Optimal Operation Schedule of Battery Energy Storage System for Supporting Variable Renewable Energy in Generation System

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การกำหนดเวลาการทำงานที่เหมาะที่สุดของระบบกักเก็บพลังงานประเภทแบตเตอรี่สำหรับรองรับพลังงานหมุนเวียนที่ผันแปรในระบบผลิตไฟฟ้า

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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Field of Study	Electrical Engineering
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เฉลิมจิต กลั่นสุภา : การกำหนดเวลาการทำงานที่เหมาะที่สุดของระบบกักเก็บพลังงานประเภทแบตเตอรี่สำหรับรองรับพลังงานหมุนเวียนที่ผันแปรในระบบผลิตไฟฟ้า . (Optimal Operation Schedule of Battery Energy Storage System for Supporting Variable Renewable Energy in Generation System) อ.ที่ปรึกษาหลัก : รศ. ดร.สุรชัย ชัยทัศนีย์

การผลิตไฟฟ้าจากระบบผลิตไฟฟ้าพลังงานหมุนเวียนที่มีความแปรปรวน เช่น ระบบผลิตไฟฟ้าพลังงานแสงอาทิตย์ และ พลังงานลม ส่งผลให้ค่าความต้องการใช้ไฟฟ้ามีการเปลี่ยนแปลงไป นอกจากนี้ยังเพิ่มต้นทุนการทำงานของเครื่องกำเนิดพลังงานแบบดั้งเดิม เนื่องจากการผลิตไฟฟ้าที่ไม่แน่นอนนั้นทำให้ค่าความต้องการใช้ไฟฟ้าและการผลิตไฟฟ้าไม่สอดคล้องกัน ส่งผลให้โอกาสที่จะเกิดไฟฟ้าดับในระบบไฟฟ้ามีมากขึ้น และ ส่งผลต่อค่าใช้จ่ายในการรักษาระบบไฟฟ้าให้มีความมั่นคงเช่นเดิม ระบบกักเก็บพลังงานด้วยแบตเตอรี่ขนาดใหญ่ เป็นวิธีที่ใช้ลดผลกระทบจากระบบผลิตไฟฟ้าพลังงานหมุนเวียน โดย ระบบกักเก็บพลังงานด้วยแบตเตอรี่ขนาดใหญ่ สามารถใช้ในการสำรองพลังงาน รวมถึงเพิ่มความยืดหยุ่นในการเพิ่มและปรับลดการผลิตไฟฟ้า ในงานวิจัยนี้ ได้นำเสนอวิธีการเพื่อกำหนดการทำงานที่เหมาะสมสำหรับ ระบบกักเก็บพลังงานด้วยแบตเตอรี่ขนาดใหญ่ ซึ่งคำนึงถึงค่าใช้จ่ายในการทำงาน ข้อจำกัดด้านความน่าเชื่อถือในการผลิตไฟฟ้า ค่าใช้จ่ายที่เกิดจากความน่าจะเป็นที่จะเกิดเหตุการไฟฟ้าขัดข้องในระบบ โดยวิธีการที่นำเสนอนี้จะเสนอแนวทางการใช้งานระบบกักเก็บพลังงานด้วยแบตเตอรี่ขนาดใหญ่ หลายรูปแบบการทำงานใน 1 วัน ผลการวิจัยแสดงให้เห็นว่าการใช้งาน ระบบกักเก็บพลังงานด้วยแบตเตอรี่ขนาดใหญ่ หลายรูปแบบการทำงาน สามารถเพิ่มคุณค่าและประโยชน์ของระบบไฟฟ้ามากกว่าการใช้งานเพียงรูปแบบการทำงานเดียว

สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต	
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KEYWORD: energy storage system, expected energy not supplied, mixed-integer programming, optimal sizing, optimal daily operation schedule, power generation cost, variable renewable energy

Chalermjit Klansupar : Optimal Operation Schedule of Battery Energy Storage System for Supporting Variable Renewable Energy in Generation System. Advisor: Assoc. Prof. SURACHAI CHAITUSANEY, Ph.D.

Variable renewable energy (VRE) generation alters residual demand curves, leading to high operating costs for conventional generators. Additionally, the variable nature of VRE causes a mismatch between electricity demand and generation, resulting in greater expected energy not supplied (EENS) values, which represent a critical component of power generation costs. To alleviate the impact of VRE, utility-scale battery energy storage systems (BESSs) provide ancillary services. The BESSs' general applications are spinning reserve, regulation, and ramping. This paper proposes a method to determine daily operation schedules for grid-scale BESSs, compensating for the negative impacts of VRE on operating costs, power generation reliability constraints, avoided outage costs, and BESS installation expenses. The optimal BESS application at a specific time of day can also be selected. The method is based on a multiple BESS applications unit commitment problem (MB-UC) solved with mixed-integer programming (MIP). The results demonstrate that each application offers the best value for BESS operations at different times of day, and operating BESS in multiple applications results in more significant benefits.

Field of Study:	Electrical Engineering	Student's Signature ....
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Chalermjit Klansupar

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Chapter 1
Introduction

This chapter presents the problem statement that identifies an overview of the necessity of using batteries to support the impacts of Variable Renewable Energy (VRE). The objectives of the dissertation are also stated. In addition, scope of work, step of study, expected benefits, literature reviews, and the dissertation structure are included.

1.1 Problem Statement

As the penetration of VRE sources, such as solar and wind, increases in power systems, there are new challenges that arise due to their variable and uncertain nature. VRE generation is dependent on weather conditions, making it difficult to predict the amount of energy that will be generated. This has significant implications for the operation and planning of power systems, particularly as the shape of residual demand curves is changed due to VRE penetration.

In a power system, the residual demand is the net demand that must be served by conventional power generation after accounting for the available VRE generation. Figure 1 which shows the residual demand curve for California's power system on March 13, 2021, illustrates the variability of residual demand over the course of the day. As shown in the figure, conventional generators need to decrease their output during the day when solar energy is available to serve electricity demand. At night, when solar energy is not available, conventional generators must increase their output to meet the demand.

The variability of VRE generation poses a significant challenge for power system operators, as it requires them to continually adjust the generation from conventional power sources to meet the changing residual demand. Inaccurate predictions of VRE generation can result in sub-optimal scheduling and dispatching of conventional generators, leading to higher costs and reduced efficiency.

To address this challenge, accurate and reliable forecasting of VRE generation is essential. However, forecasting the generation from solar and wind stations can be difficult, as it is strongly related to changes in weather patterns that have become more unpredictable in recent years. As such, the development of new forecasting techniques and models is necessary to improve the accuracy of VRE generation forecasting.

Furthermore, the integration of VRE sources into power systems can have significant impacts on the operation and planning of power systems. The increased variability and uncertainty of VRE sources require a comprehensive analysis of the impacts on power system operation and the development of new methods to handle the challenges. This includes the need for additional ramping and balancing reserves to maintain system stability, as well as the integration of VRE sources into day-ahead planning to ensure reliable and efficient operation.

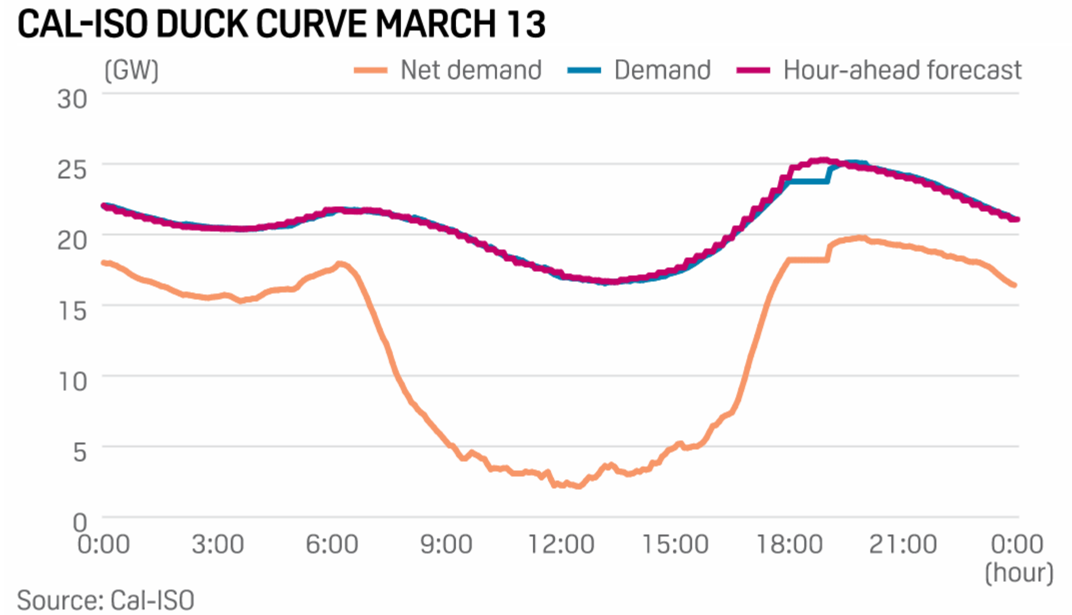

Figure 1 CAL-ISO Duck curve March 13.[1]

The increasing deployment of VRE sources in power systems has brought new challenges to power system operation and planning. While VRE sources such as wind and solar have the potential to provide clean and sustainable energy, their variability and uncertainty can result in significant mismatches between electricity supply and demand. This issue can lead to negative impacts on power system reliability and increase the value of Expected Energy Not Supplied (EENS), which is a measure of the possibility of electricity outages.

