MSc Program
Renewable Energy Systems

Analysis of possible measures for Peak Demand Reduction in a Smart Grid with high penetration of Photovoltaics and Electric Vehicles in Thailand in a Scenario up to 2040

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 20.02.2020

Affidavit

I, **DECHAWAT TAMANEEWAN**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ANALYSIS OF POSSIBLE MEASURES FOR PEAK DEMAND REDUCTION IN A SMART GRID WITH HIGH PENETRATION OF PHOTOVOLTAICS AND ELECTRIC VEHICLES IN THAILAND IN A SCENARIO UP TO 2040", 77 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Global electricity demand is increasing every year. New services appear on the market in order to make our daily life easier. Decarbonization in transport sector makes electric vehicles more popular. Those electric vehicles are considered new demand in electricity sector. New power plants are to be built in order to serve those increasing demand. Due to climate change and global warming, many countries tend to increase the share of renewable energy. Those renewable power plants such as wind and photovoltaic tend to be, not only unpredictable, but also, distributed generation. They tend to be a number of small-scale power plants which are installed close to the loads in order to reduce the transmission losses. This high number of small-scale power plants makes it more challenging to manage. With all these challenges, the electrical grid must be smarter in order to be able to deal with the increasing demand and also be able to balance between power demand side and power supply side. It should be monitored and be able make real-time adjustment in order to deliver electricity efficiently with standard power security and power quality to consumers.

There are various types of smart grid technologies that can contribute directly to the reduction of electricity production cost. The reduction of peak demand is the key. Smart grid technologies such as Home energy management system, utility-scale battery storage system, and vehicle-to-grid are investigated in this master thesis in order to reduce the peak demand.

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Chapter 1: Introduction

1.1 Relevance of the topic

In 2037, the electricity consumption in Thailand is expected to increase by 80.8% compare to the consumption in 2018. In order to supply the new demand, new power plants are planned to be built in total of 54 GW. Due to climate change and CO_2 reserve, Thai government plans to increase the share of renewable power generation to 37% of those new power plants and they are prone to be distributed generation (PDP, 2018).

Photovoltaic (PV) is one of the most potential renewable distributed generation in Thailand. In Thailand, sunlight can be expected throughout the year with only small seasonal difference. Together with the falling price of PV panels, PV can be more common in Thailand in the near future.

One major reason for the increase in electricity consumption in 2037 is from the use of electric vehicle (EV). The government has supporting programs in order to promote the use of EV in Thailand. It is expected that by 2037 the number of EVs in Thailand will reach 1.2 million (1.7% of total population as of 2019). The existing of EVs will affect directly to the power grid. They will not only add the additional electricity demand, but also the complexity to the grid in terms of power security and quality (EGAT et al., 2017).

Uncontrolled EV charging can also affect the cost of electricity generation. When a lot of EVs get charged during peak demand period, the demand from EV will add up the previous peak demand. Additional power plants must be operated in order to fulfil the increasing demand. Those power plants usually have high production cost. As a result, electricity generation per unit increases therefore electricity price also increases.

The increase in electricity demand, the increase in the number of distributed generations, and existing of EVs in the future make it challenging for the power grid to balance between power supply and power demand because they have to be equal all the time, otherwise the problems will occur such as overload, power loss, voltage drop, unbalanced load, harmonics, and blackout. In order to prevent those problems, the power grid must be smarter. In other words, Thailand needs to develop its power grid into "Smart Grid".

1.2 Objectives of the thesis

The objectives of this master thesis are as follows:

- To investigate the impact of high penetration of PV systems on the electrical power grid in Thailand
- To predict the future electrical load profile with the consumption from EVs and point out the impacts to the electrical power grid
- To evaluate the profitability of a PV system
- To investigate and suggest how to reduce peak power demand in residential sector
- To evaluate how to mitigate peak demand using utility-scale electricity storage
- To analyze how to charge/discharge EVs and how it will impact the daily peak demand

1.3 Structure of the thesis

This master thesis is structured as following:

- Chapter 2 gives an overview of the basics of smart grid, smart grid components, power quality, energy storage system, electric vehicles.
- Chapter 3 shows method of approach and data retrieval. The power generation from PV systems in Thailand is simulated. The actual electrical load profiles are investigated into 3 sectors; residential load, industrial load, and commercial load.
- In chapter 4, a daily load profile of a city called "Smart City A" is created in order to investigate the impacts of the increase in power demand due to the use of electric vehicles and how the high penetration of photovoltaic systems

affects power grid in 2040. After that, smart grid technologies are investigated and assumed to be implemented in Smart City A in order to reduce daily peak demand.

- Chapter 5 gives the conclusions and suggestions.

Chapter 2: Background Information

2.1 What is Smart grid?

A smart grid is a future electrical grid which is integrated today's grid with many technologies such as renewable technology, communication technology, computer technology, control technology, advanced measurement technology and power distribution technology in order to deliver electricity which is more efficient, reliable, safe, sustainable, and eco-friendly.

The today's grid was designed long time ago as centralized power grid which deliver the electricity only one direction. The electricity is generated in the large power plant which is normally located far away from where the electricity is consumed. The major types of these power plants are fossil fuel based, nuclear, or hydro which can be easily controlled and can generate the electricity continuously. Then the electricity is transferred through the transmission network. The longer the cables are, the more losses are generated. Then the electricity is delivered to the consumers through the distribution network.

The smart grid is quite different. Due to the realization of climate change and global warming, the use of renewable energy is getting more and more popular. The learning curve of the renewable energy makes it more affordable. Solar panel is now very common that it can be seen on many residential roof-tops. The consumer nowadays does not only just consume the electricity from the grid but also produce it and feeds to the grid. As a result, the grid tends to be more decentralized in the future. There are some challenging tasks to operate this grid. For example, planning electricity supply gets more difficult with the renewable sources because they are unreliable. No one can guarantee if the sun will shine or the wind will blow at a certain point of time. And that affects the whole electricity system since the supply side must be equal to the demand side at any time. Otherwise, it will affect the system's voltage and frequency which are to be controlled as steady as possible.

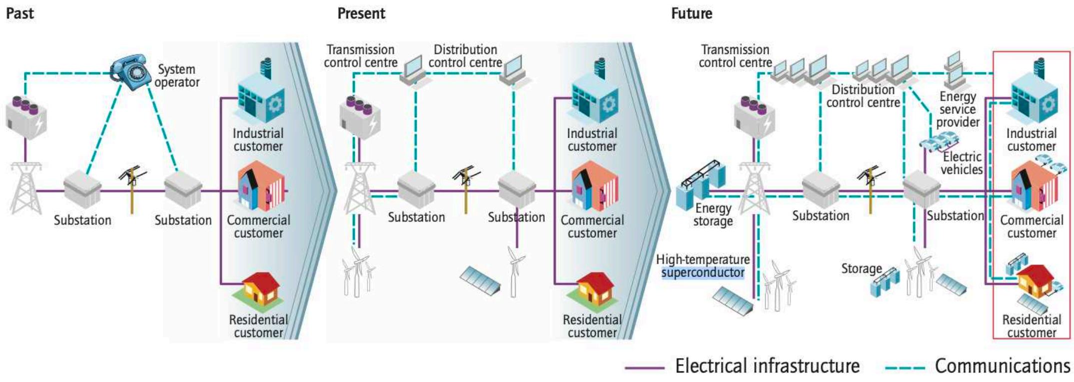


Figure 1: Smarter electricity system

Source: IEA, 2011

Figure 1 shows the evolution of electricity system suggested by IEA. The Future scenario in this Figure portrays the electricity system of a Smart grid. The power generations from renewable resources are prominent. Consumers produce electricity using PV panels. Storage systems store electricity during the period where the power production from renewable resources exceeds power demand and supplies later when the demand increases. People in the future tend to use electric vehicles as their personal cars. In this electricity system, smart grid controller controls components in the grid via communication system which connects all components in the grid.

According to International Energy Agency (IEA), a smart grid should have the characteristics as following:

1. Enables informed participation by customers: Electricity consumers take part on supply and demand balancing. The consumers change their habits of consuming electricity. There will be more different choices of purchasing electricity on the market regarding new technology, information, pricing pattern, and supporting schemes.

2. Accommodates all generation and storage options: All types of electricity generation either large-scale or small-scale, either centralized power plants or distributed generation can be fit in a smart grid. Together with renewable power plants and energy storage systems, this will exist widely in the electricity value chain, from producers to consumers.

3. Enables new products, services and markets: Grid variables such as energy, capacity, time, and quality can be managed using marketing mechanism. The well-designed electricity markets in smart grid allow consumers to choose among those competing services. Smart grid offers the flexibility to improve the way of doing business to every party in the market chain.

4. Provides the power quality for the range of needs: In a smart grid, the quality of power supply can be customized concerning the needs of individual customers. There are various types of electrical load. Some of which are more sensitive than the others. Smart grid, using advanced control approach, can offer the premium power which is supplied to those customers who require high quality of power supply. Higher price of electricity can be expected.

5. Optimizes asset utilization and operating efficiency: A smart grid uses advanced technologies that help increasing the utilization of its assets. For instance, dynamic rating pushes assets to be used beyond their usual limits. This helps increasing the grid capacity. Condition-based maintenance allows smart grid to increase its maintenance efficiency using advanced censoring systems that monitor the equipment condition and provide the maintenance plan at the right moment. Advanced system-control devices help minimizes losses and congestions within the system. Electricity delivery cost can be reduced by choosing the low power-delivery system. As a result, the operating efficiency increases.

6. Increase overall system reliability: When it comes to catastrophic events such as big flooding or tornado, the self-healing technology of smart grid cuts fault equipment out of the system immediately that allow the other parts of the system continue operating normally. This results in less interruption of services. (IEA, 2011)

2.2 Grid components

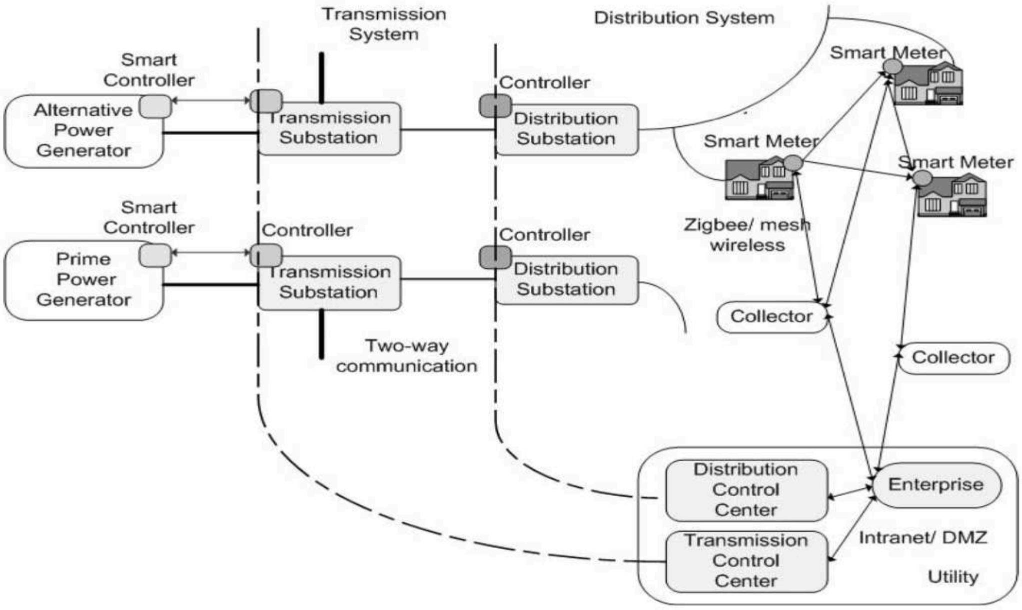


Figure 2: Block diagram of smart grid components

Source: Mavridou et. al., 2012

Figure 2 shows a block diagram of smart grid components. Smart grid components consist of electric power generators, electric power substations, transmission and distribution lines, controllers, smart meters, collector nodes, distribution and transmission control centers, and storage systems (Mavridou et. al., 2012).

Unlike the traditional centralized electricity generation, the newly to be installed electricity generation in smart grid is usually distributed as small-scale power plants which are situated close to the loads in order to minimize transmission loss. Sources of electricity generation in the future smart grid are usually come from the renewable resources such as wind energy, solar energy, bioenergy, and small hydropower plant. Fossil fuel power plants such as diesel engine will only be used as back-up power plants or just for the grid stabilization purposes, or in the peak period that the electricity generation from renewable sources cannot supply the overall demand.

Smart grid controller is a component that makes smart grid smarter than the traditional grid. It controls other components in the grid. The controller will collect data from other components within the grid then calculate and analyze for an optimum point for the grid. The criteria for the optimum point can be set and adjusted in dimensions of effectiveness, safety, stability and so on. After the analysis, the smart grid controller will give the command of actions to other components within the grid, so that every component in the grid will operate harmoniously. It manages the electricity generation and electricity consumption within the grid. Self-consumption of the electricity produced within the grid is set as top priority. The controller also controls the storage systems whether they should be charged or discharged in a certain time. Advanced smart grid controller can also work with the weather forecast and predict power output from renewable sources and use the prediction to manage the electricity generation, consumption and storage within the grid.

Smart meter transfer information between electricity producers and consumers. On one hand, it notifies actual consumption of each consumer to the utility. This allows the utility to create automatic billing system. Smart meter can also detect device failures and send signal to notify the utility. As a result, the utility operators can solve those problems more quickly. On the other hand, smart meter transfers information of real-time electricity price to consumers. This allows consumers to manage the use of their devices (Mavriodou et. al., 2012).

Electrical appliances used in smart grid tend to be intelligent appliances. They can be operated automatically on schedule based on consumer's preferences. Some appliances can be programmed to operate only during non-peak demand period when the electricity price is low. This helps not only consumers to manage their own electrical bills, but also the overall system to reduce peak loads. This also affects directly to the reduction of electricity generation costs. (Jagtap, 2018)

Storage system stores the excess energy during the time when the electricity supply is greater than electricity demand and releases the electricity to the grid when the electricity demand is higher than supply. Furthermore, the storage systems can also be used to stabilize the grid and maintain voltage and frequency in order to deliver good quality of electricity. There are various types of storage systems that can be used in smart grid such as battery, small pumped hydropower, or small compressed air energy storage. The potential of each type depends on where the grid is located.

A smart grid can be totally different from one another depending on a number of components within the grid. Moreover, a number of generations, types of consumers, a number of storage systems are factors that make an individual grid has different performances.

2.3 Quality of power supply

The quality of power supply can be defined as the capability of energy source that supply power properly to an electrical equipment which is connected to a supply network. The two primary components of supply quality are continuity and voltage level. Continuity is the consistency of power supply which should be available to the consumers all the time. Voltage level should be maintained within a specific range, consistent amplitude with proper sine waveform and proper frequency (Antony, 2018).

The most common phenomena that degrade power quality are harmonics, voltage fluctuations, voltage dips, unbalanced voltages, and transient over voltages (Antony, 2018).

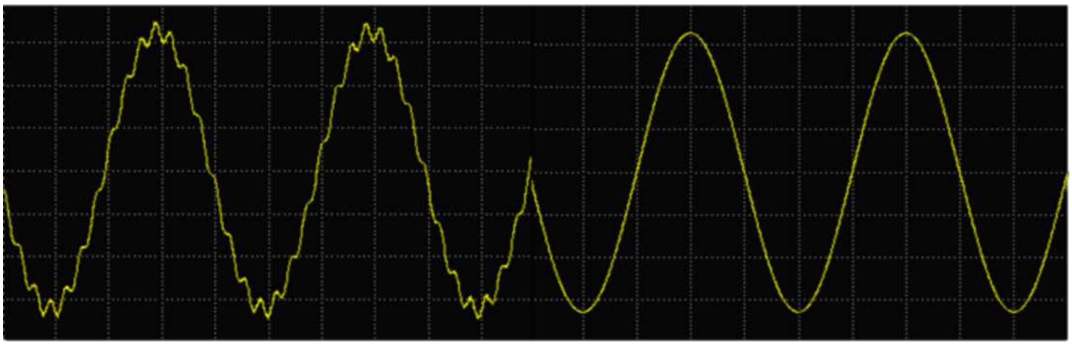


Figure 3: Voltage waveform with harmonics (left) and ideal voltage waveform (right)

Source: Antony, 2018

Figure 3 shows, on the left-hand side, a poor-quality voltage waveform with harmonics compare to, on the right-hand side, an ideal voltage waveform. The negative effects of harmonics to the electrical loads. For example, they heat up conductors in the equipment that would result in shorten equipment's lifetime.

Power quality is the same as voltage quality. It has to be controlled because it has economic value. For example, poor quality of voltage can cause direct economic impacts many industrial consumers, especially ones with more automation and more modern equipment which means more electronic devices. These devices are very sensitive to deviations in supply voltage. A small disturbance of supply voltage can result in a malfunction of electronic devices which can cause a downtime of production line. So industrial consumers would nowadays pay more attention to the small disturbances in the power system (Dugan, 2003).

The balance of power demand and supply is one major part to maintain power quality. The amount of electricity fed into the grid must always be equal to the amount of electricity consumed. If the electricity fed into the grid is more than it is consumed, the voltage will increase so as frequency. This can cause damage to electrical devices. If frequency increases to a certain level, there will be a risk that power plants will disconnect to the grid after a period of time. On the other hand, if the electricity fed into the grid is less than it is consumed, in this case the frequency will drop and so as the voltage. In this case, electrical devices cannot function properly. So it is very important to balance power supply and demand all the time (Antony, 2018).

2.4 Mixture of power supplies

Power supply has to be equal to demand in every second. Power supply is a total power generated from many power plants in a certain moment. The mixture of those power plants affects the cost of electricity production because each power plant has different cost of production. For example, electricity produced from wind power plants is cheaper than electricity produced from diesel engine power plant because wind is for free while diesel is considered expensive. In a certain period, if power supply comes from power plants that has low electricity production cost, it can be assumed that the electricity price at that period will be low. On the other hand, if the next hours later the demand increases, the additional power plants which have higher production cost have to operate, the electricity price at that time will be higher.

