand is approximately 60,000 MW at 19.00 PM of weekday. During the evening time, especially from 18.00-20.00 PM, the non-renewable electricity needs to rapidly generated. This causes the trouble in demand-sided management.

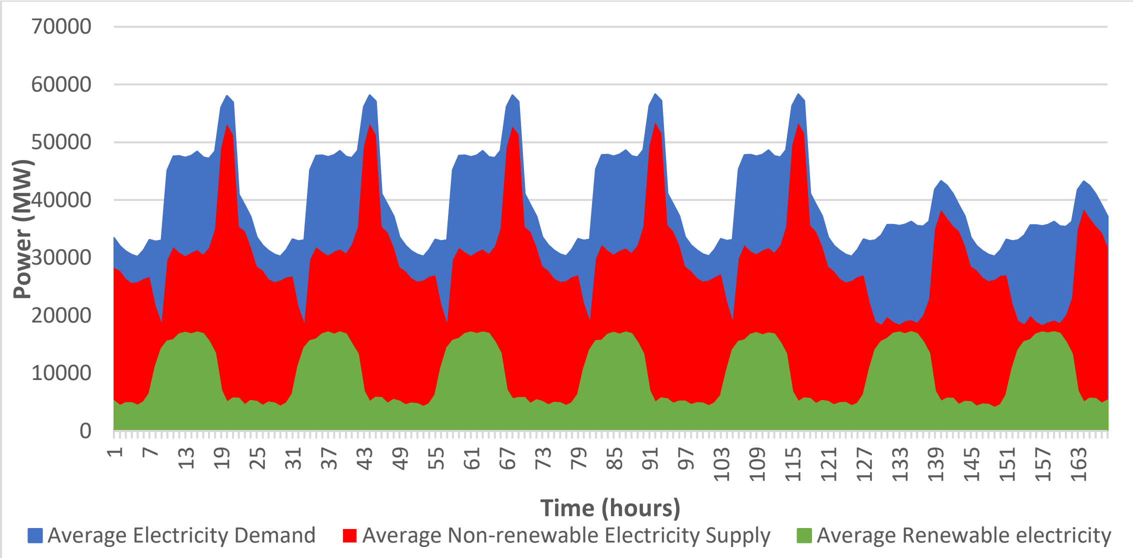


Figure 41 National Power Characteristic of Thailand (Future Scenario - Case 2)

To archive 6000-MW wind installed capacity and 12,000 MW solar power generation capacity, over 60,000 wind turbines and roundly 20 million solar panels are required for installations. Capital cost of new installed wind system costed over 7,653 million USD with operation and maintenance cost around 323 million USD annum. Meanwhile the capital cost of solar systems is estimated as 9,172 million USD, and 151 million USD per year for operating. Consequently, the LOCE of wind energy and solar energy were estimated to be 46.83 USD/MWh and 20.15 USD/MWh in 2036, respectively. There are represented as 67% and 77% decreasing from 2021.

The results of Case 2 indicated that even the installed capacity of wind and solar were doubled from the numbers that proposed by PDP2015, there are not archive the minimum target yet. To supply the remained has to be supplied by natural gas, coal and other fuel. This results in carbon emissions of more than 128,125 thousand tonnes CO_2.

Even when the overall among grows, the carbon intensity is 0.3201 kgCO2/kWh. It decreased by more than 31% from the baseline situation, and around 8.9% from the previous case.

For security perspective, although this scenario provided the better reduction about dependency of power sector about imported fossil fuels, but another issue that must concern is the flexibility of non-renewable power plant. To maximise the electricity energy efficiency and optimise energy resources, the demand-sided management is required in this stage, decreasing the peak demand or peak cutting is suitable with Thailand load profile in 2036.

4.4 Future Scenario (Case 3)

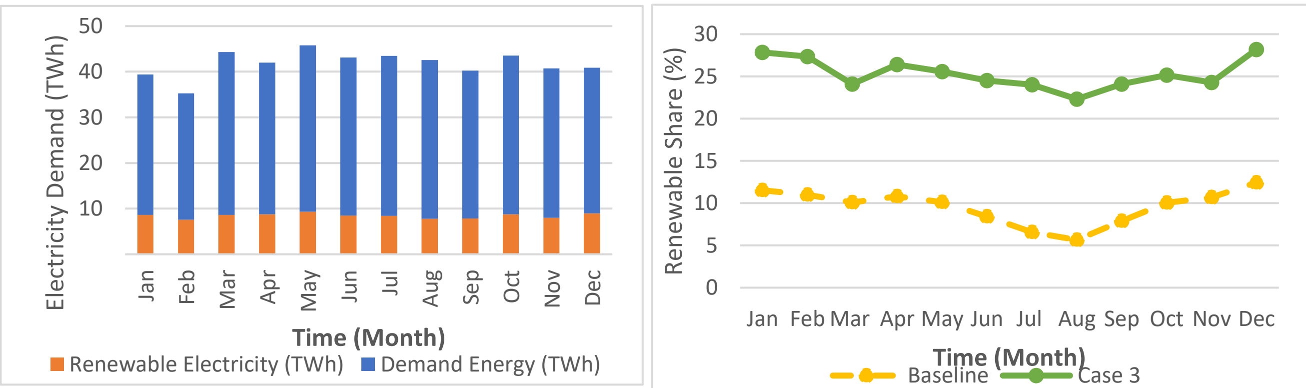


Figure 42 Monthly electricity demand and renewable electricity supply (Future scenario – Case 3)