One of the primary challenges in integrating VRE sources into power systems is the need for instantaneous ramping, frequent startup and shutdown of conventional generators, and other related operations. These operations can result in high operating costs for generators during the day, as well as potential risks of equipment damage and increased maintenance costs. Moreover, the increased mismatches between electricity supply and demand due to VRE can further exacerbate these issues.

In Thailand, for example, the integration of VRE sources has posed significant challenges to the reliability of the power system. The country has set a target to generate 20% of its electricity from renewable sources by 2036, with a focus on solar and wind power. However, the variability and uncertainty of these sources can lead to mismatches between electricity supply and demand, which can result in a greater value of EENS and increase the risk of electricity outages.

To mitigate these risks, various measures have been proposed to improve the integration of VRE sources in power systems. One approach is to develop new forecasting methods and tools that can provide more accurate predictions of VRE generation. For example, stochastic optimization and scenario-based methods have been proposed to consider the uncertainty of VRE sources and provide more reliable and robust forecasts.

Another approach is to develop new operational strategies that can help to better balance electricity supply and demand. For example, the use of energy storage systems, demand response, and curtailment forecasting can help to reduce mismatches between supply and demand and improve the efficiency and reliability of the power system.

These operations of conventional generators require instantaneous ramping, and frequent startup and shutdown, which lead to high operating costs of the generators during the day [2]. Moreover, VRE poses negative impacts to power systems' reliability in many countries including Thailand because it contributes to mismatches between electricity demand and power generation [3, 4]. The increased mismatches will result in a greater value of Expected Energy Not Supplied (EENS) which is the possibility of electricity outages. EENS involves expected outage cost that is one of the important components of power generation costs [5]. The causes of the outage in the United States can be illustrated as shown in Figure 2.

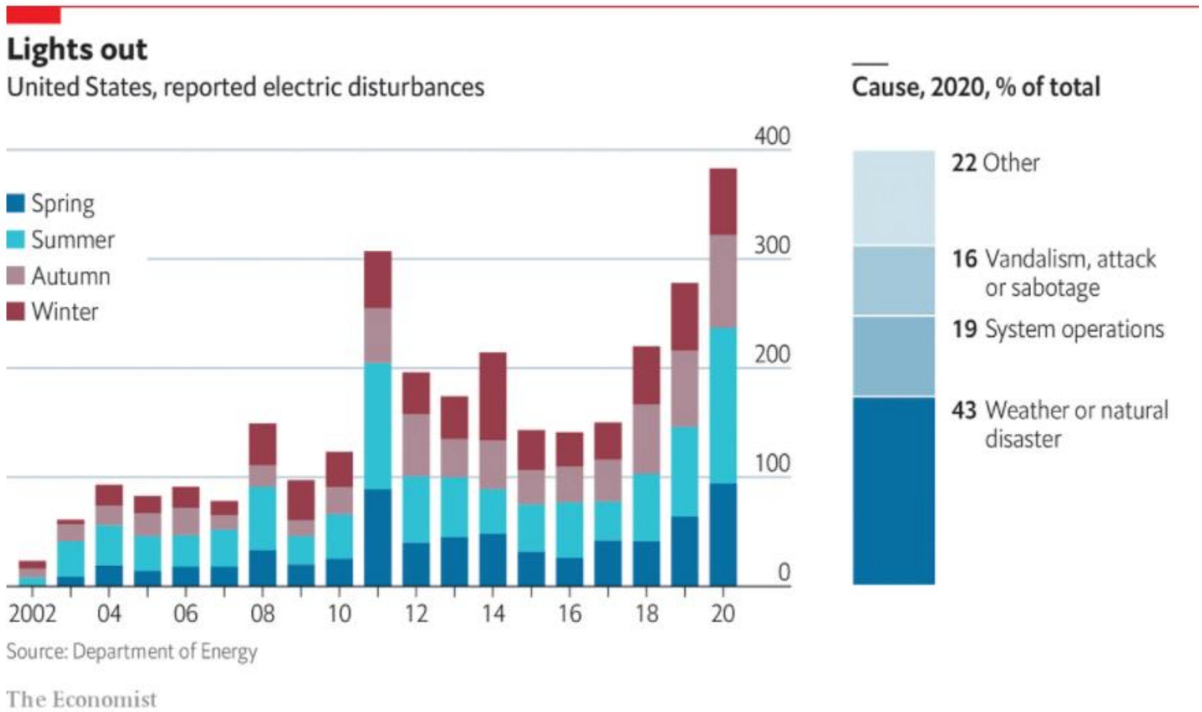

Figure 2 The cause of VRE outage in the United States [6].

Energy storage such as compress air energy storage system, flywheel energy storage system, pump storage system, and Battery Energy Storage System (BESS) are used to resolve VRE impacts. BESS is the most interesting energy storage technology for relieving the impact of VRE because of its fast response characteristics [7], and continuously decreasing installation cost [8]. Battery cost projections for 4-hour lithium-ion systems can be shown in Figure 3.

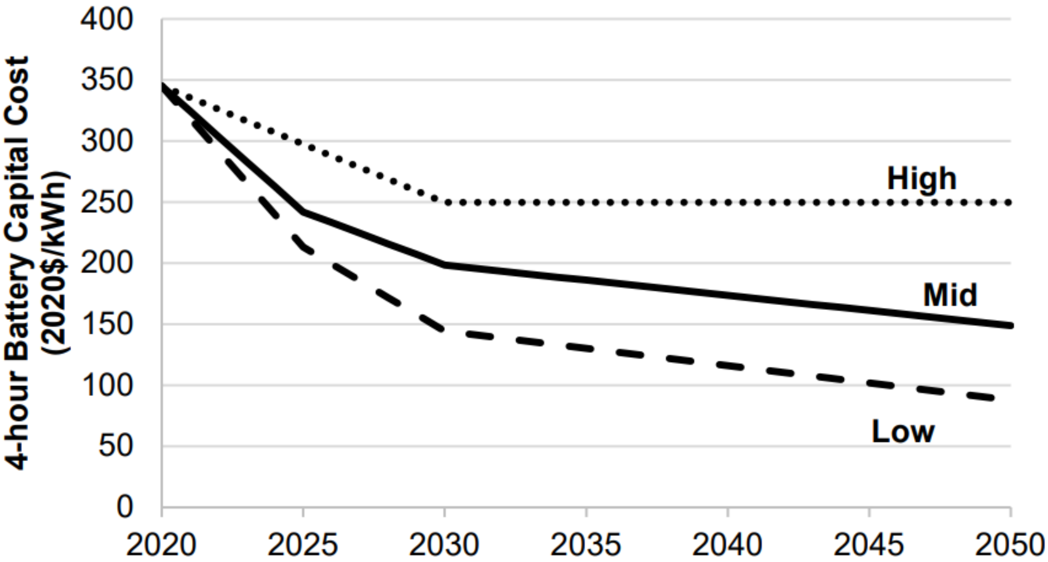

Figure 3 Battery cost projections for 4-hour lithium-ion systems [8].

BESS can provide a range of services to power systems, such as peak shaving, frequency regulation, and load shifting. Peak shaving involves storing excess energy during low-demand periods and discharging the stored energy during high-demand periods to reduce peak power demand. Frequency regulation involves using the stored energy to help balance the frequency of the power system, particularly when there is a sudden increase or decrease in demand. Load shifting involves shifting the time of energy consumption from high-demand periods to low-demand periods by storing energy during low-demand periods and discharging it during high-demand periods.

BESS can be designed using different types of battery chemistries, such as lithium-ion, lead-acid, sodium-sulfur, and flow batteries. Among these, lithium-ion batteries are the most widely used in BESS due to their high energy density, long cycle life, and relatively low maintenance requirements. The cost of lithium-ion batteries has been declining rapidly in recent years due to increasing demand and economies of scale. Figure 3 shows the projected cost reductions for 4-hour lithium-ion BESS systems.

In addition to cost reduction, there has been a growing interest in the development of new battery chemistries and technologies that can further improve the performance and cost-effectiveness of BESS. For example, the development of solid-state batteries, which use a solid electrolyte instead of a liquid electrolyte, could improve safety, energy density, and cycle life. Redox flow batteries, which use a liquid electrolyte that can be replenished, could provide longer-duration storage at lower cost.

Battery Energy Storage System (BESS) is a promising technology for mitigating the impact of variable renewable energy (VRE) on the power system. In order to maintain reliable operation of the power system and support VRE, utility-scale BESS are becoming increasingly popular, and there are many plans to install them in various countries around the world.

Behind The Meter (BTM) BESS installed on-site with VRE generators primarily aims at customer benefits such as electricity bill saving and demand-side management [9]. Utility scale BESS are more popular in providing services to maintain reliable operation of the power system (ancillary services) and support the VRE impact [10]. In many countries, there are many plans to install utility scale BESS, for example in the United States it plans to install 3,616 MW more in 2020-2023 and increase the total installed capacity to 17 GW in 2050 [11]. Planned U.S. utility-scale electricity generating capacity additions (2021) can be shown in Figure 4. The BESS is used to operate in different applications such as spinning reserve, ramp rate, firm capacity, and frequency regulation services [12, 13]. However, overinvestment in BESS probably leads to high system costs which burden customers [14]. Therefore, the method to determine the optimal sizing, and optimal daily operation schedule of grid-scale BESS is needed. The method needs to be able to trade-off between the operating costs, the power generation reliability constants, the avoided expected outage cost, and the installation cost of BESS. Additionally, the method needs to be able to select the application of BESS to operate during in the most cost-effective way.