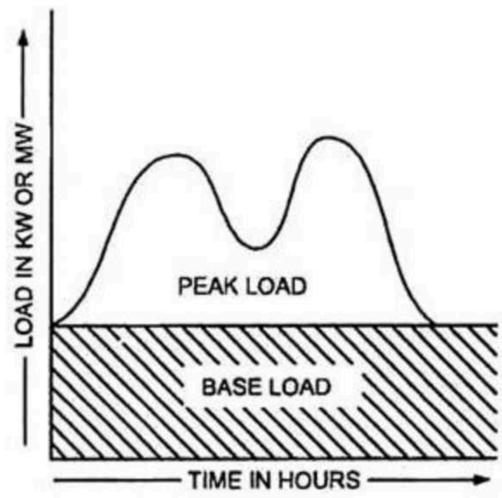


Figure 4: Base load and peak load

Source: Engineeringnotes, 2019

In a power system, power plants can be defined as base load power plant or peak load power plant. Base load power plants are the plants that operate continuously to meet the minimum level of power demand 24/7 (see Figure 4). Base load power plants are designed to supply power at a constant rate. Normally they are large-scale and cannot response to the change in electricity demand so well. They can be either renewable power plants or non-renewable power plants. The base load power plants should have low electricity generation cost, they should be able to operate continuously for a long term, and they should require only a few operators in order to minimize the operating cost. On the other hand, peak load power plants are designed to serve peak demand. They should be able to response quickly to the changing loads and also easy to start or stop. This type of power plants usually has high electricity generation cost. (Engineeringnotes, 2019).

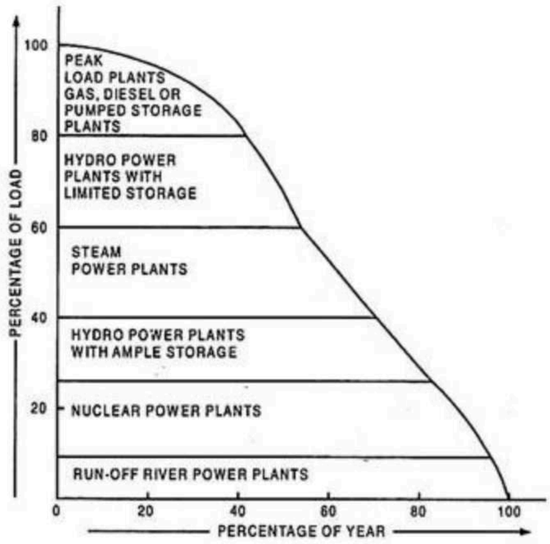


Figure 5: Example of a typical load allocation to various power stations

Source: Engineeringnotes, 2019

Figure 5 shows an example of a typical load allocation to various power stations. Hydro power plants should be served as base load power plants due to the high capital cost and very low operating cost. During draught period, they can also be served as peak load power plants. Steam power plants have the lowest cost of electricity generation per unit when they are served as base load power plants. Nuclear power plants are appropriate only for base load. Gas turbine power plants should be served as peak load power plants. Diesel engine power plants are used to be served widely as peak load power plants, but nowadays they are less likely to be operated for that purposes due to the uneconomical production costs. (Engineeringnotes, 2019).

2.5 Electricity storage system

According to International Renewable Energy Agency (IRENA), there are various types of electricity storage system worldwide such as electro-chemical storage, electro-chemical storage, pumped hydro storage, and thermal storage. In 2017, electricity storage worldwide is estimated 4.76 TWh. Pumped hydro storage plays a major role as it accounts for 96% of total. In 2030, the demand of electricity storage is estimated to increase to 11.89-15.72 TWh (155-227% higher than in 2017) and pumped hydro storage capacity will increase by 1.56-2.34 TWh above 2017. However, the share of pumped hydro storage will fall to 45-51% by 2030 due to the more rapid growth of other sources of electricity storage. In IRENA's double share of renewable energy 2030 case shows that the electricity storage will increase in transport sector due to the increasing number of EVs on the road, concentrating solar power is needed at larger scale. Together with the dropping cost of battery that enables new business opportunities such as utility-scale battery systems and the electricity storage systems for solar rooftop PV to be on the market. As a result, non-pumped hydro electricity storage is expected to increase from 162 GWh in 2017 to 5.8-8.4 TWh in 2030. (IRENA, 2017).

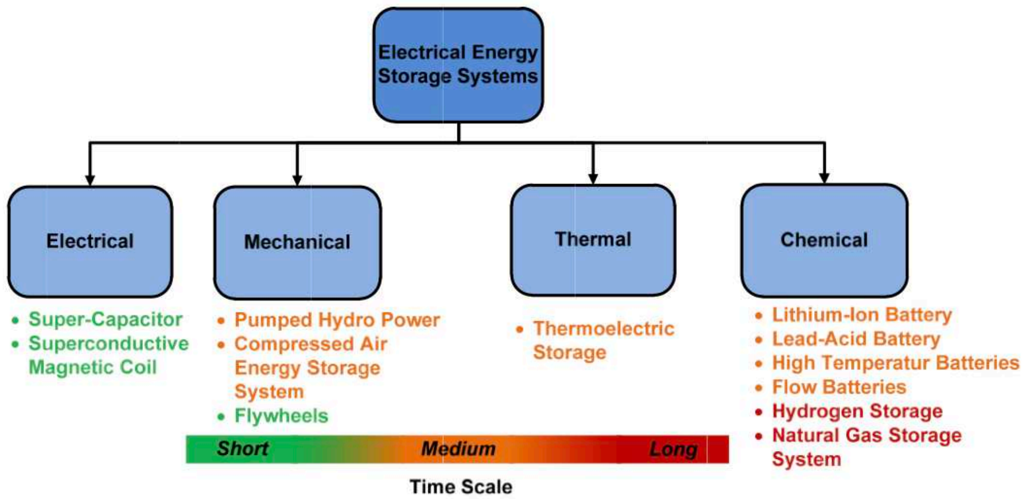


Figure 6: Energy storage technologies classification

Source: Fuchs G. et al., 2012

Figure 6 shows a classification of different energy storage technologies categorized by their work principle and typical time scale of application. The time scale indicates the typical energy to power ratio of the technologies and corresponds to the typical time of charging and discharging (Fuchs G. et al., 2012).

The most quickly expanding electricity storage on the market is electro-chemical storage. There are various technologies of this type of storage system that have high potential. Among those, the most speedily growing one is Li-ion batteries which has the biggest share of 59% of installed capacity in 2017. (IRENA,2017)

The main reason why electro-chemical storage, especially battery, is expected to get widespread acceptance over pumped-hydro storage in the future is that batteries are more adaptable in terms of sizing and location. They can be installed right next to the desired locations. Pump hydro storage, on the other hand, can only be installed on a limited location where it has the advantage of geological height differences such as up in the mountains where it has running water. (IRENA, 2019)

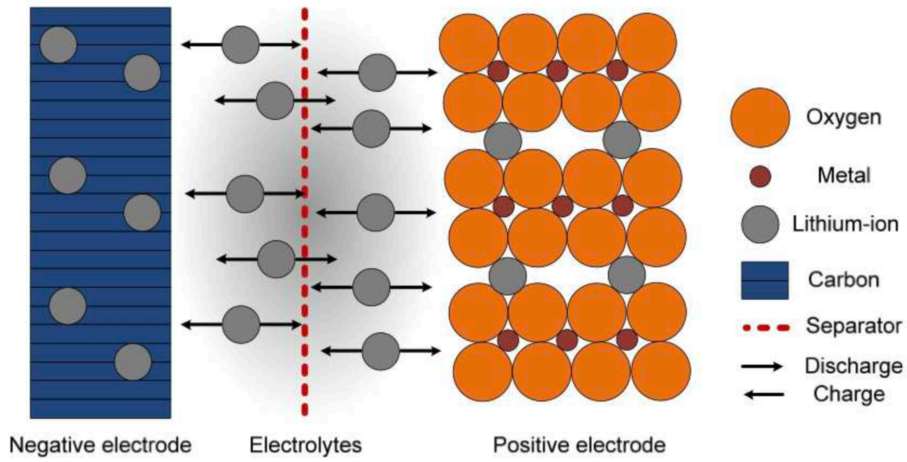


Figure 7: Charge and discharge process in a Li-ion cell

Source: Fuchs G. et al., 2012

Figure 7 shows Principle of the discharge and charge process in a Lithium-Ion cell based on a LiMeO2 cathode material and a carbon-based anode. Li-ion battery composes of negative electrode, electrolyte, and positive electrode. The negative electrode, or cathode, is made of graphite. The positive electrode, or anode, is made of lithiated metal oxide. Between cathode and anode is filled with electrolyte which allows ion to flow freely between two electrodes. When the device is plugged to a fully charged battery, positive ions from anode will try to travel to cathode.

Electrolyte blocks the electrons from travelling the same path so they use the pathway where the device is located. This is how the device gets powered. This process can be reversed during the recharging process. Li-ion batteries can be used for both medium-term and short-term electricity storage. They are popular not only for small devices such as smartphones, tablets, and laptops, but also for electric vehicles. In the future, they are assumed to be used more in stationary applications. They are several prototypes projects in the field of Li-ion battery. The different combinations of electrolytes and materials used for electrodes result in different characteristics of battery. The main focus of those going on researches are battery cost reduction, life span expansion, and safety. (Fuchs G. et al., 2012)

Table 1: Parameters for Li-ion battery

Parameters for Lithium-Ion Batteries	All numbers are indications and my vary significantly among different products and installations	
	Today	**2030**
Round-trip efficiency	83 % to 86 %	85 % to 92 %
Energy density	200 Wh/ l to 350 Wh/ l	250 Wh/ l to 550 Wh/ l
Power density	100 W/ l to 3500 W/ l[23]	100 W/l to 5000 W/l
Cycle life	1,000 to 5,000 (full cycles)[24]	3,000 to 10,000 (full cycles)
Calendar Life	5 years to 20 years (depending on temperature and SOC)	10 years to 30 years (depending on temperature and SOC)
Depth of discharge	Up to 100 %	Up to 100 %
Self-discharge	5 % per month	1 % per month
Power installation cost (converter)	150 €/ kW to 200 €/ kW	35 €/ kW to 65 €/ kW
Energy installation cost	300 €/ kWh to 800 €/ kWh	150 €/ kWh to 300 €/ kWh
Deployment time	3 ms to 5 ms	
Site requirements	None	
Main applications	Frequency control, Voltage control, Peak shaving, Load leveling, Electromobility, Residential storage systems	

Source: Fuchs G. et al., 2012

Definition of parameters:

- **Storage capacity** is the maximum amount of electricity in kWh that can be kept in the storage system.
- **Energy density** is the amount of energy in kWh divided by the volume of the storage system in m3. Energy density is one of main design factors of a storage system. For example, a project with a limited space should be designed using an energy storage system which has high energy density.
- **Power density** is the power in W divided by the volume of the storage system in m3. This parameter is important for those applications which require a certain flow of energy over a certain period. For example, hybrid electric vehicles require high power density in order to be able to meet the designed acceleration.
- **Cycle life** of battery is defined by the number of times when a battery is fully charged and discharged as a cycle until it loses the particularized criteria.
- **Depth of discharge (DoD)** of a battery is defined by the amount of energy that get discharged from the fully charged battery. 100% depth of discharge means a fully charged battery discharges all of its stored energy. 100% depth of discharge is not allowed in many storage technologies because of the technical limitations.
- **Self-discharge** is when a battery discharges itself without being connected to the load. (Fuchs G. et al., 2012)

Table 2: SWOT analysis of Li-ion battery

	Lithium-Ion-Battery	
	Strengths	**Weaknesses**
Internal	• High energy density • Long lifetime • High performance	• No inherent security (thermal runaway) • Sophisticated battery management system required (single cell monitoring) • Packaging and cooling costly depending on the cell shape • High costs
	Opportunities	**Threats**
External	• High number of items in the automotive industry lead to faster cost reduction • No special requirements for storage location (no gassing)	• Social acceptance problems due to lithium mining in problematic countries possible • Lithium resources limited to only few countries • High energy and power densities represent a low added value in most stationary applications

Source: Fuchs G. et al., 2012

2.6 Electric Vehicle (EV)

Electric mobility is expanding rapidly. According to International Energy Agency (IEA, 2019), the number of electric cars in 2018 worldwide is 5.1 million, increases from 2017 by 2 million (IEA, 2019). Electric vehicles add new electricity demand to transport sector. Changing from fossil-fuel based vehicles to electric vehicle helps get rid of pollutions caused by using fossil-fuel based vehicles in the city. For example, electric vehicles have zero tailpipe emissions so the city will get less air pollution. Electric vehicles can also have lower CO2 emission. This depends on how clean the electricity is in that certain area. For example, an electric car which consumes electricity from a decarbonized grid would emit less CO2 compare to another electric car which consumes electricity from an electrical grid which has coal power plants as major power supplies. Having additional electricity demand from electric vehicles can also be seen as an opportunity to add more renewable power plants to the electrical grid so that the total emission by electric vehicles can be minimized. (IRENA, 2017)

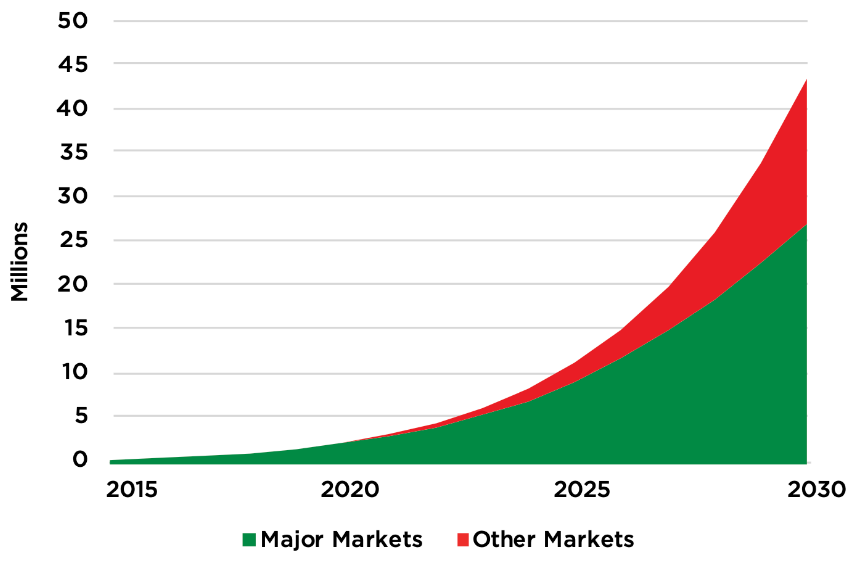


Figure 8: Global annual EV sales to 2030

Source: IRENA, 2017

Major market consists of OECD countries plus China

Figure 8 shows the projection of global annual EV sales to 2030 by International Renewable Energy Agency (IRENA). The rapid growth during 2020 to 2025 suggests that the "tipping point" may occur which means EVs are mass market and its market share will rapidly increase after the tipping point. The figure suggests that in 2030 EVs would have 40% market share and by 2040 they would become the majority on the market.

In recent years, two major types of EV have dominated the EV market worldwide. Both two have very efficient electric motors and offer zero tailpipe emissions. These are:

1. Battery electric vehicle (BEV): this type of EV has battery as its energy storage. The battery recharging process occurs when EV is plugged in to the charging station. The size of battery influences directly to the driving distance. Most recent models offer driving range around 250 km per charge which is considered limited because it cannot cover normal and long distance. However, the up-coming models are expected to be more practical that they offer up to 400 km driving distance per charge.
2. Plug-in hybrid electric vehicle (PHEV): this type of EV has both liquid-fuel tank and battery. The driving distance of PHEV is 500 km thanks to the availability of two types of energy storages. (IRENA, 2017)

The increasing number of EV affects directly to electrical grid because it is considered as an additional power demand. The grid operators must make sure that the additional demand from EV get supplied all the time the EVs are charged.

Chapter 3: Method of approach and data used

3.1 Literature review

A thorough literature review has been conducted in the last chapter background in formation. Scientific publications and peer-reviewed papers regarding smart grid technologies are mainly acquired from online database from trustworthy sites such as International Renewable Energy Agency (IRENA), International Energy Agency (IEA), RWTH Aachen University, and official sites provided by Thai government. Information on the basic of electrical grid and quality of power supply is primarily taken from the presentation of Mr. Anthony Zegers, a lecturer at TU Vienna who gives lectures on Grid integration of renewables and the concept of Smart Grids.

3.2 Steps of investigation and data acquisition

3.2.1 Climate data and PV output

In this project, the solar irradiation in Thailand is acquired from Solargis, who also provide Global radiation map using satellite historical data. Its methodology is semi-empirical and satellite-derived, relying on validated, published models to build a clear sky model, and uses a proprietary cloud detection model. The model's resolution is around 4 km^2 grid (Solargis, 2019).