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For the this future scenario, with the installed capacity of wind energy 7,000 MW and solar system 14,000 MW. The monthly demand and renewable electricity supply during the year are presented in **Error! Reference source not found.**. Green electricity is generated 8.42 TWh in a month. Total national generated renewable power accounted as 25.25% of total demand, or 101 TWh. This simulation shows these number of renewable installed capacity can archeive the minimum target of Power Development Plan 2015.

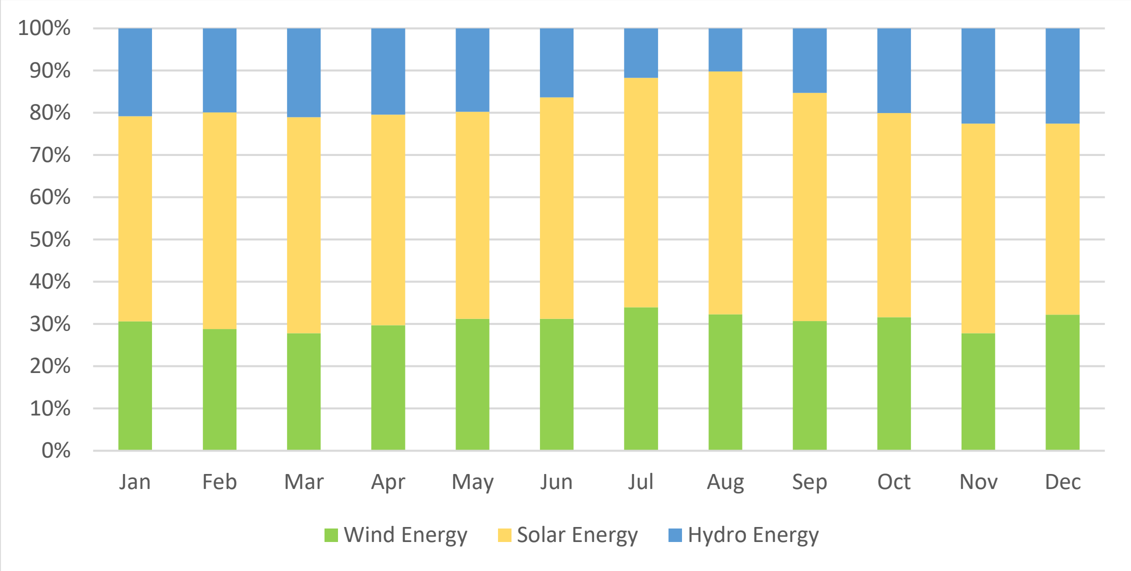

Figure 43 Shares of different renewable electricity supply (Future Scenario - Case 3)

Error! Reference source not found. displays the shares of monthly generation of three renewable electricity technologies, hydroelectricity has the lowest market share of three forms of technology with 18.7 TWh per year or 18.6%. Wind power ranks second electricity producing technology around 31 TWh and solar systems account the most of renewable electricity for 50.8 TWh per year.