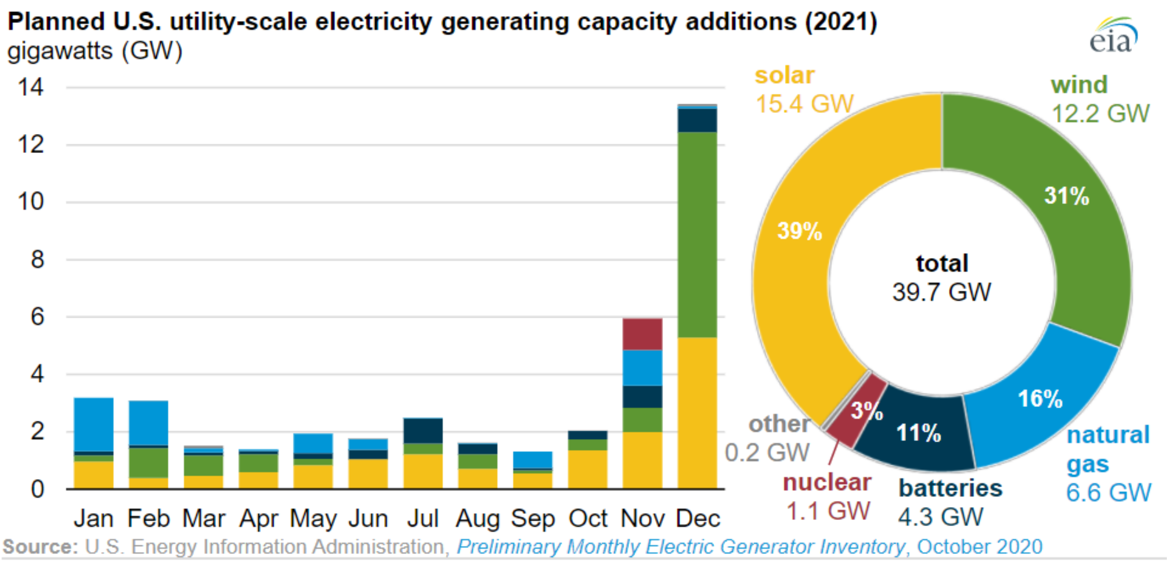

Figure 4 Planned U.S. utility-scale electricity generating capacity additions (2021).[15]

The main contributions of this study are as follows.

1. The BESS optimal daily schedule are determined considering operating costs, power-generation-reliability constraints, avoided expected-outage costs, and the installation costs of BESS. These considerations make the method comprehensive and fill the research gaps in the existing studies.

2. The optimal BESS application at a specific time during the day can be selected among reserve, regulation, and ramping, making the operation of BESS more cost effective.

3. The results from a proposed method were compared with the existing method and applied to different scenarios.

1.2 Objective

The objectives of this dissertation proposal are as follows.

1. To propose a method for analyzing power generation patterns that are suitable for working with BESS.

2. To propose the optimal BESS application among reserve, regulation, and ramping at a specific time that compensates for the impacts of VRE.

1.3 Scope of Work

The scopes of work of this dissertation are listed below.

1. The proposed method focused on compensating the impacts of variable renewable energy by using battery energy storage systems and conventional power plants, i.e., thermal, combined cycle, and gas turbine power plants.

2. The proposed method was modeled using the VRE generation error from the difference between VRE actual power and the VRE seasonal average power.

2. The proposed method was modeled using the unit commitment problem, in the considered hour period and 15 min period, for 24 hours, on a typical day.

3. This simulation model used Thailand's power generation system in 2021 as the test system.

4. This simulation model focused on grid-scale lithium-ion battery energy storage systems.

1.4 Step of Study

The steps of the study of this dissertation can be summarized as follows.

1. Studying the relevant research work as follows.

   1.1 Studying the principle of generation system both conventional and renewable power plants

1.2 Studying the general grid services of BESS

1.3 Studying the BESS characteristics

1.4 Studying the impacts of variable renewable energy on power generation system

2. Analyzing and identifying the problems as follows.

   2.1 Identifying impacts of VRE on power generation system.

   2.2 Determining the optimal daily operation schedule of grid-scale BESS.

   2.3 Comparing the result from a proposed method with the existing method and applied to different scenarios.

3. Defining the scopes of work.
4. Collecting the relevant simulation data
5. using MATLAB to model the power generation system
6. Analyzing and concluding obtained preliminary simulation results.
7. Presenting the dissertation proposal and future work.
8. Edit an analysis based on comments received from the presentation.
9. Presenting the improved method.

1.5 Expected Benefit

The expected benefits of this dissertation are as follows.

1. Reducing the impact of VRE on power generation system

2. Supporting power system planners and policymakers to integrate the grid-scale BESS into power generation systems effectively

1.6 Literature review

There are numerous studies from earlier research. Discussed the solution to the volatility of renewable energy by changing the method of operating the power generation system and applying variables related to the volatility of renewable energy to design the method of operating the power generation system.

The articles [16] presents Real-time Economic dispatch, considering the time interval of dispatch every 5-15 minutes considering fluctuations. By adding variables related to the error in forecasting electricity generation of solar and wind power generation systems. The article [17] introduces the idea of unified unit commitment and economic dispatch modeling within a unique tool that performs economic dispatch with up to 24-hour look-ahead capability. A model has been developed for the solution of the unified unit commitment and economic dispatch problem in systems with high renewable penetration. The article [18] presents a stochastic method for the hourly scheduling of optimal reserves when the hourly forecast errors of wind energy and load are considered. The article [19] analyzes the ramping needs in system operations to incorporate the uncertainty of renewable generation and proposes a ramp enhanced unit commitment model for the day-ahead energy scheduling. The article [20] proposes a fast calculation method for long-term SCUC of large-scale power systems with renewable energy. The article [21] proposes a new two-stage robust security-constrained unit commitment (SCUC) model, which aims at minimizing the operating cost in the base scenario while guaranteeing that the robust solution can be adaptively and safely adjusted according to the uncertainties of wind power, load, and N-k fault. However, these articles do not mention the use of energy storage technology to help mitigate the negative impacts of renewable energy generation systems. At present, energy storage technology has evolved in terms of both potential and cost, until there are many countries that have adopted energy storage technology, including many related studies.

In general, the methods to determine the optimal operation schedule of grid-scale energy storage are illustrated by Unit Commitment Problem (UCP). The articles [22-29] proposed the UCP method determining optimal daily operation schedules of the grid-scale energy storage considering the power system's reliability. Where [22-24] focused on the use of energy storage to accommodate an imbalance between the power supply and the power demand (regulation). The articles [25-27] use energy storage to provide the operating reserve. The article [30] presents the economic dispatch model when solar power generation systems and electric vehicles are integrated into the distribution network, The purpose is to minimize the cost of purchasing electricity and use batteries for Arbitrage. The article [31] accommodates high penetrations of wind power with the integration of battery energy storage (BES) in power systems. the proposed concept of composite operating costs includes the unit operation cost, environmental cost, reserve cost, compensation cost for wind power curtailment by battery. However, these articles have focused on specific applications of energy storage.

Many articles also support the idea that a single battery should provide multiple applications. These articles explicitly analyzed energy storage applications. The authors of [32] stated that energy storage can generate much more value when multiple, stacked services are provided by the same device or fleet of devices. The author [33] gave a general overview of the BESS applications that have demonstrated a high potential in the past few years and also described revenue-stacking possibilities. The article [34] analyzed the techno-economic performance of single-use and multi-use operation strategies on a stationary lithium-ion BESS serving a characteristic commercial consumer in Germany. The results show that the stationary BESS is highly profitable under a dynamic multi-use operation strategy.

Based on the literature review, the previous studies have mainly focused on finding energy storage operation schedules and considering minimizing energy storage operation costs and system-reliability constraints. A few studies have included multi-applications into their methods. However, none of them have considered all the mentioned issues in a single study.

1.7 Dissertation Structure

this dissertation structure is organized as follows.

Chapter 1 Introduction: This chapter presents the problem statement that identifies an overview of the necessity of using batteries to support Variable Renewable Energy (VRE) impacts. The objectives of the dissertation are also stated. In addition, scope of work, step of study, expected benefits, literature reviews, and the dissertation structure are included.

Chapter 2 Power generation systems and battery energy storage systems: This chapter provides basic knowledge about electrical system generation from conventional power plants, i.e., thermal, combined cycle, and gas turbine power plants, and renewable energy power plants, i.e., solar, wind, hydro, waste, biomass, and biogas power plants. Information about BESS, i.e., the grid services of BESS and the characteristics of BESS also stated. These are essential basic knowledge for forming the unit commitment problem.

Chapter 3 Impacts of variable renewable energy on power generation systems: This chapter provides basic knowledge about the impacts of VRE, i.e., the day-ahead planning impact, the regulation impact, and the reliability impacts.