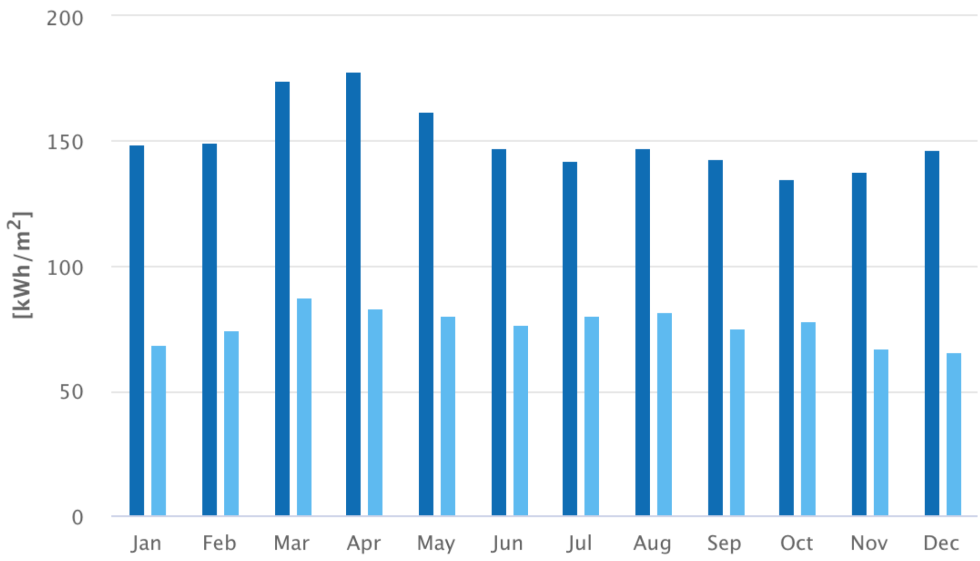


Figure 9:Global and diffuse horizontal irradiation in Thailand

Source: Solargis, 2019

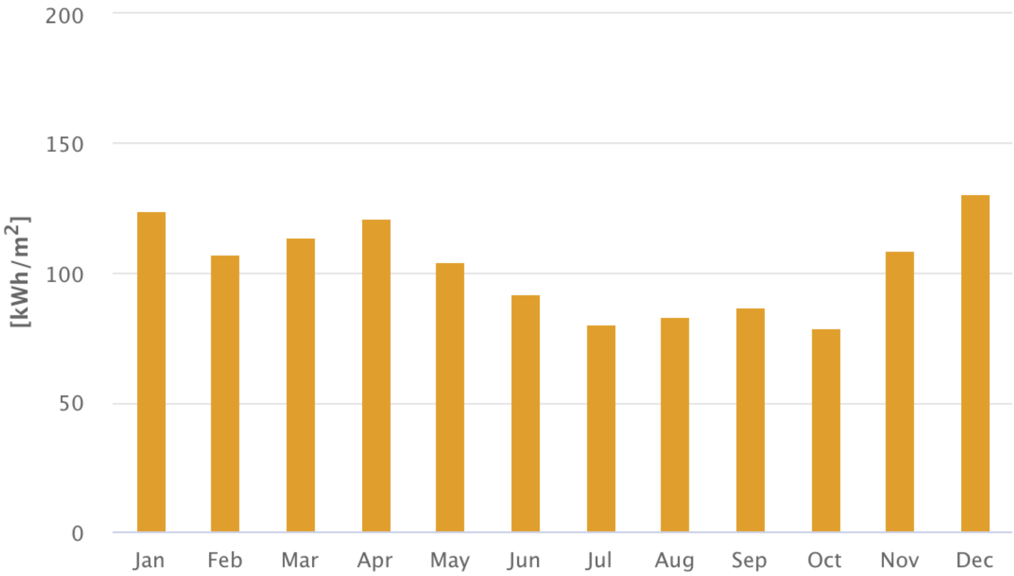


Figure 10:Direct normal irradiation in Thailand

Source: Solargis, 2019

Figure 10 shows solar irradiation in Thailand. As Thailand is situated in the tropical zone, therefore, it has abundant of sunshine. Throughout the year, there is no big difference of daily sunshine hour. Even in winter, it still has a lot of sunshine hour. Therefore, the balance of electricity production in this country can be optimized easier than those, such as Europe or North America, who has big difference of daily sunshine hour throughout the year. Note that the drop of direct normal radiation from July to October is due to the raining season where it has periods that direct radiation is blocked.

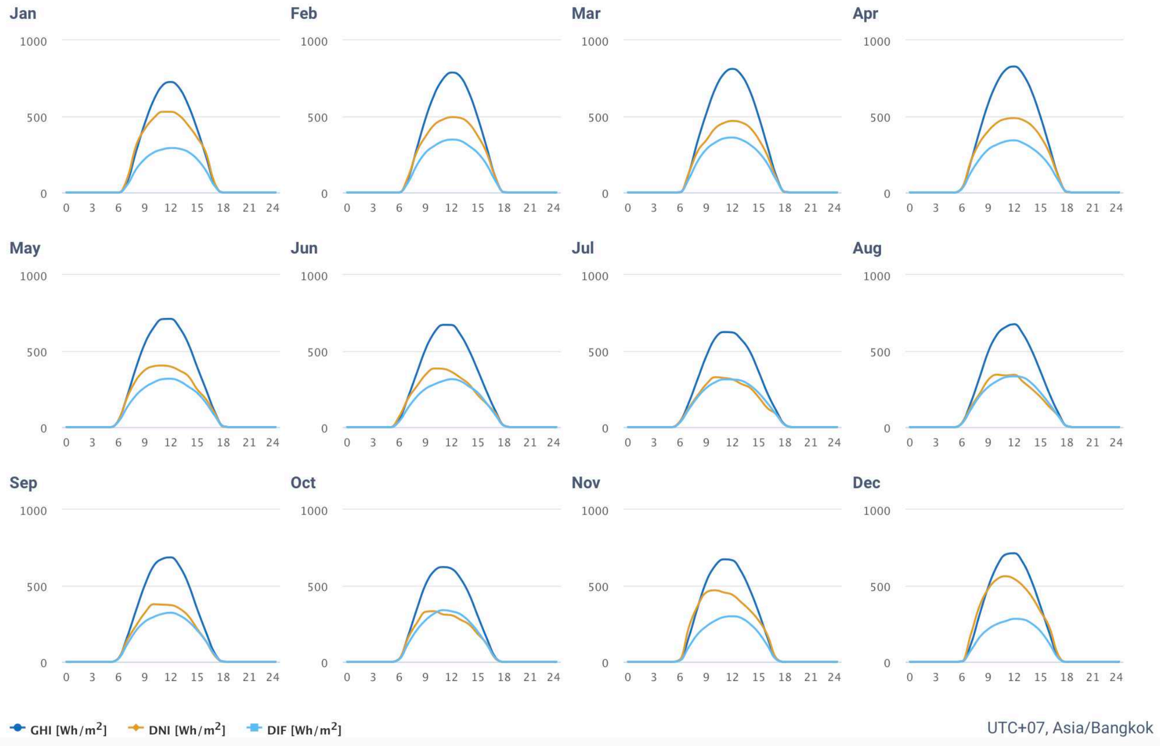


Figure 11:Average hourly irradiations in Thailand

Source: Solargis, 2019

There are three types of irradiation. First, direct normal irradiation (DNI) is the solar irradiation received from the sun without having been scattered by the atmosphere. Second, diffuse horizontal irradiation (DIF) is the solar radiation which has been absorbed, scattered by molecules, aerosols, and clouds within the atmosphere. Third, global horizontal irradiation (GHI) is the sum of direct normal irradiation, diffuse horizontal irradiation, and ground-reflected radiation which can be used to generate electricity by PV cells (Weiss, 2018).

In order to simulate the PV output, it is assumed in this project that there are three major types of PV electricity generations in Thailand, Residential Roof-top PV system (RR-PV), Industrial Roof-top PV system (IR-PV), and Ground based Fixed-mounted PV system (GF-PV).

Table 3: Input data for PV output simulation

input data	RR-PV	IR-PV	GF-PV
installed capacity	3 kWp	80 kWp	1000 kWp
PV module type	crystalline silicon	crystalline silicon	crystalline silicon
Tilt	35°	20°	15°
inverter type	small	string	string
inverter efficiency	95.90%	96.40%	96.40%
transformer type	None	standard (1% loss)	high efficiency(loss 0.9%)
soiling losses	3.50%	3.50%	3.50%
system availability	97%	98%	99.50%

Source: Sarun, 2019

According to a PV expert in Thailand, single houses in Thailand normally have tilt angle between 30-40°, therefore, 35° is selected as input data for Household Roof-top PV(HR-PV). The area of their roof-tops which is suitable for PV installation is around 20 m^2 which can be used to installed PV panels up to 3 kWp which is directly connected to a low voltage grid through an inverter. Industry's roofs have tilt angle around 20° (Sarun, 2019). For Ground based fixed-mounted PV, theoretically, the most efficient tilt angle would be 0° but in order to create self-cleaning effect- effect that the rain washes PV modules and leaves minimal water on them, the tilt angle should be at least 15° (Fechner, 2018).

PV-output of three PV systems in Thailand is simulated using Solargis online simulation. These outputs have been taken theoretical losses due to energy conversion in the PV power system into account recommended by Solargis.

Table 4: Theoretical losses due to energy conversion in PV systems

	RR-PV	IR-PV	GF-PV
solar losses			
dirt, dust and soiling	-3.5%	-3.5%	-3.5%
angular reflectivity	-3.2%	-3.1%	-3.1%
electric system losses			
spectral correction	0.5%	0.5%	0.5%
converstion of solar radiation to DC in the modules	-11.7%	-11.3%	-10.4%
electrical losses due to inter-row shading	0.0%	-0.9%	-0.5%
mismatch mand cabling in DC section	-1.8%	-1.5%	-2.3%
inverters (DC/AC) conversion	-4.5%	-3.9%	-3.8%
transfrmer and AC cabling losses	-0.2%	-1.4%	-1.4%
technical availabiity	-3.0%	-2.0%	-0.5%

Source: Solargis, 2019

Definition of each theoretical losses due to energy conversion in PV systems.

- Dirt, dust and soiling - Optical losses of solar radiation at the level of surface of PV modules due to surface pollution
- Angular reflectivity - Optical losses from angular reflectivity (angle of incidence effects) on the surface of PV modules where the magnitude of effects depends on the relative position of the sun, plane of the module, and type and cleanliness of the modules surface.
- Spectral correction - Losses in the energy conversion process caused by spectral mismatch between the properties of the semiconductor material and light spectrum
- Conversion of solar radiation to DC in the modules - Photovoltaic conversion of irradiation into electricity in semiconductor material. The conversion efficiency is non-linear and depends on the distribution of both irradiation and temperature values
- Electrical losses due to inter-row shading - Losses of electricity due to a decrease in irradiation, which is caused by the preceding rows of PV modules blocking the irradiation.
- Mismatch and cabling in DC section - Losses of electricity caused by the mismatch of different MPP operating points of modules connected into an

inverter and heat losses in the direct current (DC) interconnections and cables.

- Inverters (DC/AC) conversion - Losses in inverter due to the efficiency of the conversion process from direct to alternate current. If inverter contains built-in transformer, its efficiency is included in this parameter.
- Transformer and AC cabling losses - External MV or HV transformer electricity losses and heat losses in alternate current (AC) cabling and connections. This parameter includes losses in AC cables on the low-voltage side, losses in AC cables on the medium (high) voltage side (up to grid connection point with electricity meter), and also on all devices which are in the path of AC current produced by inverters (Solargis, 2019).

Monthly PV output of three PV systems in Thailand is simulated using Solargis PV simulation software which uses satellite-derived irradiation as shown in three following figures. The patterns of three figures are quite similar. They experience decreases of electricity production due to raining season. The amount of electricity generation in kWh of each PV system is different from one another due to the differences of installed capacity of each system.

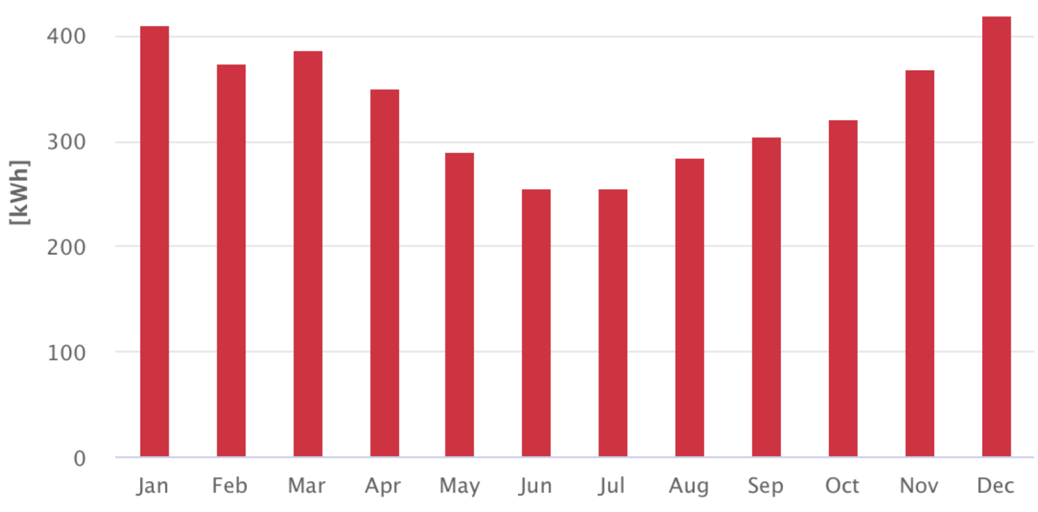


Figure 12: Monthly PV output for a Residential Roof-top PV

Source: Own calculations

Figure 12 shows the simulated monthly PV output for a Residential Roof-top PV system. The annual PV output for this system is 4,020 kWh. The maximum output occurs in December with the output value of 419 kWh. The minimum output occurs in June and July with the output value of 255 kWh.

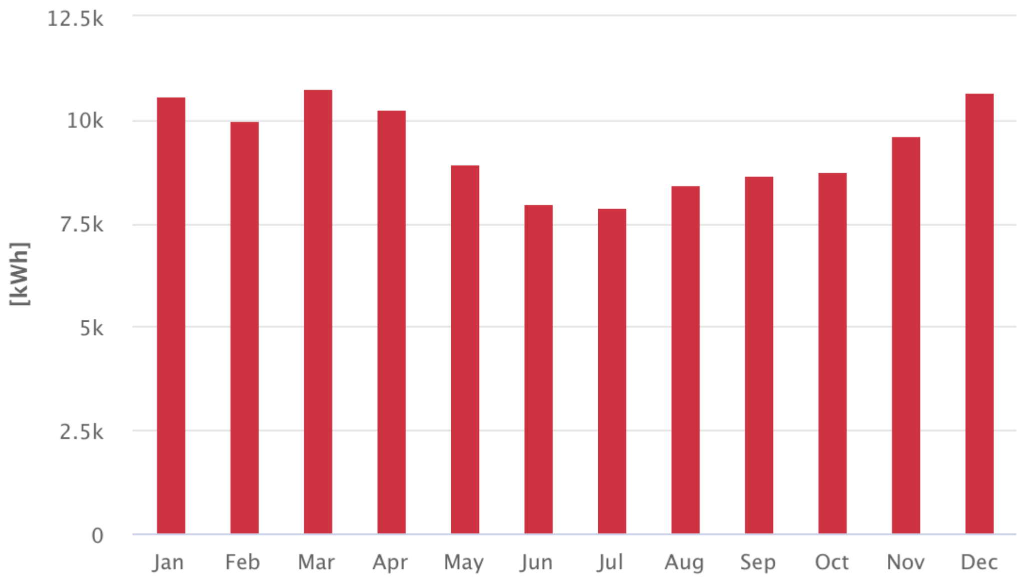


Figure 13: Monthly PV output for an Industrial Roof-top PV

Source: Own calculations

Figure 13 shows the simulated monthly PV output for an Industrial Roof-top PV system. The annual PV output for this system is 112,536 kWh. The maximum output occurs in March with the output value of 10,755 kWh. The minimum output occurs in July with the output value of 7,875 kWh.

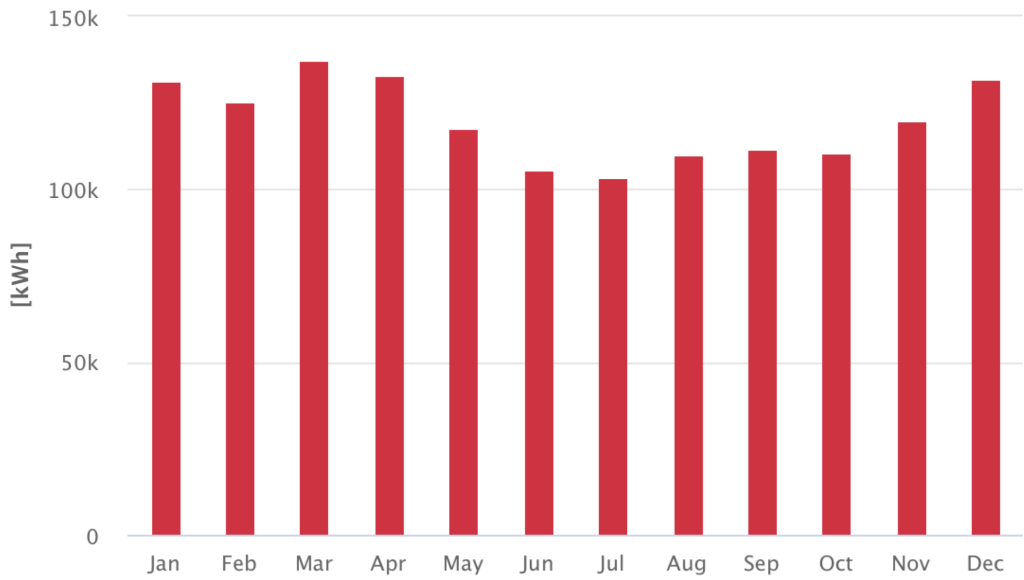


Figure 14: Monthly PV output for Ground based Fixed-mounted PV

Source: Own calculations

Figure 14 shows the simulated monthly PV output for a Ground based Fixed-mounted PV system. The annual PV output for this system is 1,439,277 MWh. The maximum output occurs in March with the output value of 137,417 MWh. The minimum output occurs in July with the output value of 103,697 MWh.