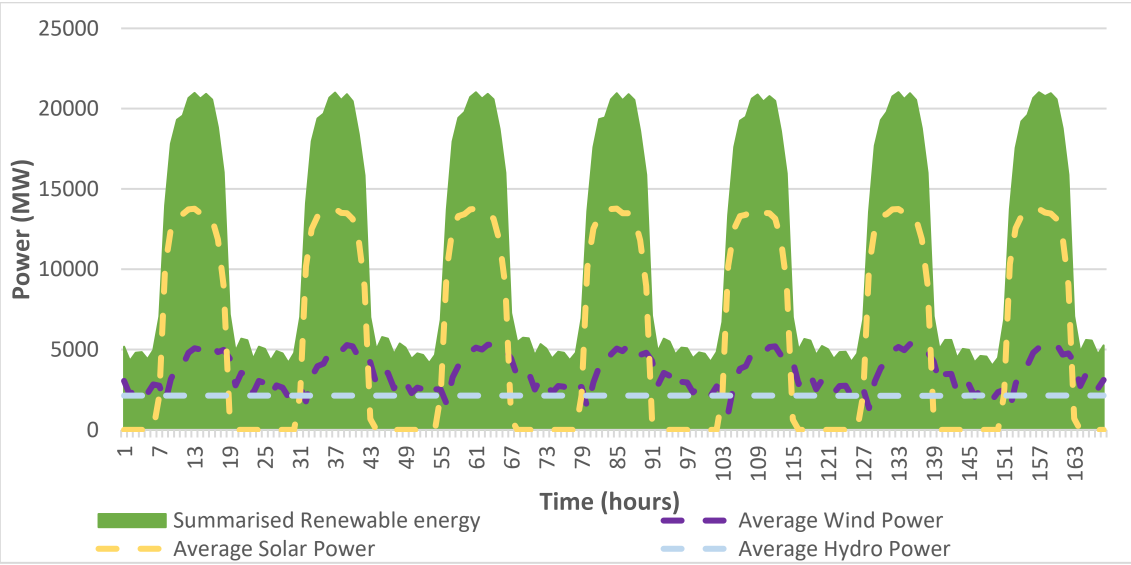

Figure 44 Characteristic of Renewable energy (Future Scenario - Case 3)

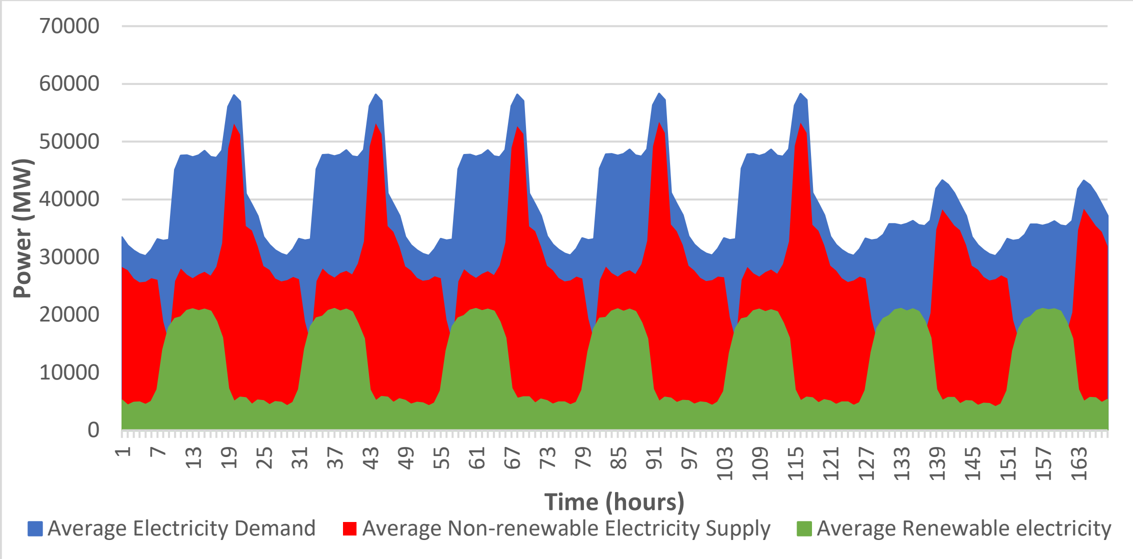

Figure 45 National Power Characteristic of Thailand (Future Scenario - Case 3)

Error! Reference source not found. depicts the features of renewable electricity production, whereas **Error! Reference source not found.** depicts the net power generation from various resources. With these installed capacity, maximum output from renewable sources is around 21,000 MW, and can supply over 60% of electricity demand during the weekend afternoon. However, power that generated from fossil fuel still play an important role. and power must be generated quickly in the evening, particularly between 18.00 and 20.00 PM, the rapid increasing of electricity demand from around 30,000 MW to 52,000 MW that cannot be supplied by renewable power generation at evening can cause the flexibility issue in non-renewable power plant.

For this case study, the total capital fund is approximately 19,863 million USD. Over 71,327 wind turbines and over 23 million solar PV modules to reach this renewable installed capacity. Around 558 million USD is estimated for O&M cost per year for the newly installed project. Thus, in 2036, the LOCE of wind energy and solar were projected to be 38.45 USD/MWh and 21.03 USD/MWh, calculated as 73% and 77% reduction in 15 years, respectively.

Fossil fuels must be consumed to supply the remainder. This simulation shows that when Thai power sector can pass the minimum target at 25%, the total carbon dioxide emission during the year is 121,544 thousand tonnes CO_2. The carbon intensity is 0.3037 kgCO_2/kWh.

Energy security problem that needs to be address in this case is as same as the second scenario, flexibility of fossil fuel power plants. By 2036, government of Thailand should consider about cutting the peak, especially during 18.00 – 20.00 PM on weekdays. As a consequent, this can reduce the pressure on supply side to satisfy the national demand.