Chapter 4 The proposed method to determine grid-scale BESS's optimal sizing and daily operation schedule: This chapter presents the proposed method to determine the optimal sizing and daily operation schedule of grid-scale BESS using the unit commitment problem.

Chapter 5 Data and assumptions: This section provides information about the data used in evaluating the BESS operation schedule consisting of conventional power plants and electricity demand data. This dissertation used Thailand's power system as the test system.

Chapter 6 Preliminary result and discussion: This chapter presents preliminary results and discussions. The results of determining the optimal sizing and operation schedule by performing the proposed methods are shown.

Chapter 7 Conclusion and Future work: This chapter summarizes the conduct of this dissertation and proposes. Furthermore, this dissertation's statements of future work are listed at the end of this chapter.

Chapter 2

Power generation systems and battery energy storage systems

Nowadays, electric power is an essential part of daily life. As a result, the electricity demand tends to increase rapidly. Figure 5 shows the growth of renewable energy installed capacity. Therefore, the power generation system needs to have enough capacity and operating reserve to meet the increasing demand. For example, the reserve capacity in Thailand can be shown in Table 1.

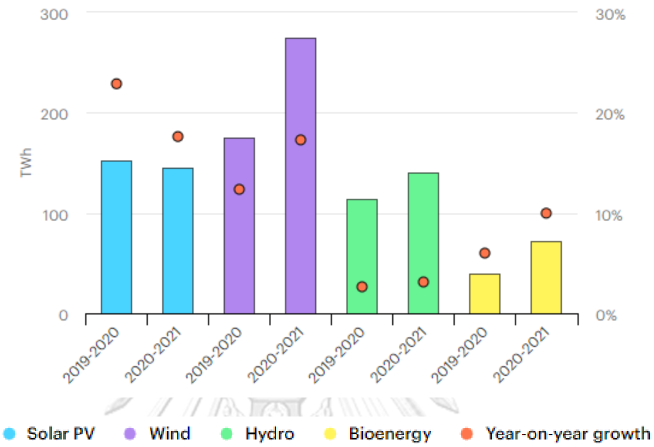

Figure 5 Renewable electricity generation increase by technology, 2019-2020 and 2020-2021 [35]

Table 1 Proportion of fuel use in electricity generation of EGAT in 2021

Years	Peak load (MW)	Installed capacity (MW)
2564	34,006	53,966
2565	35,213	55,731
2570	41,070	57,569
2575	47,303	67,731
2580	53,997	77,211

The main energy source for electricity generation in Thailand in 2021 is natural gas fossil fuels, which accounts for about 52.0% of electricity generation, followed by hydro at 14.6% and coal at 11.3%. Due to the limited availability of fossil fuels, the price of fossil fuels tends to rise. In addition, the production of electricity from fossil fuels affects the environment. Therefore, renewable energy plays an increasingly important role in generating electricity. The proportion of fuel used in electricity generation by the Electricity Generating Authority of Thailand is shown in Table 2.

Table 2 Proportion of fuel use in electricity generation of EGAT in 2021 [36]

Fuel type	Installed capacity (MW)	Percentage (%)
Gas	28,057	52.0
Hydro	7,866	14.6
Coal	6,110	11.3
Fuel Oil/Diesel	2,972	5.5
Renew	8,663	16.1
HVDC (Thai-Malaysia)	300.00	0.5
Total	53,968	100.00

This chapter provides basic knowledge about electrical system generation from conventional power plants, i.e., thermal, combined cycle, and gas turbine power plants, and renewable energy power plants, i.e., solar, wind, hydro, waste, biomass, and biogas power plants. Information about BESS, i.e., The grid services and features of BESS are also described. These are necessary foundational skills for solving the unit commitment dilemma.

2.1 Fossil fuel power plants

A fossil fuel power plant is a power plant that uses fuel, coal, natural gas, diesel, and fuel oil to generate electricity. Fossil fuel power plants are the power plants that are considered dispatchable power plants. System operators can operate the power plants. The system operators know which type of power plant should be utilized more to adequately accommodate the fluctuation of electricity demand and VRE generation. In this dissertation, it is divided into three types as follows:

2.1.1 Thermal power plants

Thermal power plants are power plants that use coal or fuel oil as fuel to generate electricity. By relying on the heat obtained by burning fuel to boil water. to obtain steam with high temperature and pressure to drive a steam turbine with a shaft to connect to the generator. Then the steam passing through the steam turbine passes through the condenser to condense into water. And was sent back to use the heat in the radiator again. The working principle of the thermal power plants is shown in Figure 6.

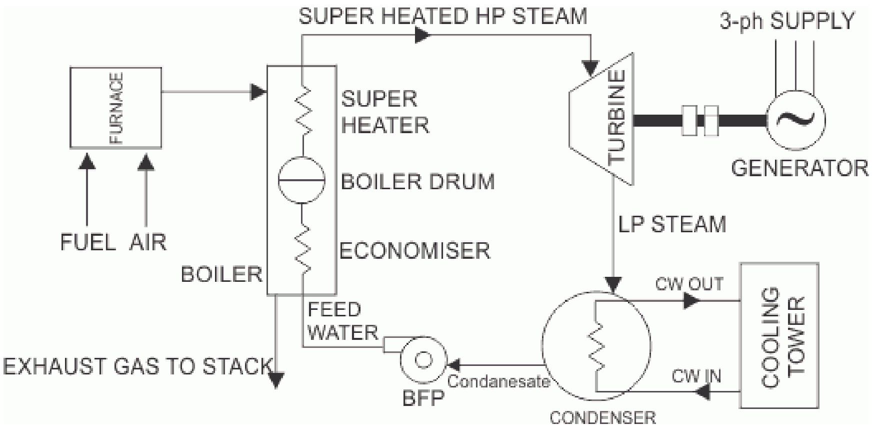

Figure 6 The working principle of thermal power plants [37]

As mentioned above, thermal power plants will use coal as the main fuel. Coal is a large energy source with a reserve that can be used for more than 200 years. As a result, coal is an easily available, cheap energy source. It is stable. In addition, coal is safe, easy to transport, and store compared to natural gas. But the disadvantage of coal is that it is a very high carbon-emitting fuel compared to other fuels such as natural gas. It also emits other pollutants such as oxides of nitrogen and sulfur (NOx, SOx).

Advantages of thermal power plants:

- It is suitable to be used as a power plant as a production base (Baseload).
- Low running costs
- The fuel used to generate electricity is cheap.

Disadvantages of thermal power plants:

- Start-up takes approximately 2-3 hours.
- have an impact on the environment.
- Contains ashes from coal fuel Requires a lot of storage space.

2.2.2 Combined cycle power plants

Combined cycle power plants are power plants that use natural gas as fuel to generate electricity. The working principle consists of two systems together, namely the gas turbine power plant system and the steam turbine power plant system by relying on the heat generated by the ignition of fuel to drive a gas turbine to generate electricity. The exhaust from a gas turbine, which has a temperature of around 500 degrees Celsius, turns the water into steam at a high temperature and pressure, which is then used to drive steam turbines for additional power generation, which is a cost-effective use of fuel. One to four gas turbines and one steam turbine make up a combined cycle power plant. The working principle of the combined cycle power generation system is shown in Figure 7.

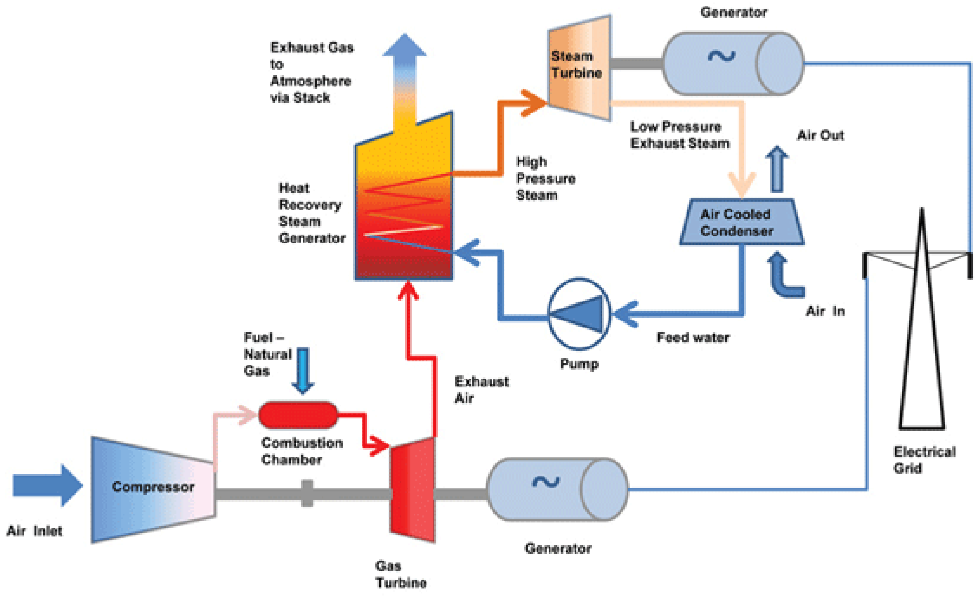

Figure 7 The working principle of combined cycle power plants [38]

Generate electricity by a combined cycle power generation system is a method that can greatly increase thermal efficiency. As the thermal efficiency gains by raising temperature and pressure are approaching their limits, the above technology is rapidly spreading as a technology that can meet the needs of the times. It has now become the main method of generating electricity, that is, generating electricity from the combined cycle power generation system. Even with a simple open cycle gas turbine with a turbine inlet gas temperature of 1,100 °C, the power generation efficiency was approximately 43% with a high-efficiency gas turbine at 1,350 °C. Celsius will have an efficiency of about 48%. At present, a new generation of gas turbines with a temperature of 1,500 ° C is being developed, which will increase the efficiency of combined cycle power generation by 53%.