Hourly averages of specific PV output of the three PV systems is also simulated as following:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	-	-	-	-	-	-	-	-	-	-	-	-
1 - 2	-	-	-	-	-	-	-	-	-	-	-	-
2 - 3	-	-	-	-	-	-	-	-	-	-	-	-
3 - 4	-	-	-	-	-	-	-	-	-	-	-	-
4 - 5	-	-	-	-	-	-	-	-	-	-	-	-
5 - 6	-	-	-	-	-	-	-	-	-	-	-	-
6 - 7	-	-	-	14	21	21	16	12	13	14	10	1
7 - 8	76	81	94	120	106	92	82	91	114	143	171	133
8 - 9	281	263	260	267	229	196	181	208	247	290	349	334
9 - 10	439	422	396	394	334	298	281	324	368	415	486	491
10 - 11	556	539	508	484	403	369	357	400	454	474	556	595
11 - 12	625	608	573	535	440	402	386	432	483	485	578	645
12 - 13	635	633	590	544	439	402	383	442	486	473	567	642
13 - 14	600	614	564	511	401	364	354	399	447	428	507	590
14 - 15	514	538	493	437	333	297	302	327	365	350	415	491
15 - 16	390	414	374	325	236	214	217	234	248	237	296	353
16 - 17	238	259	227	191	137	124	126	135	135	123	152	198
17 - 18	53	85	76	61	48	49	53	51	34	19	17	32
18 - 19	-	-	1	2	2	4	6	3	-	-	-	-
19 - 20	-	-	-	-	-	-	-	-	-	-	-	-
20 - 21	-	-	-	-	-	-	-	-	-	-	-	-
21 - 22	-	-	-	-	-	-	-	-	-	-	-	-
22 - 23	-	-	-	-	-	-	-	-	-	-	-	-
23 - 24	-	-	-	-	-	-	-	-	-	-	-	-
Sum	**4407**	**4456**	**4156**	**3885**	**3129**	**2832**	**2744**	**3058**	**3394**	**3451**	**4104**	**4505**

Figure 15:Hourly averages [Wh/kWp] specific PV output of a Residential Roof-top PV

Source: Own calculations

Figure 15 shows simulated hourly average specific PV output of a Residential Roof-top PV in Wh/kWp. The maximum specific PV output of each month occurs between 11:00 to 13:00 with the maximum output value of 645 Wh/kWp in December and the minimum output value of 383 Wh/kWp in July. (See more in Appendix 1)

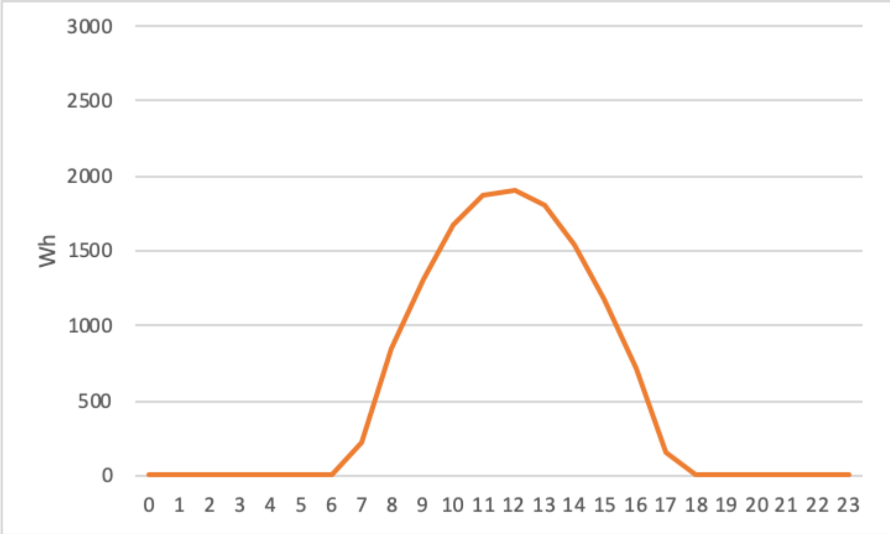


Figure 16: Hourly simulated production of Residential Roof-top PV

Source: Own calculations

Figure 16 shows a simulated PV output of a Residential Roof-top PV within a day. The PV production starts from 6:00 to 18:00. The total output is 13,222 Wh a day. The maximum output occurs between 12:00 to 13:00. Production during this hour is 1,904 Wh.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	-	-	-	-	-	-	-	-	-	-	-	-
1 - 2	-	-	-	-	-	-	-	-	-	-	-	-
2 - 3	-	-	-	-	-	-	-	-	-	-	-	-
3 - 4	-	-	-	-	-	-	-	-	-	-	-	-
4 - 5	-	-	-	-	-	-	-	-	-	-	-	-
5 - 6	-	-	-	-	-	-	-	-	-	-	-	-
6 - 7	-	-	1	19	27	27	21	17	16	15	10	1
7 - 8	69	79	101	142	135	123	105	111	126	145	158	118
8 - 9	263	259	273	299	273	242	219	238	266	295	335	310
9 - 10	421	420	413	432	385	353	328	362	391	421	473	466
10 - 11	540	539	528	526	457	428	409	442	480	483	546	572
11 - 12	610	610	595	579	493	461	436	474	510	495	570	624
12 - 13	621	635	613	588	492	459	432	483	514	483	560	623
13 - 14	587	616	586	554	452	416	400	438	473	436	501	571
14 - 15	500	538	512	476	379	345	345	361	388	358	408	473
15 - 16	376	413	390	360	275	254	253	262	266	244	288	335
16 - 17	225	257	239	218	167	155	152	157	149	127	145	183
17 - 18	50	85	83	74	63	64	68	63	40	21	16	30
18 - 19	-	1	2	3	3	5	8	4	1	-	-	-
19 - 20	-	-	-	-	-	-	-	-	-	-	-	-
20 - 21	-	-	-	-	-	-	-	-	-	-	-	-
21 - 22	-	-	-	-	-	-	-	-	-	-	-	-
22 - 23	-	-	-	-	-	-	-	-	-	-	-	-
23 - 24	-	-	-	-	-	-	-	-	-	-	-	-
Sum	**4262**	**4452**	**4336**	**4270**	**3601**	**3332**	**3176**	**3412**	**3620**	**3523**	**4010**	**4306**

Figure 17: Hourly averages [Wh/kWp] specific PV output of an Industrial Roof-top PV

Source: Own calculations

Figure 17 shows simulated hourly average specific PV output of an Industrial Roof-top PV in Wh/kWp. The maximum specific PV output of each month occurs between 11:00 to 13:00 with the maximum output value of 624 Wh/kWp in December and the minimum output value of 432 Wh/kWp in July. (See more in Appendix 2)

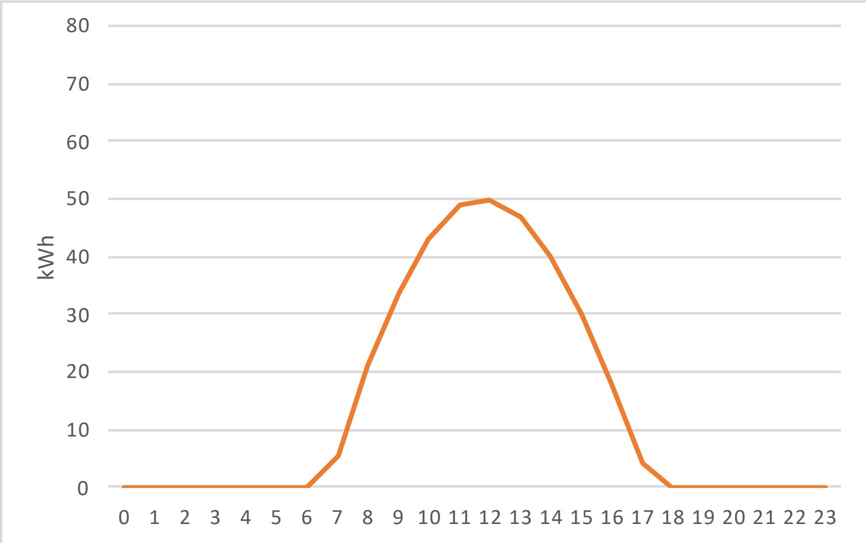


Figure 18: Hourly simulated production of an Industrial Roof-top PV

Source: Own calculations

Figure 18 shows a simulated PV output of an Industrial Roof-top PV system within a day. The PV production starts from 6:00 to 18:00. The total output is 341,025 kWh a day. The maximum output occurs between 12:00 to 13:00. Production during this hour is 49,678 kWh.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	-	-	-	-	-	-	-	-	-	-	-	-
1 - 2	-	-	-	-	-	-	-	-	-	-	-	-
2 - 3	-	-	-	-	-	-	-	-	-	-	-	-
3 - 4	-	-	-	-	-	-	-	-	-	-	-	-
4 - 5	-	-	-	-	-	-	-	-	-	-	-	-
5 - 6	-	-	-	-	-	-	-	-	-	-	-	-
6 - 7	-	-	1	20	30	30	23	18	17	16	9	1
7 - 8	67	78	102	149	146	134	113	117	130	146	154	113
8 - 9	258	258	279	311	290	259	232	249	274	297	331	302
9 - 10	417	422	421	448	405	374	346	378	402	426	471	459
10 - 11	538	543	540	545	479	452	429	460	494	490	546	569
11 - 12	610	616	609	600	517	485	458	493	525	503	572	622
12 - 13	622	642	627	610	515	482	453	503	529	491	563	622
13 - 14	587	622	600	574	473	438	420	455	486	443	503	570
14 - 15	499	542	524	494	398	363	362	375	399	363	408	469
15 - 16	373	415	398	374	289	268	266	274	274	247	287	331
16 - 17	220	256	244	227	178	165	161	164	153	129	142	177
17 - 18	49	84	85	78	68	70	73	67	41	22	16	28
18 - 19	-	1	2	3	3	6	9	5	1	-	-	-
19 - 20	-	-	-	-	-	-	-	-	-	-	-	-
20 - 21	-	-	-	-	-	-	-	-	-	-	-	-
21 - 22	-	-	-	-	-	-	-	-	-	-	-	-
22 - 23	-	-	-	-	-	-	-	-	-	-	-	-
23 - 24	-	-	-	-	-	-	-	-	-	-	-	-
Sum	**4240**	**4479**	**4432**	**4433**	**3791**	**3526**	**3345**	**3558**	**3725**	**3573**	**4002**	**4263**

Figure 19: Hourly averages [Wh/kWp] specific PV output of a Ground based Fixed-mounted PV

Source: Own calculations

Figure 19 shows simulated hourly average specific PV output of a Ground based Fixed-mounted PV in Wh/kWp. The maximum specific PV output of each month occurs between 11:00 to 13:00 with the maximum output value of 627 Wh/kWp in March and the minimum output value of 453 Wh/kWp in July. (See more in Appendix 3)

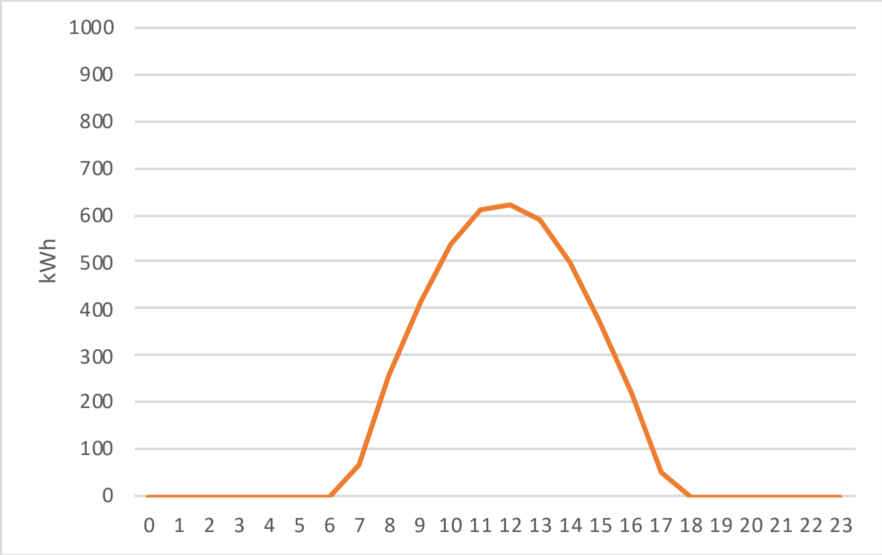


Figure 20: Hourly simulated production of a Ground-based Fixed-mounted PV

Source: Own calculations

Figure 20 shows a simulated PV output of a Ground-based Fixed-mounted PV system within a day. The PV production starts from 6:00 to 18:00. The total output is 4,240 MWh a day. The maximum output occurs between 12:00 to 13:00. Production during this hour is 622 MWh.

3.2.2 Load data

In this project, it is assumed that there are three major types of electrical loads - residential load, industrial load, and commercial load. A 24-hour electricity consumption of each load type was then created based on the actual load profile provided by Provincial Electricity Authority of Thailand (PEA) which is the actual electricity consumption data of PEA's consumers in its authority.

3.2.3 Residential load

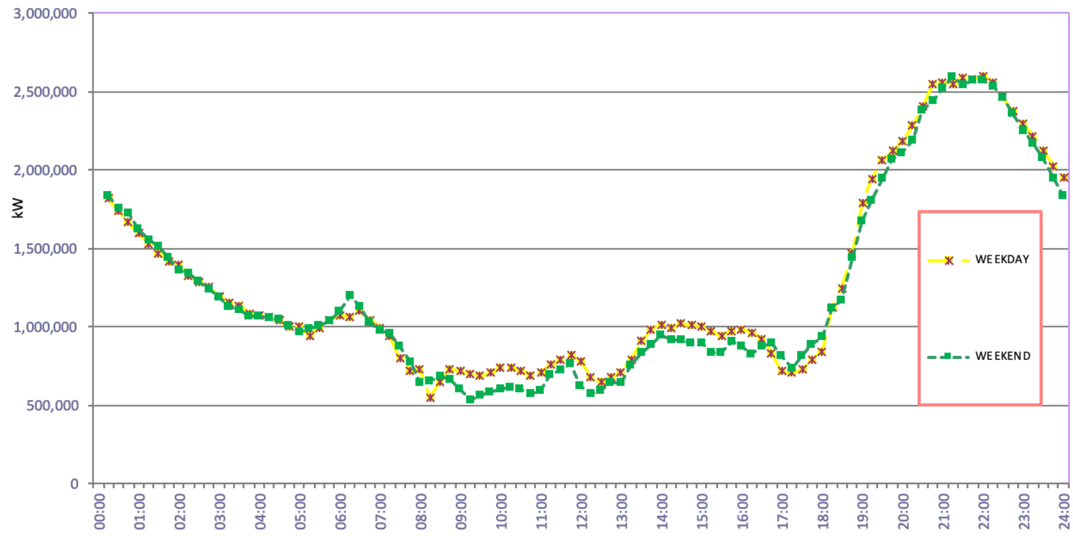


Figure 21: Actual residential load profile

Source: Provincial Electricity Authority of Thailand (PEA), 2019

Figure 21shows actual electricity consumption of residential load in Thailand. As shown in the figure, the consumption during weekday is quite similar to the consumption during weekend, the consumption is low during working hours from 8:00 to 17:00 then rapidly increase in the evening after 18:00 and reaches its peak around 21:00 – 22:00. After that, the consumption decreases over nighttime.

According to a survey conducted in Thailand on the behavior of thai people in terms of using electrical appliances in their residential buildings. The survey states that two story houses are the most common houses in Thailand. A number of family member per a house is usually 3 or 4. 70.4% of houses in Thailand has at least one electric air conditioner. Refrigerator and television are very common appliances that every house has. Table 5 shows a list of common electrical devices in Thailand (Opas, 2013).

Table 5: Common electrical appliances in Thailand

Electrical loads	quantity	watt
air conditioner	1	2500
refridgerator	1	100
fan	2	60
microwave owen	1	750
hair dryer	1	500
vacuum cleaner	1	800
washing machine	1	1200
water heater	1	3000
computer	1	330
rice cooker	1	750
TV	2	70
lightbulb	18	18

Source: Opas, 2013

In addition, 34-59% of monthly electricity consumption is from using air conditioners, 7-22% is from using refrigerators, 6-20% is from using fans, 5-15% is from watching televisions, 5-15% is also from using lightbulb, 2-8% is from using rice cooker, 2-6% is from using water heater (Opas, 2013).

An hourly electrical consumption of each appliances was assumed for a single house based on data given from the survey and the actual residential load profile. The estimated load profile for a residential building is shown in Figure 22.