4.5 Comparison of Scenarios

This following table presents the main results of the simulations.

	Baseline Scenario	**Future Scenario (Case 1)**	**Future Scenario (Case 2)**	**Future Scenario (Case 3)**
Fossil Fuel installed Capacity (MW)	28,583	50,701	50,701	50,701
Wind installed Capacity (MW)	224	3,002	6,000	7,000
Solar installed Capacity (MW)	1,298	6,000	12,000	14,000
Hydro installed Capacity (MW)	3,048	3,282	3,282	3,282
Renewable Annual Electricity Production (TWh)	23.13	53.97	84.85	101.05
Share of renewable electricity Production	9.54%	13.48%	21.20%	25.25%
Capital cost for new renewable installed capacity (million USD)	-	7,710	16,825	19,863
O&M cost for new renewable installed capacity (million USD/year)	-	222	474	558
Levelized cost of wind energy (USD/MWh)	-	39.42	46.83	38.45
Levelized cost of solar energy (USD/MWh)	-	19.97	20.15	20.31
CO_2 intensity (kgCO2/kWh)	0.4616	0.3515	0.3201	0.3037

Table 17 Summarised results of scenarios

As presented in Table 17 Summarised results of scenarios, the more of renewable installed capacity, annual the more share in the electricity production. To meet the minimum target 25%, Thailand will require approximately 14,000 MW of solar and 7,000 MW of wind system. LCOE of wind energy of Case 2 is the highest out of three future scenarios, with 46.83 $/MWh, following by the Case 1 and Case 3. Meanwhile, the LCOE of solar energy of all cases have no significant different, accounted around 20 $/MWh. For CO_2 intensity, case 3 is the largest reduction, calculated as 34% from the baseline.

5 FINAL REMARKS

According to the fast expansion in the industrial sector and electricity consumption in Thailand, the government proposed to develop the national power generating infrastructure to meet rising demand in the near future. The power development plan launched in 2015 addressed the renewable-based power supply as 25-30% per year. As a result, the aim of this project is to investigate the feasibility of the development plan within energy security, financial, and environmental aspects. Also, to find an appropriate model that includes at least 25% renewable power production by 2036. In addition, EnergyPLAN was chosen to be the simulation software of this study.

However, EnergyPLAN can deliver findings on detailed technical results, the study also limits the sort of electricity generating input components. For instance, some modelling input parameters, such as actual hourly wind speed and actual hourly solar irradiance, are missing critical information. Therefore, assumptions based on findings and studies in public areas were made in order to produce the most exact answers feasible.

5.1 Conclusion

In terms of project results, there are three cases that were investigated using EnergyPLAN and proved to be technically feasible. However, only the last scenario can hit the target 25-30% that was mentioned in power development plan addressed since 2015. According to the findings, the scenario with major renewable production systems will assist the environment by reducing CO2 emissions by a greater proportion. In contrast, it appears that the biggest impediments to scenarios with a substantial renewable portion model would be financial constrain consequences.

Based on data and analysis reported in this dissertation the following conclusions can be obtained:

- Solar PV plays a key part in green electricity transition in Thailand since it produces the most electricity, and its installation may be less complex than other renewable systems. In addition, Thailand has solar as the most potential renewable sources.

- Both solar PV and wind turbines may produce power at daytime and hit their peak at midday. Meanwhile the hydroelectricity is produced steadily from day to night.
- The renewable installed capacity cannot achieve the goal 25-30% renewable power production by 2036. Thailand requires over 14,000-MW of solar systems and 7,000-MW of wind to accomplish that target. As a consequence, capital cost is approximately 20,000 million USD, and 558 million USD/year is required as O&M cost.

Overall, this power development plan is unlikely possible to accomplish the goal which set as 25-30% power generated by 2036. Because of technological advancements and government backing for renewable energy systems, this strategy may become more efficient in the future. Finally, due to the limits listed above or others, this project may have certain drawbacks. As a result, the next section will highlight potential future work that might benefit the project.

5.2 Future Works

According to the results of this study, there are some more additional improvements to improve this project that have not been done due to the time constrain and lacking some details and input components. As a result, the following approaches will highlight some ways that might be improved for this project.

- *Precise variables* – Since there are some input components calculated based on the assumptions, they should be performed as real data for a more realistic output.
- *Sensitivity analysis* – Due to the fixed input data and distributed profiles were used for simulations as independent variables. The study about how they affect other variables would illustrate of the results.
- *Location Analysis* – To improve the more precious feasibility study, the analysis about location should be investigated in more details, consists the available resources, social impact and the power system in each areas.

- *Demand side analysis and management* – This study mainly focused on supply side of Thai power sector. However, the methods for reducing the peak demand and lowering the load factor will help the country power sector become more efficient.
- *Storage system* – the storage system should be investigated because this is a potential technique to improve the effectiveness of whole power system.

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