Natural gas is a highly efficient fuel and can be used in various ways, but the disadvantage is the limited sources of natural gas. Natural gas storage and transportation are dangerous and expensive, as they are only found in limited areas due to geological circumstances. Natural gas may also be utilized as a feedstock in a variety of petrochemical processes. Natural gas comprises a large number of hydrocarbon molecules. As a result, natural gas prices are becoming increasingly high. For example, in Thailand, there are two methods of transportation technology. First, at the station in Map Ta Phut, Rayong Province, and transport natural gas from Map Ta Phut to users in Chonburi province (Bang Pakong Power Plant Industrial Estates in the vicinity). Second, transport by ship. This method is to transport from production sites to remote areas that cannot be transported via pipelines, such as transporting natural gas from the Middle East to the country. Japan uses this method which is quite cumbersome and costly the first liquefaction method of natural gas is used by lowering the gas temperature under pressure. Packed into containers that maintain temperature. and ship transport.

Advantages of Combined Cycle Power Plants

- Save fuel costs in the power generating unit in the steam turbine system.
- Suitable to increase power generation.
- Natural gas fuel and fuel oil can be used in generating electricity
- The efficiency of the power plant is up to 50%, which is better than the thermal power plant.

Disadvantages of Combined Cycle Power Plants

- The cost of building a power plant is high.
- In the case of using natural gas, fuel will be limited to use fuel from government policies
- It takes about one time to start up in a power plant but faster than a thermal power plant. Therefore, it is suitable for generating electricity in the Base Load range.

2.2.3 Gas turbine power plants

A gas turbine power plant is a power plant that uses diesel fuel to generate electricity. By using compressed air to high pressure of 8-10 times and sent to burn together with the fuel in the combustion chamber. Expand the air with high temperature and pressure The air is then sent to spin the gas turbine to generate electricity. The working principle of the gas turbine power generation system is shown in Figure 8.

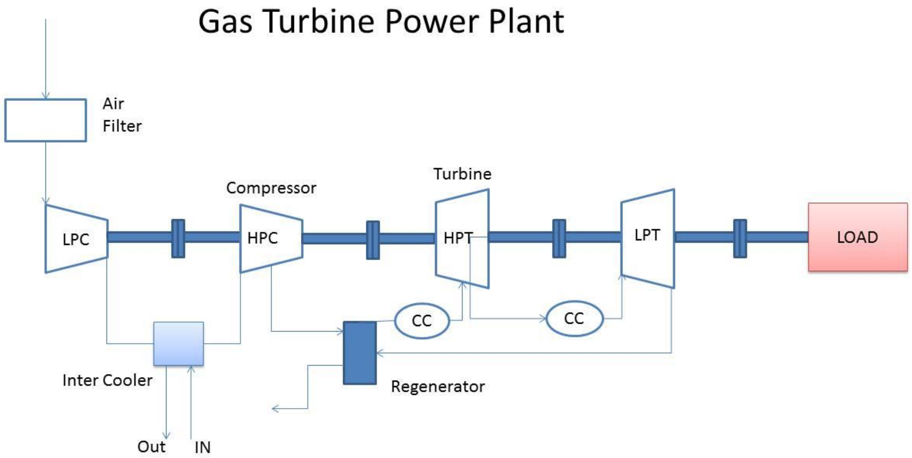

Figure 8 The working principle of gas turbine power plants. [39]

The gas turbine power generation system uses diesel fuel mainly. by diesel It's an easy-to-use fuel. No hassle to store and transport including various engines that use diesel as fuel Has been developed in technology to a high level but the disadvantage of diesel fuel is Diesel is a high-carbon fuel. The price is quite high and the price is unstable. The world's oil reserves are limited. and the amount of oil reserves has been steadily decreasing.

Advantages of gas turbine power plants.

- Able to produce additional power into the system efficiently
- It takes a short time to start the machine. Suitable to generate electricity when the electricity demand is in the peak load range.
- It takes less time to construct and install power plants than other types of power plants.

Disadvantages of gas turbine power plants

- The fuel used to generate electricity is expensive. Must purchase from abroad
- Gas turbines are expensive.

Fossil fuel power plants take responsibility for compensating variability and fluctuation in power systems. According to [40], the three key features of operational flexibility are:

- **Minimal load:** The lower the minimum load, the larger the range of generation capacity. A low minimum load can also avoid expensive start-ups and shutdowns. However, at minimum load, the power plant operates at lower efficiency and the lower the load means the more difficult it is to ensure stable combustion without supplemental firing.
- **Start-up time**: The shorter the start-up time, the quicker a power plant reaches its minimum load. Nonetheless, faster start-up times put greater thermal stress on components which reduces their lifetime. The limitation of start-up time is the allowable thermal gradient for components.
  Ramp rate: A higher ramp rate allows a power plant operator to adjust net output more rapidly. Nevertheless, rapid change in firing temperature results in thermal stress. The limitation of ramp rate is allowable thermal stress and unsymmetrical deformations, storage behavior of the steam generator, quality of fuel used, time lag between coal milling and turbine response

2.2 Renewable energy power plant

Since almost all renewable and alternative power plants are non-firm power plants, the power generation cannot be controlled. As a result, the country's maximum power generation cannot be reduced (Peak load cannot be reduced). The power generation capacity depends on various factors. According to the technology of electricity production as follows.

- Solar PV
- Wind Turbine
- Hydro power plants
- Mini hydro power plants
- Waste power plants
- Biomass power plants
- Biogas power plants

Each power plant may consist of different generator technologies. Suitable for that fuel, for example, the production of electricity from the sun with a solar photovoltaic system requires inverter technology to convert electricity from direct current to AC. In contrast, wind and hydro power generation rely on wind turbines or water turbines and synchronous/inductive generators to produce alternating current.

In addition, the production of electricity from biomass, biogas, and waste will rely on piston engine technology. Steam generation systems, steam turbines, gas turbines, converters, and synchronous/inductive generators. However, the technology mentioned above is just the basic technology for generating electricity.

Each renewable power plant may use more, less, or equal to the technology mentioned above. It depends on the technology being developed more and more each year. The power generation of renewable and alternative energy power plants is divided into two types as follows:

Power plants from renewable energy that cannot control their capacity are power plants that cannot determine or control the amount of fuel source when they need to generate electricity from that power plant, comprising solar power plants and wind power plants.

2.2.1 Solar PV power plants

Solar PV power plants, also known as solar farms, generate electricity by converting the sun's energy into electricity through the use of photovoltaic (PV) cells. The amount of electricity generated by a solar PV power plant is affected by various factors, including the intensity and duration of sunlight, the orientation and angle of the solar panels, and the weather conditions. The amount of sunlight that hits an area on a surface is commonly referred to as solar insolation, and it directly affects the solar potential at that area. Solar insolation varies depending on several factors such as geographic location, season, and time of day. For example, solar insolation is higher in equatorial regions compared to polar regions, and it is generally higher in the summer months compared to the winter months.

The relationship between solar insolation and solar power generation can be represented graphically as a bell curve, with the peak of the curve representing the maximum solar power generation capacity and the tail of the curve representing the minimum solar power generation capacity. On a typical sunny day, solar power generation is at its peak during the middle of the day when the sun is highest in the sky, and it gradually decreases towards the morning and evening. However, on cloudy or rainy days, the amount of solar insolation decreases, leading to a lower solar power generation capacity. Similarly, solar power generation is affected by seasonal changes in solar insolation, with the highest solar power generation capacity observed during the summer months and the lowest during the winter months.

In addition to solar insolation, the orientation and angle of the solar panels also affect the solar power generation capacity of a solar PV power plant. The orientation of the panels determines the direction that they face, while the angle of the panels determines the tilt or angle of the panel relative to the ground. The orientation and angle of the solar panels are optimized based on the location of the solar PV power plant and the expected solar insolation patterns in that area.

Weather conditions, such as clouds, haze, and atmospheric pollution, also affect the solar power generation capacity of a solar PV power plant. Clouds and haze can reduce the amount of solar insolation that reaches the solar panels, leading to lower solar power generation capacity. Similarly, atmospheric pollution can also reduce the amount of solar insolation that reaches the solar panels, leading to lower solar power generation capacity. Moreover, extreme weather conditions such as high winds, snow, and hail can damage the solar panels and reduce the solar power generation capacity.

To maximize the solar power generation capacity of a solar PV power plant, various technological advancements have been made to improve the efficiency and reliability of solar panels. For example, the development of new materials such as perovskite and tandem solar cells has led to higher conversion efficiencies and lower production costs of solar panels. Similarly, the development of solar tracking systems and advanced control algorithms has led to more precise and efficient solar panel orientation and angle adjustments, maximizing the solar power generation capacity.