Table 6: Estimation of the hourly used of electrical appliances in Wh

Electrical loads	quantity	watt	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
air conditioner	1	2000	1400	1400	1400	1400	1200	1000	1000	1000	0	0	0	0	0	0	0	0	0	0	1400	1400	1400	1400	1400	1400
refridgerator	1	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
fan	2	60	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	60	60	60	60	120	120
microwave owen	1	750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	187.5	0	0	0	0	0
hair dryer	1	500	0	0	0	0	0	0	250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	250	250	0
vacuum cleaner	1	800	0	0	0	0	0	0	0	0	400	400	400	400	400	0	0	0	0	0	0	0	0	0	0	0
washing machine	1	1200	0	0	0	0	0	0	0	0	0	0	0	0	0	600	600	600	600	600	0	0	0	0	0	0
water heater	1	3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	300	900	600	0
computer	1	330	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	330	330	330	330	0
rice cooker	1	750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	187.5	0	0	0	0	0
TV	2	70	0	0	0	0	0	0	0	70	70	70	70	70	70	70	70	70	70	70	70	140	140	140	140	140
lightbulb	18	18	72	72	72	72	72	72	72	36	36	36	36	36	36	36	36	36	36	36	36	324	324	324	324	324

Source: Own assumptions

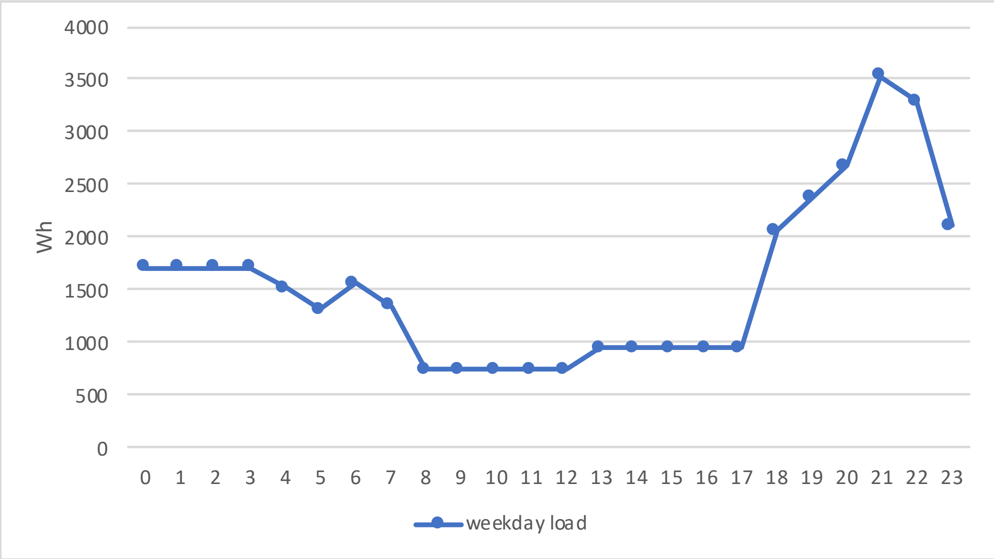


Figure 22: Estimated load profile for a residential building

Source: Own calculations

Figure 22 shows an estimated load profile for a residential building. The peak consumption occurs at 21:00. In this estimation, the consumption of air conditioner accounts for 49.11% of the total consumption. While the consumptions of refrigerator, fan, lightbulb account for 7.77%, 7.12%, 6.19% respectively, which are in the range of consumption showed by the given survey.

3.2.4 Industrial load

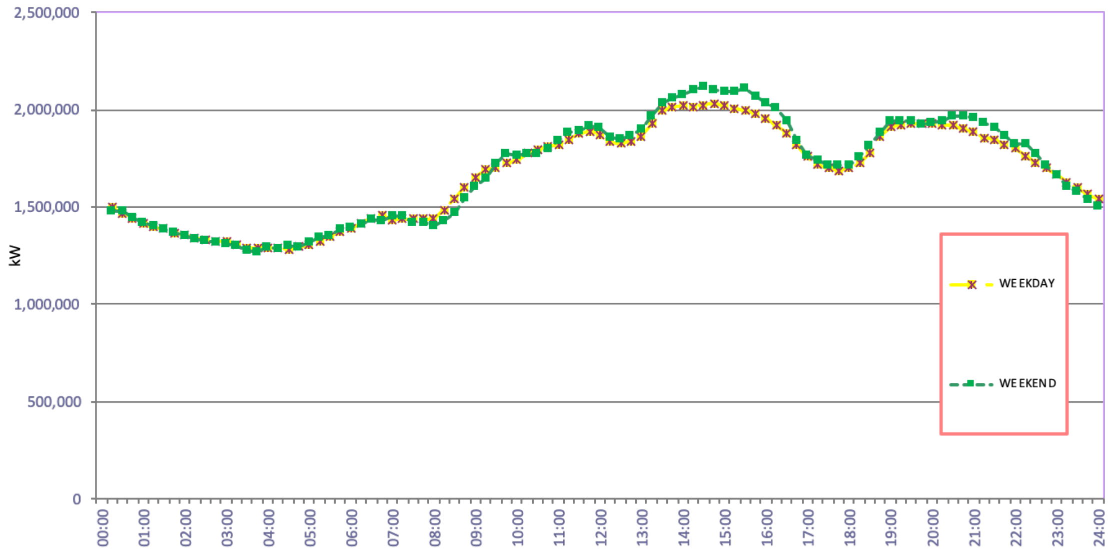


Figure 23: Actual industrial load profile

Source: Provincial Electricity Authority of Thailand (PEA), 2019

Figure 23 shows the actual industrial load profile in Thailand. According to the figure, the consumption during weekday and weekend are quite similar. The consumption gradually increases from 8:00 and has its peak at around 14:00 – 15:00. there are some demands during 0:00-8:00 so it can be assumed that there are some machines which is still running at that time.

3.2.5 Commercial load

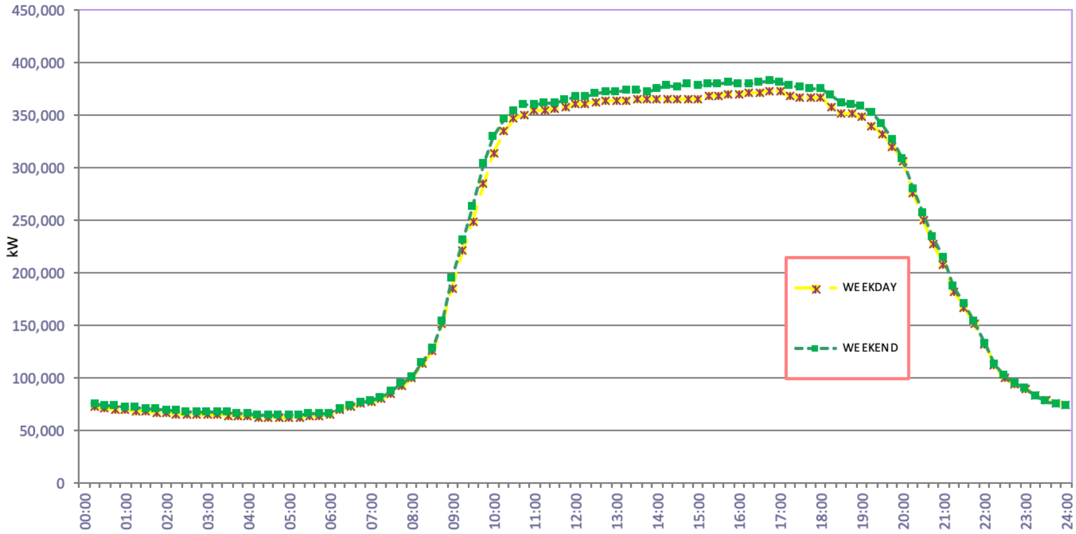


Figure 24: Actual commercial load profile

Source: Provincial Electricity Authority of Thailand (PEA), 2019

Commercial load consists of department stores, restaurants, shops. Figure 24 shows the actual consumption of commercial load in Thailand within 24 hours. As shown in the figure, the electricity consumption of this type of load is more during daytime than it is during nighttime. During the high consumption period, between 10:00 to 19:00, the demand is steady. The consumption on weekend and weekday are similar to each other, so it can be assumed from this figure that those loads operate 7 days a week.

3.2.6 Total load

Smart City A is created for the analysis in this master thesis. It is a city situated in Thailand (more detail of Smart City A can be seen in Section 4.1). Total load profile of Smart City A is the combination of residential load, industrial load, and commercial load. Percent share of each load is assumed to have the same share as the whole country in 2015 reported by International Renewable Energy Agency (IRENA). According to IRENA, the economic sector that consumed electricity the most is industrial sector with 42 percent. The first runner up is commercial sector with 34 percent. The second runner up is residential sector with 23 percent. Follow by agriculture sector, transport sector, and others sector which have the share of 0.4 percent, 0.4 percent, and 1 percent respectively (IRENA, 2017). Note that for the electricity consumption of Smart City A, the percent share of agriculture sector, transport sector, and others sector are negligible.

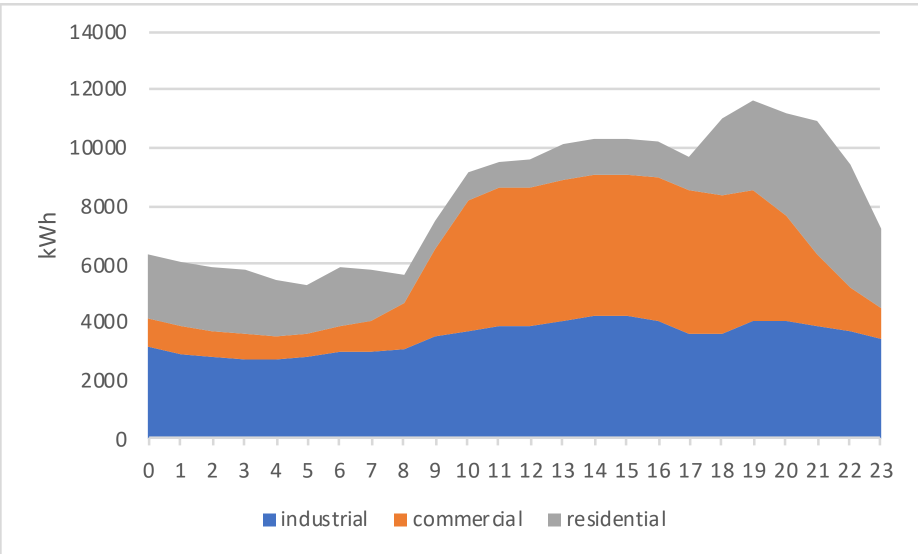


Figure 25: Estimated load profile for Smart City A

Source: Own calculations

Figure 25 shows estimated load profile of Smart City A. It is assumed that a daily electricity consumption in Smart City A is 200 Megawatt-hours (MWh) per day. As can be seen in the figure, the based load for Smart City A is around 5.3 Megawatts (MW). The consumption is higher during working hours. The peak load 11.6 MW occurs around 19:00.

Chapter 4: Results and discussion

In this chapter, electricity consumption of Smart City A will be projected to year 2040. Electricity generation in Smart City A will be focus mainly on PV production. The total load profile will be simulated then several scenarios will be discussed in order to smoothen the total consumption of the grid.

4.1 Estimated load profile of Smart City A in 2040

Table 7: Assumptions for Smart City A in 2040

Assumptions	unit	year 2040
number of households	#	1300
daily electricity consumption	MWh	208
daily peak demand	MW	12.8
installed PV capacity	MWp	10
number of RR-PV system	#	650
number of EVs	#	600

Source: Own assumptions

The electrical load of Smart City A consists of residential load, industrial load, commercial load, and electric vehicle (EV). It is assumed that Smart City A has 1,300 residential building, 50 percent of which has Residential Rooftop PV system (RR-PV) installed. The number of populations living in Smart City A is 5,200. The number of EVs in Smart City A is 600.

Electricity production from PV within Smart City A acquires from following PV systems (see Figure 26).

- 650 of 3-kWp Residential Rooftop PV (RR-PV)
- 20 of 80-kWp Industrial Rooftop PV (IR-PV)
- 7 of 1-MWp Ground based Fixed-mounted PV (GF-PV)

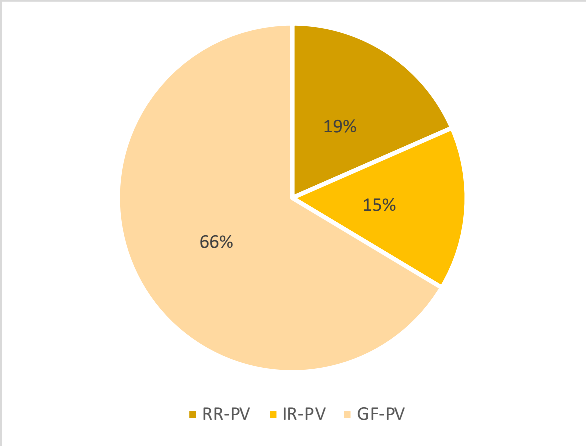


Figure 26: %Share of 3 PV production systems in Smart City A

Source: Own calculations

An electric car used to determine the total demand of EVs in Smart City A is Hyundai Ioniq Electric 2019 and it is also assumed that in Smart City A people drive the same type of EVs. The car can be driven for 280 km distance per a full charge. Its battery capacity is 28 kWh. There are 3 charging options available.

- Regular electricity outlet: charging power 2.3 kW on a 220V socket. Duration of charging time is 12 hours
- EVbox 1 phase 32A: charging power 7.4 kW. Duration of charging is 4 hours and 10 minutes.
- EVbox DC fast charging: charging power 50 kW. Duration of charging is 35 minutes. (EVbox, 2019)

For the 600 EVs in Smart City A, it is assumed that 300 EV owners chose regular electricity outlet and another 300 EV owners chose EV box 1 phase 32A.

In order to determine the total demand of 600 EVs in Smart City A, the travel pattern of the EV owners is assumed as following

- The owners are commuters and have daily driving distance 150 km.
- They charge their EVs at their own houses right away after coming back from work between 18:00-22:00.

- The batteries of EV will get discharged 54% of its capacity after the EV has been driven for 150 km, so the charging time will reduce to 5 hours 36 minutes for regular electricity outlet and 2 hours for EVbox 1 phase 32A.

Table 8: Number of EVs charging hourly

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
regular electricity outlet	200	130	70	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	140	200	260	300	270
EVbox 1 phase 32A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	140	140	120	100	40

Source: Own assumptions

Table 9: Electricity consumption of EV in kWh

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
regular electricity outlet	460	299	161	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	138	322	460	598	690	621
EVbox 1 phase 32A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	444	1036	1036	888	740	296
Total	460	299	161	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	582	1358	1496	1486	1430	917

Source: Own assumptions

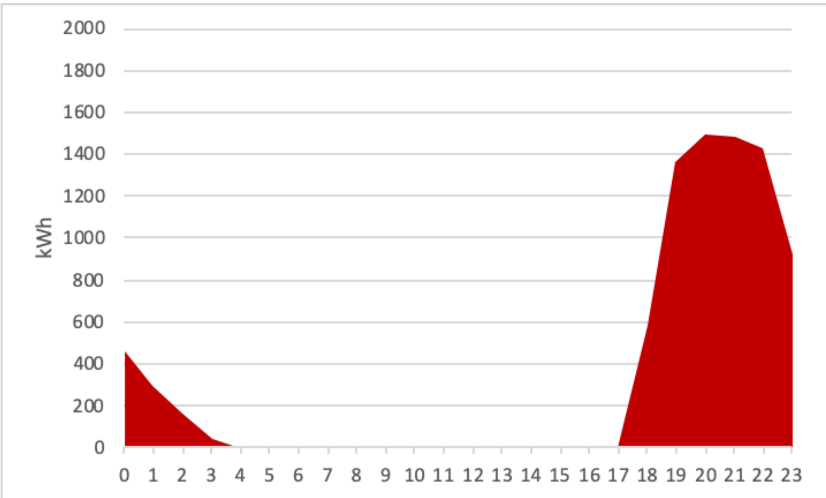


Figure 27: Electricity consumption of EV

Source: Own calculations

Figure 27 shows the estimated consumption of EVs in Smart City A. The consumption is high during from 18:00-22:00.

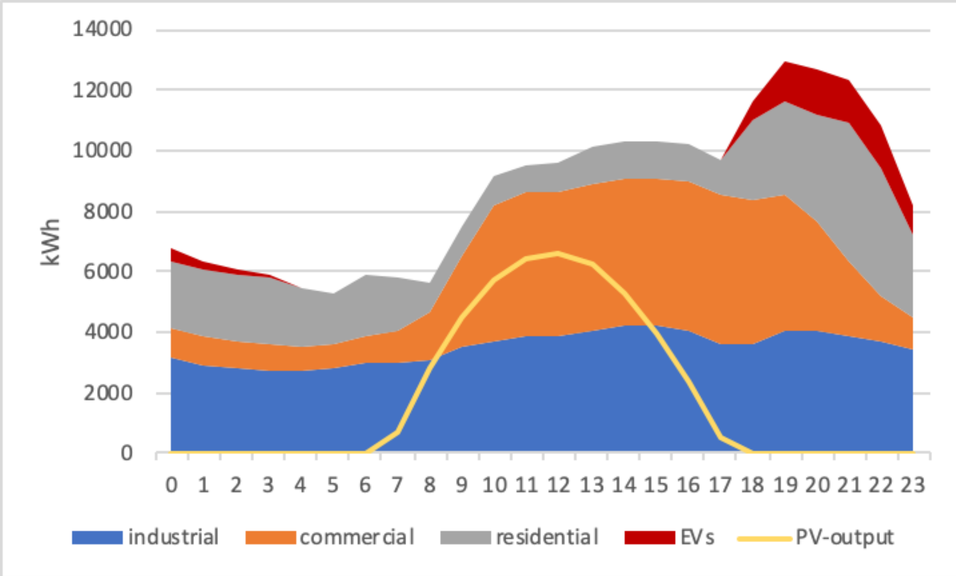


Figure 28: Estimated total electricity consumption by load types and the production of PV systems in Smart City A in 2040

Source: Own calculations

Figure 28 shows the estimated total electricity consumption by load types and the production of PV systems in Smart City A in 2040. The production of PV can cover some demand during daytime. The peak consumption occurs around 19:00. The presence of EVs adds the peak demand around 1 MW.

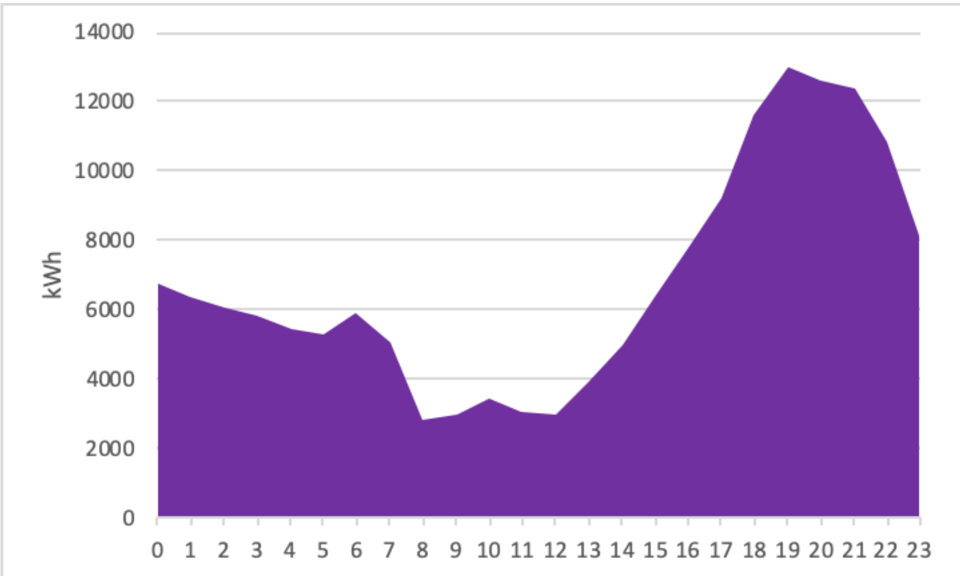


Figure 29: Total electricity supply exclude PV

Source: Own calculations

Figure 29 shows total electricity supply excludes PV of Smart City A. It has the peak around 19:00. In order to supply this peak demand, in this case 13 MW, the network operator must run additional power plants. Those power plants have lower start up time but the fuel used in these type of power plants is also costly such as diesel and natural gas.