The amount of sunlight that hits an area on a surface affects the solar potential at that area, resulting in a graph of solar power generation versus time that resembles an inverted bell as shown in Figure 9. on normal days, solar power is highest during the day and lowest at night. However, on days when the weather is inclement or unusual, it may change the nature of the solar power generation capacity.

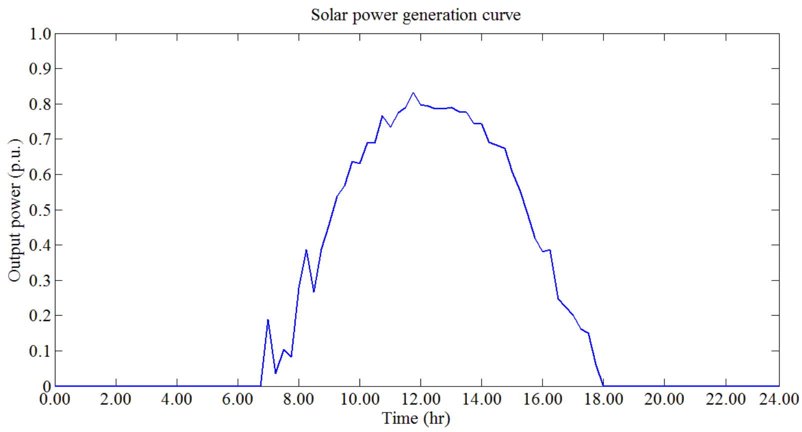

Figure 9 The example of solar power generation in a day.

2.2.2 Wind turbine power plants

Wind turbine power plants rely on the movement of wind to generate electricity. As wind speeds increase, the blades of the turbines rotate faster, producing more electricity. Conversely, as wind speeds decrease, the turbines generate less electricity. The relationship between wind speed and power output is nonlinear, and power output increases with wind speed to a certain point, beyond which the power output reaches a maximum and then begins to decrease.

The amount of electricity that can be generated from a wind turbine depends on several factors, including the wind resource, the size and type of the turbine, and the height of the turbine tower. Wind resources vary depending on location, with some areas being more favorable for wind power generation than others. In general, wind speeds are higher in areas with fewer obstructions to the flow of wind, such as open fields or coastal regions.

The southern region of Thailand, for example, has a high potential for wind power generation due to the influence of the northeast and southwest monsoons. During the northeast monsoon season from November to March, wind speeds in the lower southern region of Thailand are relatively high, making it a favorable location for wind power generation. The upper southern region, on the other hand, is influenced by the southwest monsoon from May to October, which also provides favorable conditions for wind power generation.

However, wind speed changes in Thailand are relatively high, which makes power generation from wind power uncertain. Figure 10 shows the wind power generation in Thailand from 2014 to 2018, which fluctuates greatly from month to month. This high variability in wind power generation makes it difficult for utilities to plan and manage their electricity supply, as they must balance the fluctuations in wind power generation with other sources of power generation to meet the demands of their customers.

To address this issue, utilities have implemented various strategies to manage the variability of wind power generation, including energy storage systems, demand response programs, and advanced forecasting methods. Energy storage systems such as battery energy storage systems (BESS) can store excess energy generated from wind power during periods of high wind speeds and release it during periods of low wind speeds, helping to smooth out the fluctuations in wind power generation. Demand response programs encourage customers to reduce their electricity usage during periods of high demand, which can help to reduce the need for additional power generation from other sources. Advanced forecasting methods use data from weather models and real-time wind data to predict wind power generation more accurately, which can help utilities to better manage their electricity supply.

Despite the challenges associated with wind power generation, it remains a promising source of renewable energy that can help to reduce greenhouse gas emissions and dependence on fossil fuels. With continued advancements in technology and improvements in forecasting methods and energy storage systems, wind power generation can become an increasingly important component of the world's energy mix.

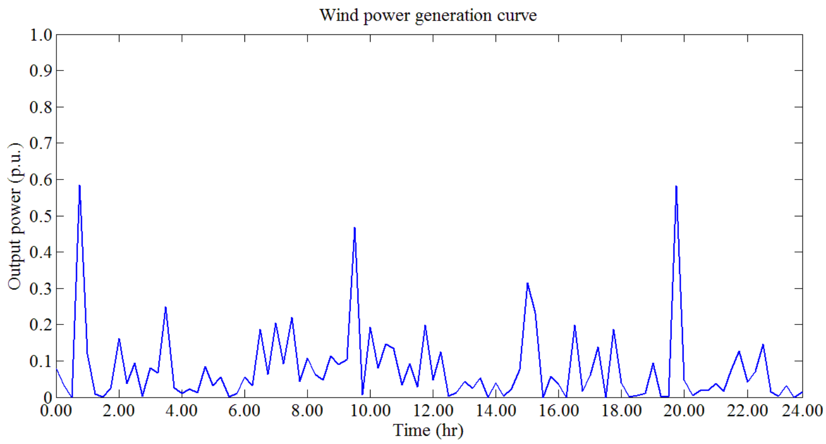

Figure 10 The example of wind power generation in a day

Power plants from renewable energy that can control their production are power plants that can determine or control the amount of fuel sources at the time they need to generate electricity from that power plant. Power plant from waste, biomass, and biogas power plants from energy plants the capacity that each power plant can produce depends on the supply capacity of each fuel. For example, Thailand is a country that has a lot of agriculture, which makes it possible to procure a large number of biomass fuel sources, making biomass power plants have quite high potential, etc. However, various types of biomass fuels There is still uncertainty in each season. Too much dependence on power generation from any biomass source can lead to low reliability of certain seasons of power generation. due to the inability to supply fuel.

2.2.3 Hydro power plants

Water is an essential natural resource that is necessary to sustain life on earth. The availability of water has played a vital role in shaping human civilization, as it has been used for various purposes such as drinking, irrigation, and power generation. In many countries, water is a scarce resource, and water conservation has become an important issue. However, in the context of power generation, water is also a valuable resource that is used to generate electricity through hydro power plants.

Hydro power plants have several advantages over other forms of power generation. One of the most significant benefits is that they are environmentally friendly and produce no emissions, which makes them a popular choice for countries looking to reduce their carbon footprint. Additionally, hydro power plants are highly flexible, with the ability to quickly adjust their output to match changes in demand, making them an ideal source of peaking power.

Another advantage of hydro power plants is their ability to provide Black Start capability. This is a critical feature that enables power plants to restart the electrical grid in the event of a power outage. In the absence of hydro power plants, restoring power to the grid after a blackout would be a difficult and time-consuming process.

The hydro power plants can restart the electrical grid by gradually distributing electricity to the main distribution system.

Furthermore, the ability to start up quickly is also an essential feature of hydro power plants. Unlike other power generation technologies, hydro power plants can start up quickly and begin generating power within minutes, which is important in the context of balancing the electrical grid during times of high demand. This flexibility is especially valuable in regions where weather conditions can cause significant fluctuations in power demand, such as during hot summer days when air conditioning use is at its peak.

However, the construction of hydro power plants also has some disadvantages. The construction of large dams and reservoirs required for hydro power generation can cause significant ecological damage and disrupt ecosystems. The high cost of building and maintaining the infrastructure needed for hydro power generation is another challenge. Additionally, the availability of water can be limited in some areas due to drought, which can affect power generation.

Hydro power plants can be divided into three types

- In a conventional hydroelectric power plant, the height difference between the reservoir and the downstream area determines the water pressure, which is used to spin the turbines and generate electricity. This type of power plant has been around for many years and has proven to be reliable and cost-effective. However, the construction of conventional hydroelectric power plants requires a significant amount of resources, including land, water, and materials. The damming of rivers for power generation can also have negative environmental impacts, such as altering water temperature and flow, affecting aquatic ecosystems, and disrupting fish migration patterns. To address some of these environmental concerns, new technologies have been developed to generate hydroelectric power without the need for large dams or reservoirs. For example, run-of-river hydroelectric power plants use the natural flow of rivers to spin turbines and generate electricity. These types of power plants have a smaller environmental footprint compared to conventional hydroelectric power plants, but their power output is more variable and dependent on the seasonal and daily flow of water in the river. Despite the challenges associated with conventional hydroelectric power plants, they remain an important part of the world's energy mix. As the world seeks to transition to cleaner and more sustainable sources of energy, the role of hydroelectric power in meeting our energy needs will continue to be an important consideration. Ongoing research and development in the field of hydroelectric power generation will help to address some of the challenges associated with this technology and ensure that it remains a valuable resource for generations to come.

- Hydroelectric power stations are operational all year long (Run-of-the-river); Water is not stored upstream in this sort of power plant. Allow the water to flow through the generator, though. As a result, when water rushes through it, electricity is generated very instantly. This means that if there is too much electricity produced, it will not be able to be stored.
- Hydroelectric power plants with pumped-back water (Pumped-Storage); Like a hydroelectric battery, this sort of hydroelectric power generating. Electricity generation is similar to a reservoir power plant in principle, but this sort of generator can also pump water back up to the reservoir above. to reintroduce water as a source of electricity Continue in this manner by power plants in Thailand that use this technology.

2.2.4 Small hydro power plants

Run-of-river (ROR) hydroelectric power plants work without the use of water reservoirs, instead using the natural flow of a river to generate electricity. They offer several advantages over conventional hydroelectric power plants, including reduced environmental impact, lower construction costs, and the ability to operate with lower water requirements. Run-of-river hydroelectric power plants can be built in areas with a relatively low head of water, which allows for the use of smaller turbines and generators. Additionally, the lack of water storage reduces the risk of flooding and other environmental impacts.

However, the reliance on natural river flow also means that the output of run-of-river hydroelectric power plants is highly dependent on weather conditions and seasonal fluctuations. During periods of drought or low water flow, the power output of these plants may be significantly reduced, which can pose challenges for meeting energy demand. Additionally, the lack of a reservoir can result in fluctuations in power output that can impact grid stability.

Despite these challenges, run-of-river hydroelectric power plants remain an important component of the global energy mix. In recent years, there has been a renewed focus on the potential for these plants to provide clean and reliable energy in remote and off-grid locations, as well as to support the integration of variable renewable energy sources such as wind and solar. As with all forms of energy generation, the key to maximizing the benefits of run-of-river hydroelectric power plants lies in careful planning, design, and management, as well as ongoing innovation and improvement to address emerging challenges and opportunities.

This type of hydroelectric power generation system does not have a reservoir. Therefore, there is no water management. This makes this type of power generation system work all the time according to the amount of water flowing in the river and fluctuation as shown in Figure 11. This type of hydroelectric power plant is usually built in a relatively flat area. with buildings for irrigating higher and are often built-in areas where there is a relatively large amount of water and water flows throughout the year.

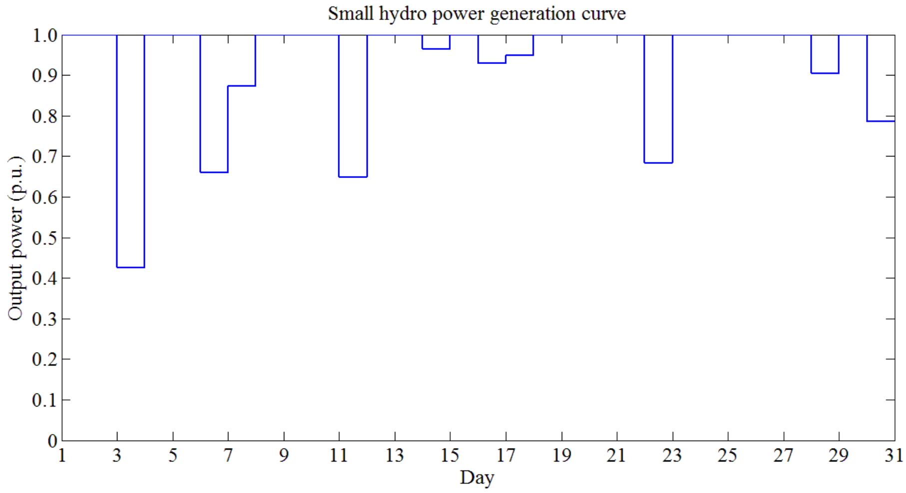

Figure 11 The example of small hydro power generation in a day

2.2.5 Waste power plants

Waste power plants are another type of renewable energy source. In contrast to other renewable sources such as solar and wind, waste power plants do not rely on weather conditions for operation. Instead, these plants generate electricity by burning various types of waste materials. However, not all waste is suitable for use in power plants. The process of choosing the right waste fuel involves separating non-burnable waste, hazardous waste, and recyclable waste. The remaining organic waste can be further segregated to produce biogas through composting, while other combustible waste is processed to reduce its size and humidity. This waste fuel is then sent into the pellet machine to obtain a waste fuel pellet that is suitable for transportation or incineration. The characteristics of electricity production from waste power plants can be seen in Figure 12. While waste power plants offer a sustainable solution for waste management, they also face challenges such as emissions and environmental concerns. Therefore, it is important to develop and implement appropriate technologies and policies to ensure the safe and efficient operation of these power plants.

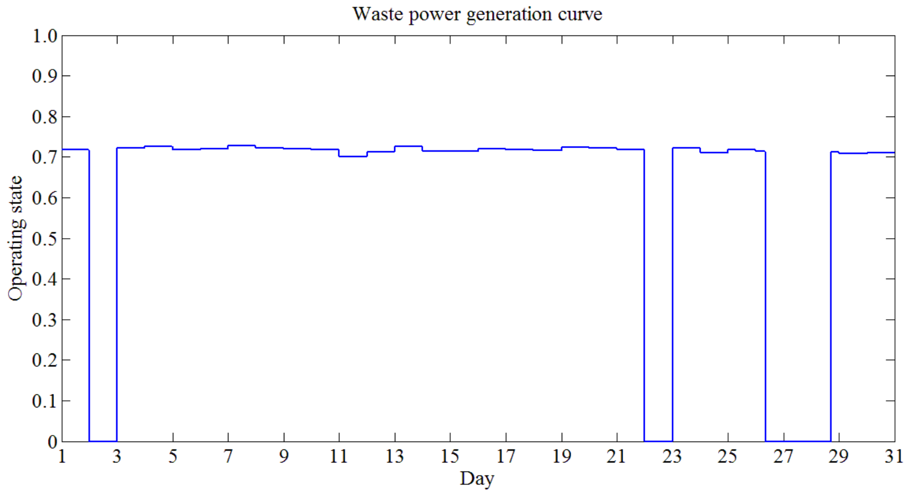

Figure 12 The example of waste power generation in a day

2.2.6 Biomass power plants

Biomass power plants offer a renewable and sustainable energy source. The use of biomass as fuel also has environmental benefits, such as reducing carbon emissions and mitigating waste disposal problems. However, there are concerns regarding the sustainability of biomass feedstocks, particularly with the increasing demand for biomass fuel for power generation. The cultivation of dedicated energy crops for biomass power generation can lead to land use conflicts and impacts on food production. It is important to ensure that the use of biomass as a fuel source is carried out sustainably and with appropriate measures to mitigate any negative impacts on the environment and society.

Biomass fuel is an organic substance that is a natural energy storage facility. which are derived from plants or animals including agricultural waste such as rice straw, rice husk, bagasse, cassava residue, etc. Most biomass power plants use direct combustion. (Direct-fired) By using biomass fuel to burn directly in the boiler (Boiler) and transfer the heat generated to the water so that the water evaporates into steam with high temperature and pressure. to spin the generator which will get the characteristics of electricity production as shown in Figure 13.

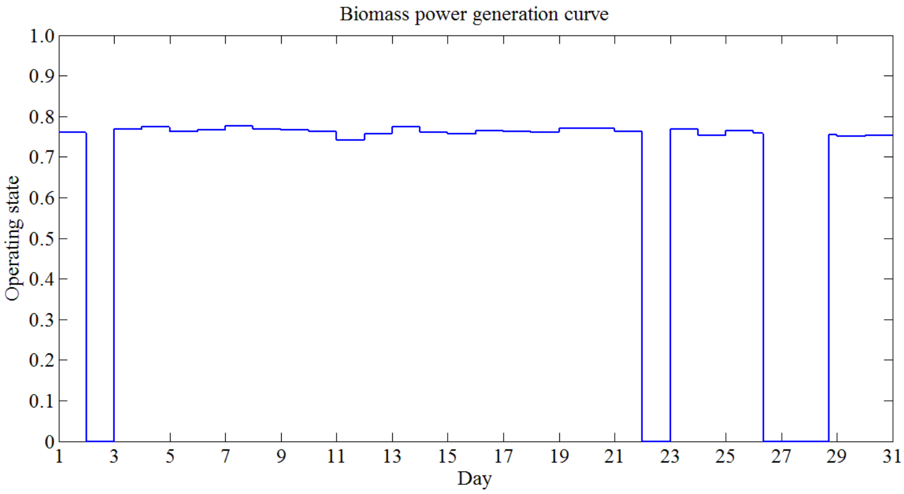

Figure 13 The example of biomass power generation in a day

2.2.7 Biogas power plants

Biogas is an attractive alternative energy source due to the wide variety of raw materials that can be used to produce it. These raw materials include waste from the industrial sector, the livestock sector, and the community sector, making biogas production a potentially valuable resource for many different types of organizations. Biogas is typically produced from the decomposition of organic substances by microorganisms, with the resulting gas consisting of methane (CH4) at a concentration of 50-70%, carbon dioxide (CO2) at a concentration of 30-40%, and other gases such as nitrogen gas (N2), hydrogen gas (H2), hydrogen sulfide (H2S), and steam. In order to generate electricity from biogas, the gas must first be processed from the biomass fuel through a process called gasification, which involves the fermentation of the fuel in anaerobic conditions. The resulting biogas can then be used to generate electricity, with the characteristics of electricity production varying depending on a number of factors, including the specific raw materials used, the efficiency of the gasification process, and the quality of the resulting biogas. The characteristics of electricity production from biogas are typically shown in Figure 14.