The following issues will discuss and raise suggestions on how to lower the peak demand.

4.2 Home energy management system (HEMS)

In this section, the electricity usage in residential building is reviewed. It is assumed that the electricity pricing in Smart City A is real-time pricing where the electricity price is adjusted over time regarding the demand and supply in the grid. When demand is high, many power plants have to be operated in order to supply the demand, including those which have high generation cost, so the electricity price is increased. On the other hand, when demand is low, only based-load power plants or the power plants that have low generation are operated. In this case, the electricity price is decreased.

It is also assumed that in Smart City A, consumers can get access to real time electricity pricing by installing smart meters. Smart meters help consumers communicate the information to the electricity supplier, the supplier gets to know real-time electricity consumption from each consumer and consumers get to know real-time price.

The realization of electricity price by consumers helps consumers decrease their daily electrical consumption voluntarily by allocating available resources and managing load appliances. This is called Demand Response (DR). DR can be defined as changes in the electric usage of customers from their normal consumption patterns in response to changes in electricity cost over time or to incentive payments designed to induce low electricity usage during times of high wholesale market prices or suspected system reliability (Hussain et al, 2018).

A home energy management system (HEMS) helps optimize the electricity demand in residential building and reduce peak demand. HEMS can be installed in residential homes to help manage power supply by communicating with household appliances and utilities, monitor energy usage, and receive information (such as tariff prices) to reduce power consumption by scheduling the usage of household appliances. The system can also manage the energy production from renewable resources (such as PV) and the storage systems whether the excess production should be stored or fed to the grid. The system consists of a personal computer (PC), which acts as a control center with software and communication protocols, such as WiFi, ZigBee, Bluetooth, and KNX. Wired or wireless communication is connected to the PC, which serves as a coordinator that receives/sends data from the utility to the smart home and controls signals to manage home appliances. Weather information is also accounted in HEMS by taking temperature readings inside/outside buildings, which can be used to determine the comfort level of customers. Moreover, renewable energy resources connected to the HEMS system, such as photovoltaics (PV), batteries, and wind generators, provide energy to homes during peak hours, thereby reducing the utility load on the electricity network (See Figure 30) (Hussain et al, 2018).

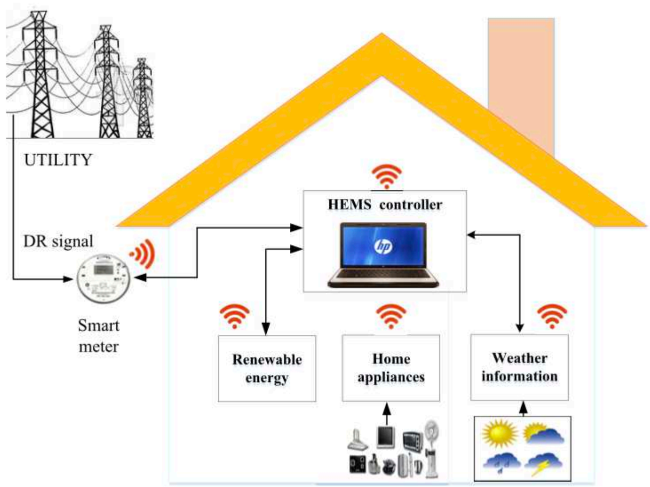


Figure 30: Architecture of home energy management system with demand response signal.

Source: Hussain et al, 2018

It is assumed that every house in Smart City A is about to use HEMS. The appliances used in the house will be controlled by HEM controller. Occupants are aware of real-time electricity price and they can set up schedule for their appliances in order to avoid the usage during peak demand time when the electricity price is high. The following figures show daily electricity consumption of a house in Smart City A before using HEMS.

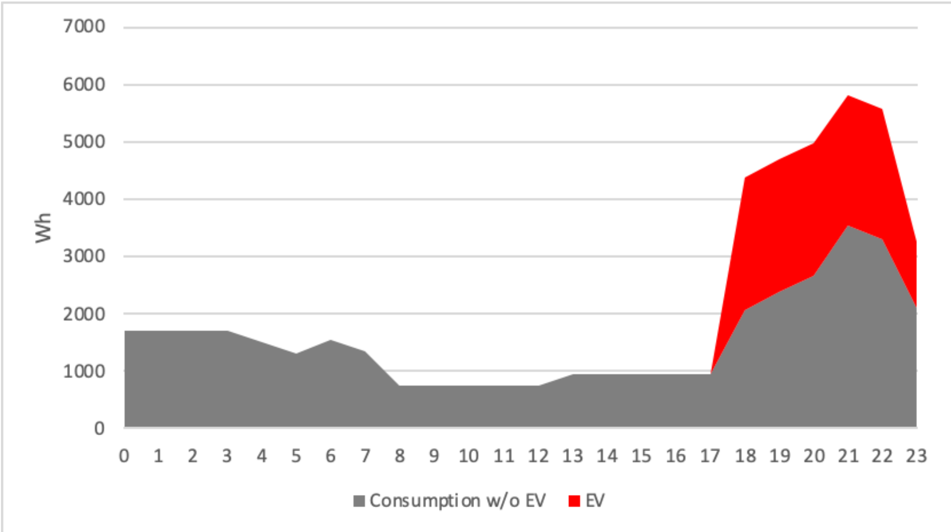


Figure 31: Daily electricity consumption of a house in Smart City A before using HEMS.

Source: Own calculations

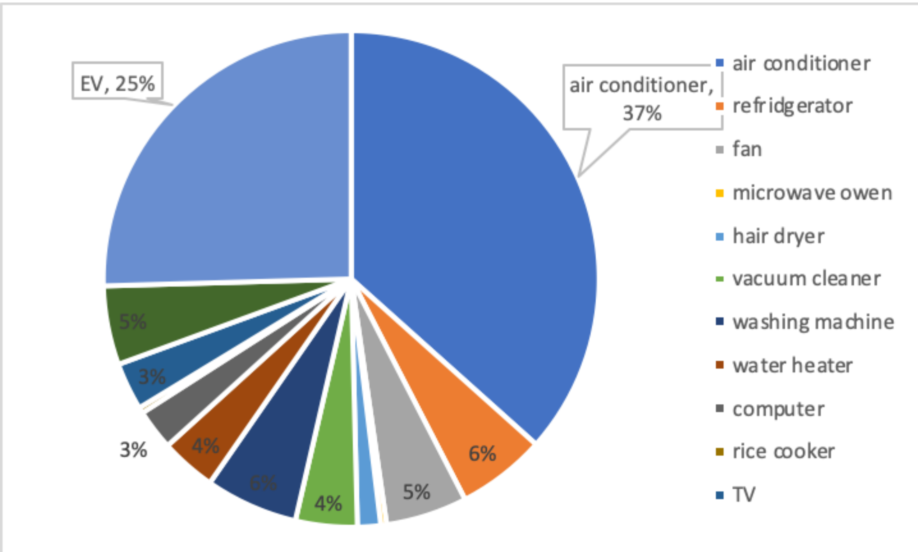


Figure 32: Electricity consumption of appliances in a house in Smart City A

Source: Own calculations

Figure 31 shows the daily electricity consumption of a house in Smart City A before using HEMS. The peak demand period of Smart City A is between 18:00 – 22:00. It is also the peak demand period of this house. The occupants want to reduce the electricity bill so they set up HEMS to avoid using appliances during peak period in order to get the cheaper electricity price. Figure 32 shows daily electricity consumption of each appliance in their house. The major consumption is from air conditioner and EV. These are suggestions given to occupants of this house.

- EV will only be charged during non-peak period, most likely after midnight. The owner can plug the cable in the charging unit right away after he come back home around 18:00. If it is still in peak demand period, the EV will not be charged at that time. Only after the peak demand period ends which can be realize by the system. Then EV will get charged automatically. However, if the battery level is lower than a certain level, in this case 40%, the system will charge EV until it reaches that level regardless of peak demand period.
- Air conditioner is used to serves comfort to the occupants. It doesn't make sense to turn the air conditioner off during peak demand period if the cooling demand is still needed. Occupants must define their comfort level. For example, the usual temperature set in the room is 25^{o} C. During the peak demand period, the system will set the room temperature to 27^{o} C. The room will be a little warmer but it is okay for those occupants because it isn't too far away from their comfort level and they get to save some money in return.
- Washing machine can be scheduled to operate at a certain time of day. The system will make sure that it isn't operate during peak demand period because this type of loads is not urgent.
- Lightbulbs in the house must be defined which one can be dimmed during peak demand period. Usually the ones in the hall way, bathroom, and bedroom. But not the ones where sufficient light is needed such as working room, reading station, or TV room. Lower level of the lightbulbs can also be used to notify the occupants the peak demand period. If the occupants realize that their lightbulbs are

dimmed, they will know that it is now peak demand period and they will be more cautious to use other appliances.

The appliances, such as TV, radio, computer, which are served for entertaining purposes will not be controlled by the system.

Table 10: Appliances controlled by HEMS during peak demand period

Appliances	During peak demand period
EV	No charging unless the battery level is lower than 40%
Air conditioner	The setting temperature will increase from 25ºC to 27ºC
Washing machine	No operation
Lightbulbs	The selected ones will be dimmed

Source: Own assumptions

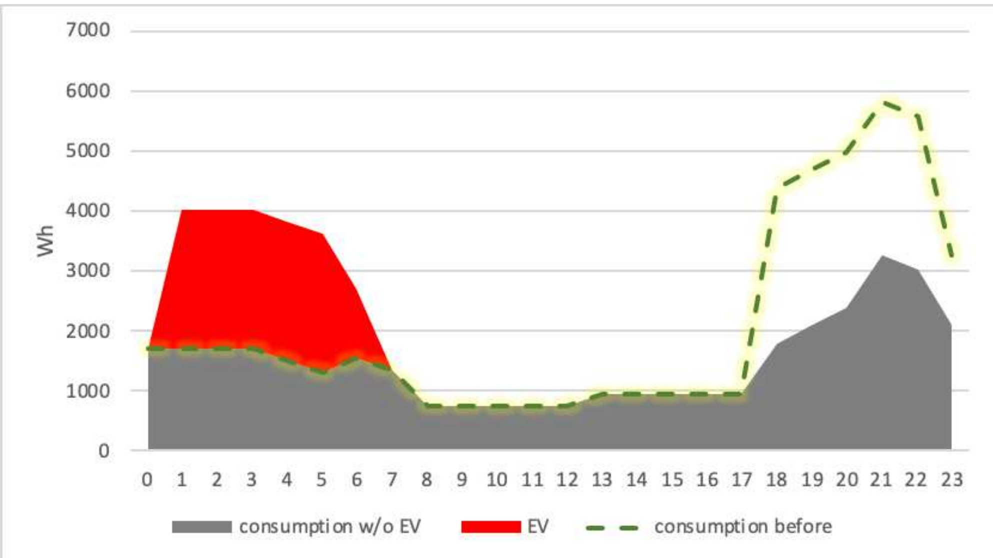


Figure 33: Estimated electricity consumption of a house after using HEMS

Source: Own calculations

An estimated daily electricity consumption for a house which uses HEMS is shown in Figure 33. The consumption from EV has shifted from charging in the evening when the electricity price is high to charging after 1:00 when the electricity price is low. The consumption during high electricity price is also decreased due to the new setting temperature from 25º C to 27º C. For this house, the highest demand is reduced from 5.8 kW to 4.0 kW from using HEMS.

4.3 HEMS with storage system

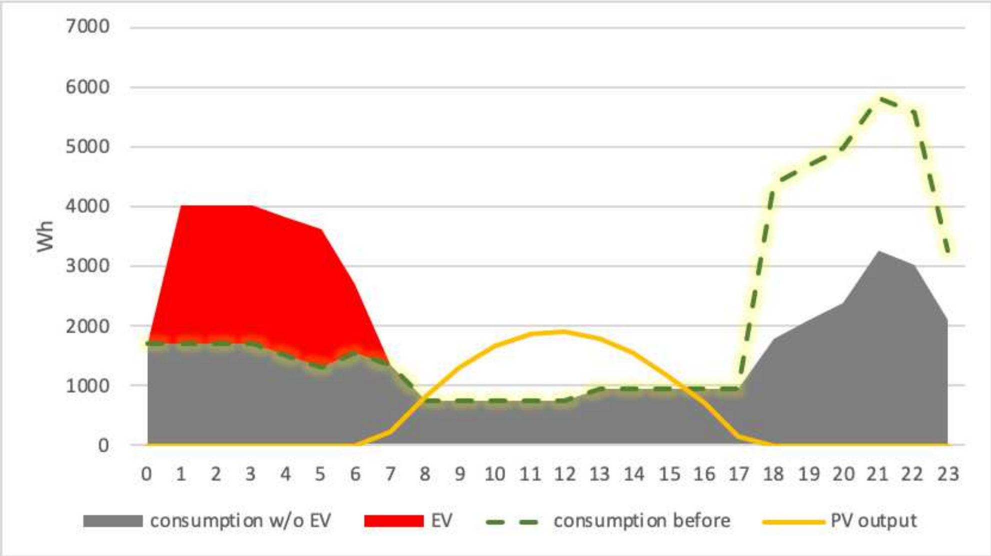


Figure 34: Electricity generation and consumption of a house after using HEMS

Source: Own calculations

As shown in Figure 34, from 8:00 to 15:00 the production from PV is more than the consumption in this house. In this section, two scenarios are created in order to help this house owner to decide on which scenario has the most economical profit.

- Scenario 1: A system with PV and sell excess electricity production to the grid
- Scenario 2: A system with PV and store excess electricity production and use it later during peak demand

In order to analyze the profitability of the two scenarios, the net present value (NPV) and annuity were calculated using the following formula.

$$\text{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

$$Annuity = NPV \times \frac{r \times (1 + r)^T}{(1 + r)^T - 1}$$

Where

- T is investment horizon (years)
- T is year-count
- C_t is cash flow in year t (bath)
- r is risk adjusted discount rate
- C_0 is initial investment (bath)

The monthly electricity generation from this RR-PV system is obtained by using Solargis online simulation. The self-consumption for both scenarios were set as 67% as calculated from Figure 34. The full load hours (FLH) is calculated using the following equation.

$$FLH = \frac{E}{P_p}$$

Where

- FLH is full load hour
- E is the production of PV system during a period of time in kWh
- P_p is the rated capacity of the PV system in kW

Table 11: Monthly PV output and FLHs of a RR-PV system

Month	Total PV output	self-consumption	excess electricity	FLH
January	410	275	135	137
February	374	251	123	125
March	387	259	128	129
April	350	235	116	117
May	291	195	96	97
June	255	171	84	85
July	255	171	84	85
August	284	190	94	95
September	305	204	101	102
October	321	215	106	107
November	369	247	122	123
December	419	281	138	140
Total	4020	2693	1327	1340

Source: Own findings

Table 12: Data input for scenario 1 and 2

Input Discription	unit	scenario 1	scenario 2
Discount rate/cost of capital	%	5	5
Rated Capacity	kW	3	3
Full Load Hours	hours	1,340	1,340
Specific investment	baht/kWp	49,000	55,240
Repair Works (in year 12)	baht/kWp	4,900	4,900
Repair Works battery (every 10 years)	baht	0	18,720
Feed-In-Tariff for 10 years	baht/kWh	1.68	0
Investment horizon	years	25	25
Yearly electricity generation	kWh	4,020	4,020
Total investment	baht	147,000	165,720

Source: Own findings

The specific investment of a roof-top PV system in Thailand costs 49,000 baht/kWp (ecosolar.co.th, 2019). For scenario 2, a 4-kWh battery system cost has been added as it was designed to store the excess electricity during daytime with charge/discharge efficiency of 80%. The battery system costs 156 USD/kWp (BloombergNEF, 2019). The investment horizon was assumed for both scenarios at 25 years with discount rate of 5%. The repair works cost was assumed after year 12nd for both scenarios due to changing new inverters. For scenario 2, the repair works cost was assumed additionally after year 10th and 20th due to changing batteries. The electricity price was assumed to increase annually by 3%

For scenario 1, the excess amount of electricity is fed to the grid. Although the average electricity price in Thailand in 2019 was 3.8 baht/kWh, the feed-in tariff rate for roof-top PV system is only 1.68 baht/kWh with 10 years contract. After contract ends, the excess amount of electricity can be fed to the grid without pay (PEA, 2019).

Table 13: NPV and Annuity of scenario 1 and 2

Scenario	NPV (baht)	Annuity (baht)
1. PV	57,358	4,070
2. PV+battery	79,848	5,665

Source: Own calculations

Both scenarios are profitable because their NVP and Annuity are positive. However, for scenario 1, its NPV is lower compare to NPV of scenario 2. One obvious reason is that after year 10th the excess amount of electricity produced in scenario 1 has to be given away to the grid. Scenario 1 would fit better with higher NPV if the installed capacity reduces so that the %self-consumption is higher. (See calculations in detail in Appendix 4 and Appendix 5)

For scenario 2, its NPV shows that it is more persuading for the house owner because it has more NPV compare to scenario 1. It has also other benefits. Storing the excess electricity during daytime and use it later during peak time helps smoothen the load profile of this house. The peak demand of this house will decrease. And with many houses combine, the peak demand of Smart City A will also decrease.

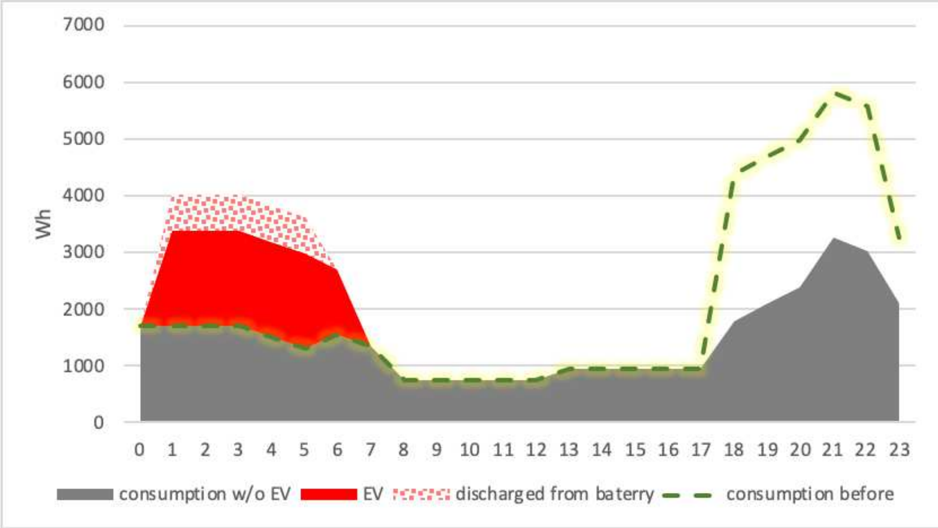


Figure 35: Electricity generation and consumption of a house after using HEMS with a battery storage system

Source: Own calculations

For this house, the HEMS is set to discharge the battery in order to charge EV as shown in Figure 35. With the use of battery storage system, the peak demand of this house is lower from 4 kW to 3.3 kW.

By assuming that every house in Smart City A uses HEMS. The load profile of Smart City A can be estimated as shown in Figure 36.

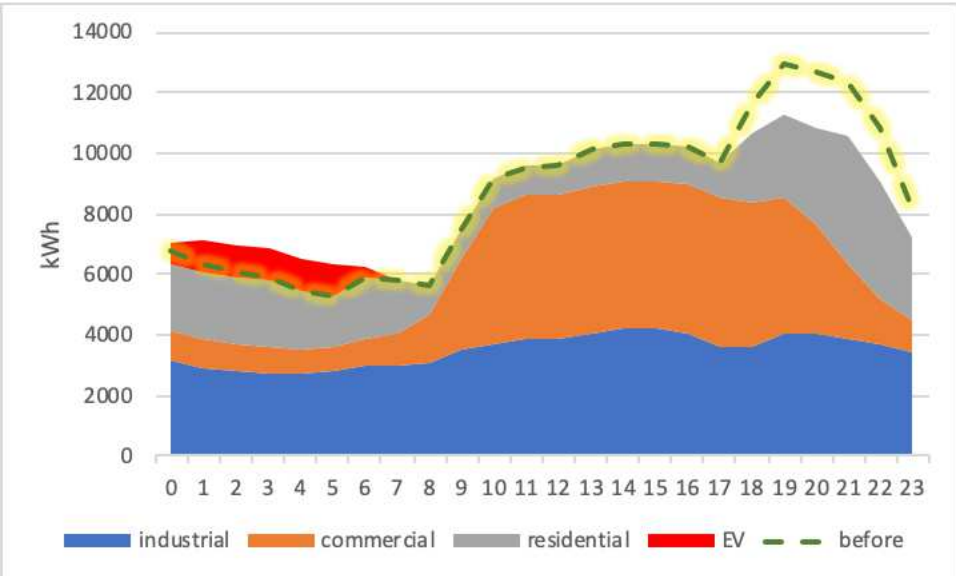


Figure 36: Estimated load profile of Smart City A after using HEMS

Source: Own calculations

The peak demand of the city decreases from 13 MW to 11.3 MW. The demand increases from 0:00 to 6:00 which is usually the low demand period

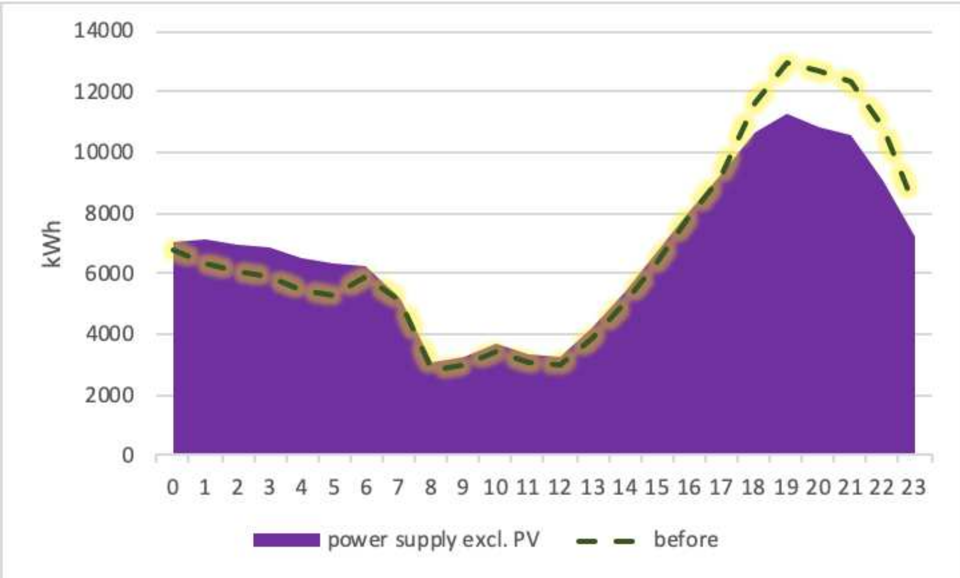


Figure 37: Total electricity supply exclude PV after using HEMS

Source: Own calculations

The total electricity supply exclude PV shows that during 18:00 to 23:00, also known as peak demand period, the city needs less electricity supply so that some of the peak load power plants are no longer needed to operate. As a result, the total cost of electricity generation will decrease and so as the electricity price. During 0:00 to 6:00 the city needs more electricity supply. But because it is in low demand period, operating some additional based load power plants would not as costly as the peak load power plants, so the electricity price at this period is assumed to increase only slightly.

The supply during 8:00 to 15:00 increases slightly because the excess electricity generation from residential rooftop PV systems that used to be fed to the grid is now being stored in battery systems. So there is some additional supply needed during this period too.

4.4 Utility-scale energy storage

As shown in Figure 37: Total electricity supply exclude PV after using HEMS, the power supply exclude PV drops during 7:00 to 15:00 due to the contribution of PV power supply to the grid. During that period, some of the power plants have to be shut down in order to keep the grid balanced. If those power plants had high production cost, it would make sense shutting them down. But if those power plants had low production cost such as hydro power plant, it would be considered an opportunity loss.

In this section, grid-scale energy storage systems are assumed to be installed in Smart City A in order to store the electricity during daytime where PV gives supply to the grid and supply the stored electricity after during peak demand period.

There are various types of battery technologies for utility-scale battery storage systems such as Li-ion, sodium sulphur, and lead acid. Among those, Li-ion battery receives most attentions over recent years. The capacity of utility-scale battery storage system can be in a range up to hundreds of megawatt-hours. (IRENA, 2019)

According to IRENA, utility-scale battery is important to energy transition. It helps increase the share of renewable energy. High percent share of renewable becomes more practical and more manageable with battery storage systems. The followings are the advantages of utility-scale battery to the grid system operators.

- Frequency regulation: frequency control is very important in terms of delivering good quality of power supply. It is controlled by balancing the power supply and demand. If power supply is more than power demand, the frequency will increase. The reverse effect is occurred when power supply is less than power demand. Normally, power supply is more manageable for the system operators. Many of peak load power plants are in costly contracts and have to be ready to start or stop. The response time is defined by how fast the power plant can start or stop. Utility-scale battery helps control frequency. For example, when the power demand is rapidly increased, the battery can provide the additional power supply, in a response time of milliseconds, during the new power plants are starting up.

- Flexible ramping: in an electrical grid that has high penetration of PV systems, its load curve decreases during daytime when there is high production form PV and increases rapidly in the evening with the absence of PV production. This load curve is called "duck curve" which is first experienced in Californian power system. Utility-scale battery system can help smoothen this curve by storing excess electricity from PV production during daytime and supply it later in the evening when it's needed.
- Black start service: black start is the restoration of the grid after being out of service due to failures. An amount of power is needed in order to perform black start. Utility-scale battery can offer the black start function which is normally provided diesel generators. Moreover, other ancillary services can be also provided by such battery systems. (IRENA, 2019)

It is assumed that in Smart City A utility-scale Li-ion battery storage systems are installed. Baseload power plants which have to run 24 hours a day are assumed to increase from 3MW to 6 MW and charge utility-scale battery storage systems during the period when the power supply is more than demand which is usually during daytime when there are power supplies from PV systems. The battery systems will discharge and supply the power to the grid later during peak demand period. In Figure 37, it can be calculated that the utility-scale battery storage systems will get charged during 7:00 to 14:00 with 16,715 kWh of electricity. The charge/discharge efficiency of the battery systems is assumed to be 90%.

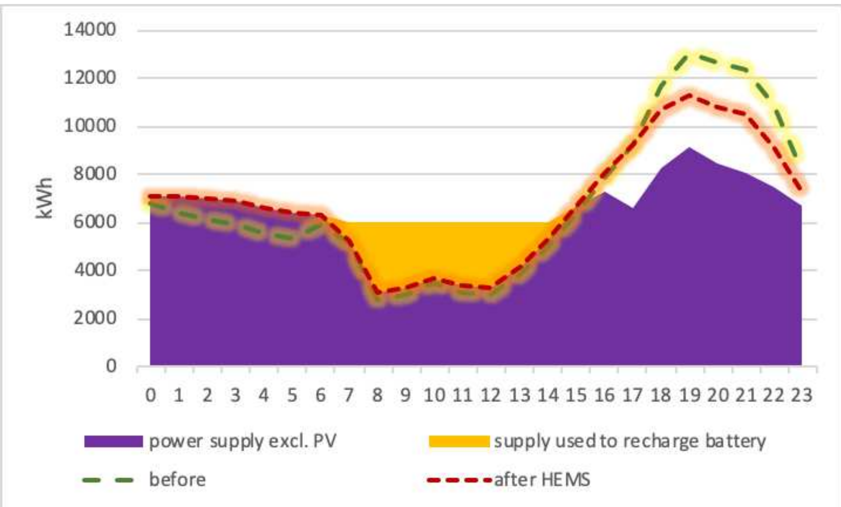


Figure 38: Total electricity supply exclude PV after using HEMS and utility-scale battery storage

Source: Own calculations

Figure 38 shows daily total electricity supply exclude PV after using HEMS and utility-scale battery storage. Due to the discharge of the battery system, the daily peak supply is decrease by 2 MW and has its peak at 19:00 at 9.2 MW (17.8% peak load reduction).

On a cloudy day where the electricity production from PV is decreased, the battery storage systems will get recharged less so the electricity stored in the batteries is also less. As a result, during peak demand period the lower amount of power discharged from the batteries cannot supply the peak demand as great as it used to supply in a sunny day, so the peak demand will increase. In this case, the smart grid system must provide additional power supply in order to balance the demand.

4.5 Vehicle to grid (V2G)

In previous sectors, EVs are considered as electrical loads which only take the electricity out of the grid. In this sector, EVs will be consider not only electrical loads, but also electrical storages which are able to supply power to the grid during peak demand period.

According to IRENA, the term Vehicle-to-grid (V2G) refers to providing services to the grid in the discharge mode. The stored electricity in EV's batteries can be used to supply peak demand and to provide frequency control and other ancillary services. In 2030 EVs will be able to provide grid's flexibility. The price of EVs will falling due to the falling battery cost and the supporting policy from government. The size of battery will be bigger-increasing from 20-30 kWh currently to 40-60 kWh which is considered a bigger potential when consider EV's battery as grid's electricity storage. The charging stations will be more accessible, the vehicles and charging points will have smart charging options including discharging as a common feature (provided by auto manufacturers), and technically enabling provision of ancillary services to the grid. A series-produced EV with alternating current (AC) charging and vehicle-to-grid (V2G) capability would greatly lower the entry cost to customers (IRENA, 2019).

EV batteries' capabilities to provide specific grid services are key in this context, setting aside their impact on the vehicle's performance. Capabilities to provide services to the grid and corresponding technologies will depend on the considered application. Battery degradation from increasing the number of charge/discharge cycles has been a long-debated issue with respect to V2G and battery swapping. For example, for balancing renewables, high depth of discharge tolerance, i.e., the extent to which the battery can be discharged, is necessary. Three hundred full cycles per year may be required if the battery is to be used to support system-wide balancing or absorption of excess renewables into the battery behind-the-meter. For ancillary services, lower depth of discharge is required. Since batteries must both be able to inject power (when frequency is too low) and consume power (when frequency is too high), the ideal standby state of charge is approximately 50%, which means that the selected batteries should be able to work at lower states of charge. Battery degradation is affected mainly by the discharge current, the depth of discharge and the temperature of operation. But recent tests have shown that battery degradation with V2G is limited if the battery stays within a state of charge of around 60-80%. The impact is similar to normal AC charging. The Warwick University degradation battery model that predicts capacity and power fade over time showed that with a V2G system, EV battery life can be extended by using profiles that are V2G friendly (IRENA, 2019).

For Smart City A, in order to determine the effects of V2G to the grid, the following assumptions for 600 EVs have been made:

- V2G charging stations are available throughout the city such as at houses, office's parking lots, department store's parking lots, restaurants, etc. EV drivers are prone to plug in their EVs to the V2G all the time while parking.
- Smart charging is available for all EV's drivers. Drivers will get notified by the system on the changing of real-time electricity price. Driver can choose which price or which time they want to charge/discharge their EVs. They set their charging/discharging criteria as following:

- During high price: EV battery will discharge until the battery level is 30%, if battery level is lower than 30% it will charge until it reaches 30%
  - During normal price: EV battery will charge until the battery level is 60%
  - During low price: EV battery will charge until the battery level is 100%
- Smart charging controls the number of EVs being charged at the same time in order to prevent peak demand of charging EVs.
- All drivers have the same driving habit. They drive from home to office at 7:00 and from office to home at 17:00. Each ride discharges battery level by 27% (75 km travel distance).
- Regular electricity outlet can charge EV battery 9.6% per hour. EVbox 1 phase 32A can charge EV battery 26.1% per hour.
- The charge/discharge efficiency is 90%

Table 14: Assumption of EVs charging/discharging schedule in Smart City A

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Electricity price	normal								low							normal			high					
EV connected to grid	o	o	o	o	o	o	o	x	o	o	o	o	o	o	o	o	o	x	o	o	o	o	o	o
regular electricity outlet																								
battery status	charge							x	charge									x	discharge					
%battery	30	40	49	59	60	60	60	x	33	43	52	62	71	81	91	100	100	x	73	63	54	44	35	30
EVbox 1 phase 32A																								
battery status	charge							x	charge									x	discharge					
%battery	30	56	60	60	60	60	60	x	33	59	85	100	100	100	100	100	100	x	73	47	30	30	30	30

Source: Own assumptions

Table 14 shows the charging/discharging schedule of an EV using regular electricity outlet and an EV using EVbox 1 phase 32 A. For EV using regular electricity outlet, the battery level is 30% at 0:00, due to normal electricity price, the battery will be charged until it reaches 60%. At 7:00 the driver drives EV to the office, the battery is discharged 27% due to traveling. When the driver arrives at the office, he plugs it to the charging station. The battery is now charging until it reaches 100% due to low electricity price period. At 17:00 the driver drives the EV home and it gets discharged 27%. He plugs the EV which has now 73% battery level at 18:00. Due to the high electricity price period, the battery is now being discharged in order to supply electricity to the grid until it reaches 30% at 23:00.

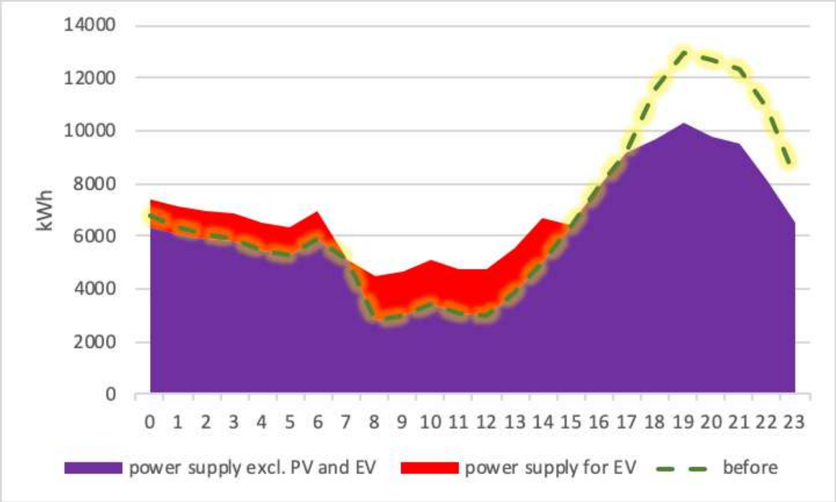


Figure 39: Total electricity supply exclude PV after using V2G

Source: Own calculations

Figure 39 shows the estimated total electricity supply exclude PV after using V2G. Due to the discharge of EV's batteries to the grid during peak demand period, the peak supply during this period is now decreased from 13.0 MW to 10.2 MW. The supply used to charge PV is higher because the EV's batteries is now discharged not only for traveling, but also for supplying electricity to electricity to the grid. The batteries are being charged partially during 0:00 to 6:00 and mostly during 8:00-14:00 when the electricity price is low due to the penetration of PV production. Baseload power supply is also increase from 2.8 MW to 4.5 MW. Note that this figure does not concern the effect of HEMS and utility-scale electricity storage systems.

Chapter 5: Conclusion and suggestions

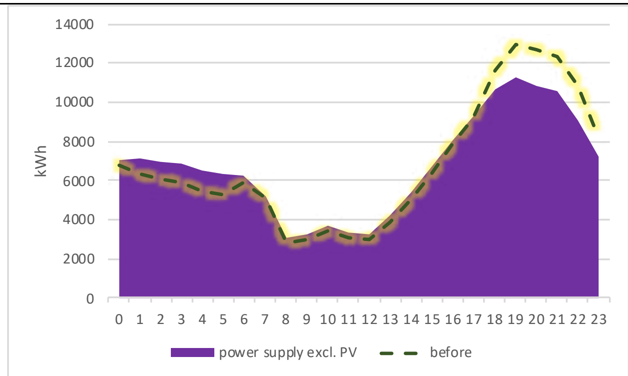
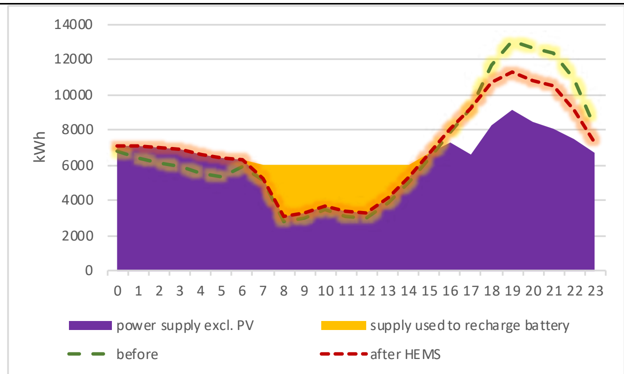
Smart City A portrayed a city in Thailand in 2040 where there are high penetration of PV and EV. The production from PV can supply the demand during daytime. However, it cannot mitigate the peak demand which occurs later in the evening. Uncontrolled charging of EVs can also generate negative effects to the electrical grid. It makes peak demand higher. The network operator must operate additional peak-load power plants in order to cover the peak demand. These power plants are more expensive to operate because they are usually fossil fuel based. As a result, the electricity price during peak demand increases. A few smart grid technologies have been suggested for Smart City A in order to reduce the peak demand.

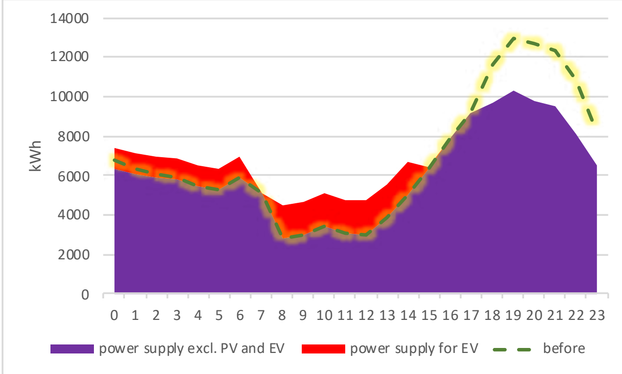
Home energy management system (HEMS) can reduce peak demand of Smart City A by 20.8%. The peak demand of a household can be reduced when the occupants realize real-time electricity price and set their appliances schedule through HEM controller in order to avoid peak demand period. HEM controller controls EV charging station which time EV should be charged. It also controls residential battery system to store excess electricity produced by PV and supply it later within the house during peak demand period.

Utility-scale electricity storage can reduce peak demand of Smart City A by 18.6%. Using Li-ion battery storage systems to store electricity during daytime where it has high penetration from PV and supply the stored electricity during peak demand period.

Vehicle-to-grid (V2G) can reduce peak demand of Smart City A by 21.5%. In this case, the batteries of EVs are considered as grid storages. They are able to supply the stored electricity to the grid during peak demand period and recharge during non-peak demand period. Charging/discharging facilities must be available so that EV drivers can get access to grid once they park their car.

Table 15: Summary of implemented technology in Smart City A

Suggested technology	Detail	Effect to power supply (excl. PV)	Figures
Home energy management system (HEMS)	Occupants realize real-time electricity price and set their appliances schedule through HEM controller in order to avoid peak demand period. HEM controller controls EV charging station which time EV should be charged. It also controls residential battery system to store excess electricity produced by PV and supply it later within the house during peak demand period.	Peak supply decreases from 13 MW to 11.3 MW (20.8%)	
Utility-scale electricity storage	Li-ion battery storage systems store electricity during daytime where it has high penetration from PV and supply the stored electricity during peak demand period. Power supply, exclude PV, from baseload power plants is increase from 3 MW to 6 MW.	Peak supply decreases from 11.3 MW to 9.2 MW (18.6%)	

Vehicle-to-grid (V2G)	Consider EV's batteries as grid storage. They are able to supply the stored electricity to the grid during peak demand period and recharge during non-peak demand period. Charging/discharging facilities must be available so that EV drivers can get access to grid once they park their car.	Peak supply decreases from 13 MW to 10.2 MW (21.5%)	

Communication is very important in smart grid. Every unit in the grid must help balancing power supply and demand because it will be more challenging in the future when there is high penetration from renewable energy and EVs. Communicating real-time electricity price to consumer through smart meter makes consumers more cautious to use electrical loads. They can plan or schedule the usage of appliance. This plan or schedule can also be sent to power producers to plan the power supply in the future.

A selected smart grid technology must be customized regarding different locations. There are quite a few technologies on the market. For example, Smart City A uses Li-ion battery as utility-scale electricity storage systems, but for Smart City B, pumped hydro storage systems could be a better choice because the location of Smart City B is more beneficial to use it.

Smart grid in Thailand is currently in a transition phase. Thai government has created road map despite few people know about it. In order to implement it more successfully, the government should also add plans for public awareness because Thai people, as consumers, will play major role in it.

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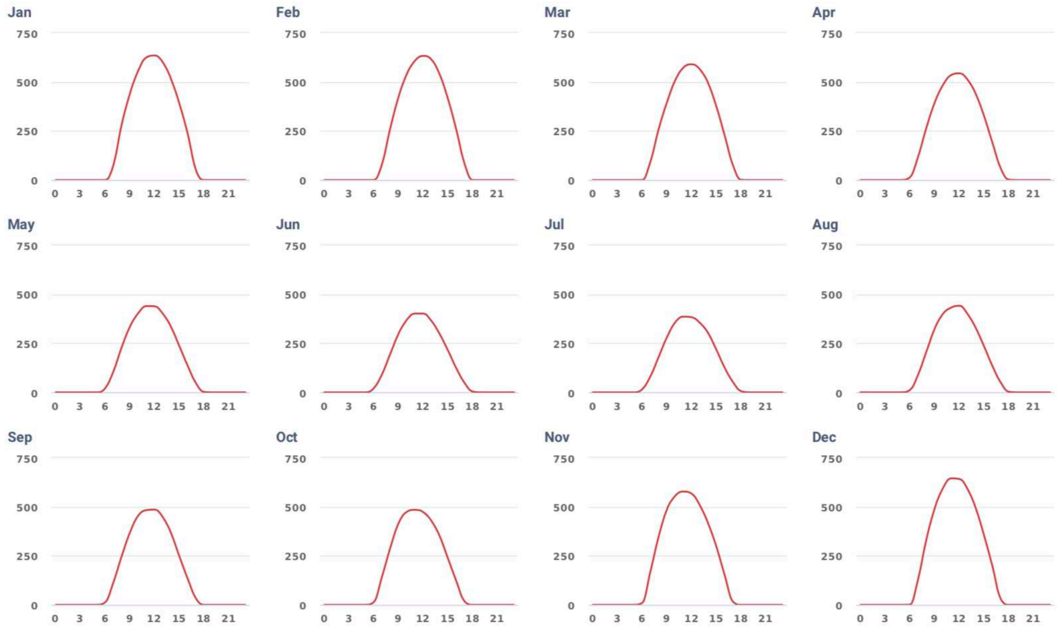
List of Abbreviations

AC	Alternating current
BES	Battery electricity storage
BEV	Battery electric vehicle
CF	Cash flow
CSP	Concentrating solar power
DC	Direct current
DFI	Diffuse horizontal irradiation
DNI	Diffuse normal irradiation
DOD	Depth of discharge
DR	Demand response
EV	Electric vehicle
FLH	Full load hour
GF-PV	Ground-based fixed-mounted photovoltaic
GHI	Global horizontal irradiation
GW	Gigawatt
GWh	Gigawatt-hour
HEM	Home energy management
HEMS	Home energy management system
HEMS	Home energy management system
HV	High voltage
IR-PV	Industrial roof-top photovoltaic
kW	Kilowatt
kWh	Kilowatt-hour
kW_p	Kilowatt peak
ms	mili-second
MV	Medium voltage
MWh	Megawatt-hour
MW_p	Megawatt peak

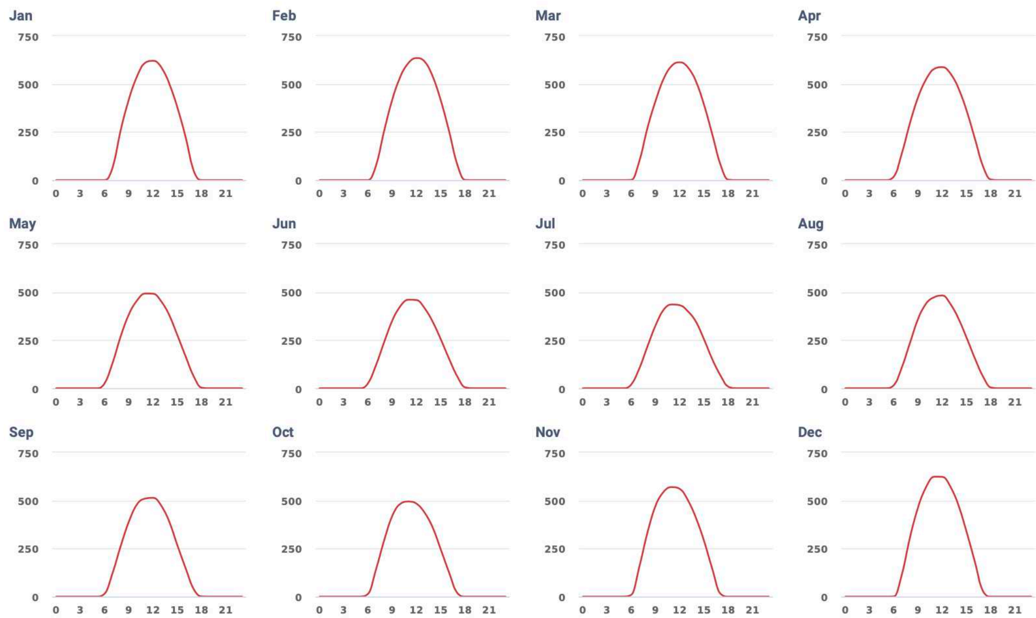
NPV	Net present value
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
RR-PV	Residential roof-top photovoltaic
TV	Television
TWh	Terawatt-hour
W	Watt

Appendixes

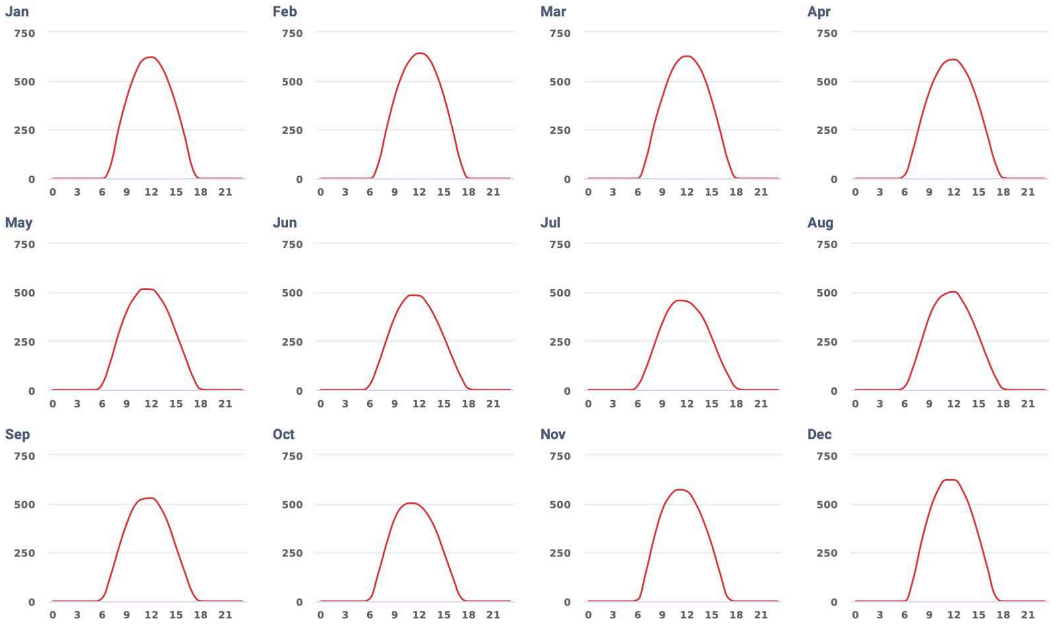
Appendix 1: Hourly averages PV specific power output [Wh/kWp] for RR-PV



Appendix 2:Hourly averages PV specific power output [Wh/kWp] for IR-PV



Appendix 3: Hourly averages PV specific power output [Wh/kWp] for GF-PV



Appendix 4: NPV calculation for scenario 1

Scenario 1

Discount rate/cost of capital	5	%/year
Rated Capacity	3	kW
Full Load Hours	1,340	hours/year
Investment Costs	49,000	baht/kWp
Repair Works (in year 9)	4,900	baht/kWh
O&M Costs	0	baht/kWh
Real Escalation of O&M	2	%/year
investment horizon	25	years

1. NPV, Annuity, LRGC

Year	Discounted CF	Nominal CF	O&M	Investment/ replacement	Electricity self consume	Electricity sale	Discounted cost
0	-147,000	-147,000		-147,000			-147,000
1	11,870	12,464	0		10,235	2,229	0
2	11,583	12,771	0		10,542	2,229	0
3	11,305	13,087	0		10,858	2,229	0
4	11,035	13,413	0		11,184	2,229	0
5	10,772	13,748	0		11,519	2,229	0
6	10,517	14,094	0		11,865	2,229	0
7	10,269	14,450	0		12,221	2,229	0
8	10,028	14,816	0		12,588	2,229	0
9	9,794	15,194	0		12,965	2,229	0
10	9,567	15,583	0		13,354	2,229	0
11	8,042	13,755	0		13,755		0
12	-297	-532	0	-14,700	14,168		-8,186
13	7,739	14,593	0		14,593		0
14	7,591	15,030	0		15,030		0
15	7,447	15,481	0		15,481		0
16	7,305	15,946	0		15,946		0
17	7,166	16,424	0		16,424		0
18	7,029	16,917	0		16,917		0
19	6,895	17,424	0		17,424		0
20	6,764	17,947	0		17,947		0
21	6,635	18,485	0		18,485		0
22	6,509	19,040	0		19,040		0
23	6,385	19,611	0		19,611		0
24	6,263	20,200	0		20,200		0
25	6,144	20,805	0		20,805		0

NPV	57,358	baht
CRF	0.0710	
Annuity	4,070	baht

NPV of Cost	-155,186	bath
Annuity of Cost	-11,011	bath
$LRGC_{EL}$	-2.74	bath/kWh

Appendix 5: NPV calculation of scenario 2

Scenario 2

Discount rate/cost of capital	5	%/year
Rated Capacity	3	kW
Full Load Hours	1,340	hours/year
Investment Costs	55,240	baht/kWp
Repair Works (in year 9)	4,900	baht/kWh
O&M Costs	0	baht/kWh
Electricity price increase	3	%/year
investment horizon	25	years

1. NPV, Annuity, LRGC

Year	Discounted CF	Nominal CF	O&M	Investment/ replacement	Electricity self consume	Electricity discharged	Discounted cost
0	-165,720	-165,720		-165,720			-165,720
1	13,588	14,268	0		10,235	4,033	0
2	13,330	14,696	0		10,542	4,154	0
3	13,076	15,137	0		10,858	4,278	0
4	12,827	15,591	0		11,184	4,407	0
5	12,582	16,059	0		11,519	4,539	0
6	12,343	16,540	0		11,865	4,675	0
7	12,108	17,036	0		12,221	4,815	0
8	11,877	17,548	0		12,588	4,960	0
9	11,651	18,074	0		12,965	5,109	0
10	-64	-104	0	-18,720	13,354	5,262	-11,492
11	11,211	19,175	0		13,755	5,420	0
12	2,812	5,050	0	-14,700	14,168	5,582	-8,186
13	10,788	20,342	0		14,593	5,750	0
14	10,583	20,953	0		15,030	5,922	0
15	10,381	21,581	0		15,481	6,100	0
16	10,183	22,229	0		15,946	6,283	0
17	9,989	22,896	0		16,424	6,472	0
18	9,799	23,582	0		16,917	6,666	0
19	9,612	24,290	0		17,424	6,866	0
20	2,374	6,299	0	-18,720	17,947	7,072	-7,055
21	9,250	25,769	0		18,485	7,284	0
22	9,073	26,542	0		19,040	7,502	0
23	8,901	27,339	0		19,611	7,727	0
24	8,731	28,159	0		20,200	7,959	0
25	8,565	29,003	0		20,805	8,198	0

NPV	79,848	baht
CRF	0.0710	
Annuity	5,665	baht

NPV of Cost	-192,453	baht
Annuity of Cost	-13,655	baht
$LRGC_{EL}$	-3.40	baht/kWh