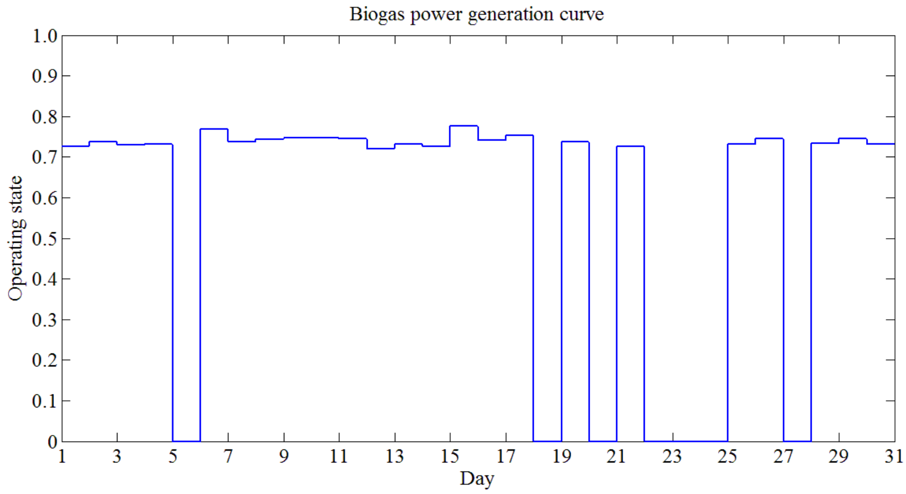

Figure 14 The example of biogas power generation in a day

2.3 Battery energy storage system

Battery energy storage systems (BESS) have become an increasingly popular technology for utilities and power system operators to store energy for later use. A BESS is an electrochemical device that charges or stores energy from the grid or a power plant and then discharges it when electricity or other grid services are required. There are different battery chemistries available or under development for grid-scale applications, including lithium-ion, lead-acid, redox flow, and molten salt, including sodium-based chemistries. Each battery chemistry has its own set of advantages and limitations, and their important technical properties differ.

Currently, lithium-ion chemistries dominate the grid-scale battery storage business in the United States and worldwide, as shown in Figure 15. This is due to the significant price drop of over 70% between 2010 and 2016, which can be attributed to technological advancements and increased manufacturing capacity. Moreover, prices are expected to continue to fall. According to Curry (2017), lithium-ion batteries are becoming more competitive as the manufacturing capacity continues to increase, driving the price of the technology down.

Additionally, the installation of lithium-ion battery storage systems has grown rapidly in recent years as a result of the falling costs and increasing demand for renewable energy. The International Renewable Energy Agency (IRENA) reported that battery storage for renewable energy applications grew at an annual rate of 100% from 2013 to 2018 (IRENA, 2018). Battery storage is an essential technology for the integration of renewable energy into the grid, providing grid operators with a means of balancing the fluctuating supply of renewable energy.

Battery energy storage systems provide many benefits for power system operators and utilities. They can help balance the supply and demand of electricity, improve power quality, increase reliability, reduce peak demand, and defer or replace the need for investment in traditional grid infrastructure. These benefits make BESS an important component of grid modernization efforts, as utilities and power system operators seek to integrate more renewable energy into the grid and improve the overall efficiency and resilience of the grid.

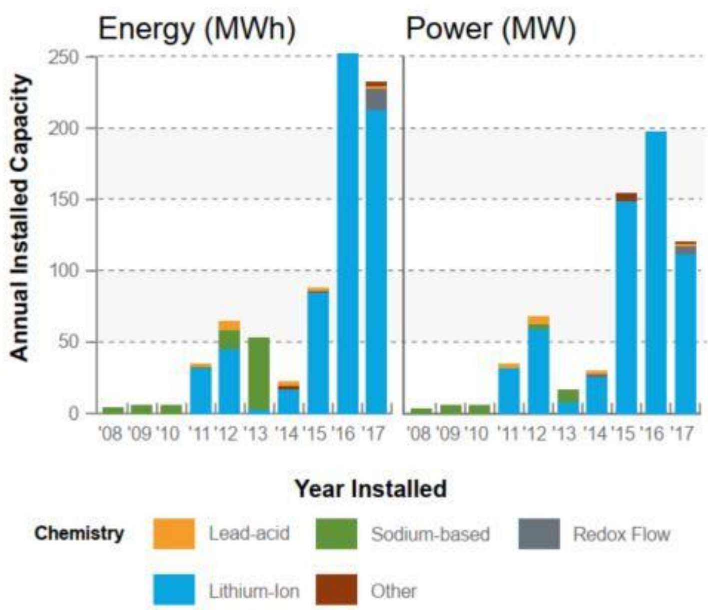

Figure 15 U.S. utility-scale battery storage capacity by chemistry (2008-2017). [12]

Lithium-ion batteries are popular in various electronic devices and electric vehicles due to their high energy density and safety features. Unlike other batteries, Li-ion batteries do not require memory or planned cycling to extend their lifespan. However, they come with certain limitations, which are summarized in Table 3.

In recent years, the adoption of Li-ion batteries for grid-scale storage applications has increased due to their ability to charge and discharge rapidly, enabling them to provide quick and effective energy storage solutions. They are also more durable than other battery chemistries, making them suitable for long-term use in a variety of applications.

However, despite the benefits of Li-ion batteries, there are also some challenges associated with their use in large-scale storage applications. One of the major challenges is the cost of the batteries. While the price of Li-ion batteries has decreased significantly in recent years due to advancements in technology and increased manufacturing capacity, they still represent a significant investment for grid-scale storage applications.

Another challenge is the limited energy density of Li-ion batteries, which limits the amount of energy that can be stored in a given space. This limitation may make them less suitable for use in applications where a large amount of energy storage is required. The maximum energy density and safety are found in Li-ion battery chemistries. To extend battery life, no memory or planned cycling is necessary. Li-Ion batteries are found in a variety of electronic gadgets, including cameras, calculators, laptop computers, and cellphones, and are increasingly being used in electric vehicles. Table 3 summarizes their advantages and disadvantages.

Table 3 Advantages and disadvantages of Li-Ion batteries.

Advantages	Disadvantages
• High specific energy and high load capabilities with power Cells	• Need for protection circuit to prevent thermal runaway if stressed

Advantages	Disadvantages
• Long cycle and extended shelf-life; maintenance-free • High capacity, low internal resistance, good coulombic efficiency • Simple charge algorithm and reasonably short charge times	• Degradation at high temperature and when stored at high voltage • Impossibility of rapid charge at freezing temperatures (<0°C, <32°F) • Need for transportation regulations when shipping in larger quantities

Battery Energy Storage System (BESS) is used to solve VRE impacts by operating as operating reserve, ramp rate, firm capacity, and frequency regulation services [10, 11]. Among all kinds of energy storage, BESS is the most interesting energy storage technology for relieving the impact of VRE because of its fast response characteristics [5] and the ability to generate reserve capacity without the minimum generation limit problem. Moreover, BESS installation cost has been decreasing [6]. Therefore, many countries have used batteries to support power system reliability and stability [5, 8, 10, 11].

2.3.1 General Grid Services Of BESS

Electricity grids require a variety of services, including frequency regulation, voltage control, spinning reserve, ramping, and black start capability, which can be provided by BESS. Frequency regulation is a critical power system service that involves continuously matching electricity supply and demand to maintain a stable grid frequency. Voltage control maintains grid voltage levels within acceptable limits to ensure the quality of electricity supplied to consumers. Spinning reserve, which is typically provided by conventional power plants, is the excess power capacity held in reserve to maintain the reliability of the power system when demand fluctuates. Ramping refers to the speed at which power generation can be increased or decreased to match changing demand, which is particularly important when integrating VRE into the grid. Finally, black start capability refers to the ability of the power system to recover from a widespread blackout and restore electricity service.

BESS can provide all of these services, and their usage in each application is dependent on the specific characteristics of the BESS technology and the power system's requirements. For instance, Lithium-ion batteries are well-suited for frequency regulation due to their high power capability and fast response time. Redox flow batteries are ideal for providing long-duration energy storage services, such as spinning reserve, due to their long cycle life and ability to provide power for many hours.

The widespread deployment of BESS can also help to reduce peak electricity demand and avoid the need for costly infrastructure upgrades. Additionally, BESS can help to increase the reliability and resiliency of the power system, particularly when integrated with renewable energy sources such as solar and wind power.

The use of energy storage systems can be used to help. The electrical system is diverse, however. The researchers will be able to summarize the classification of energy storage systems as Figure 16.

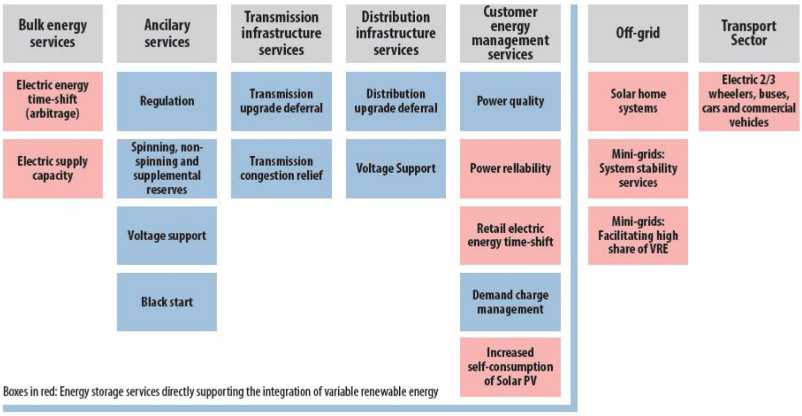

Figure 16 BESS implication.[41]

BESS is being increasingly investigated for its potential to provide significant benefits to the power system. In addition to providing power on demand, BESS have the potential to provide ancillary services to the electricity grid to ensure the reliability and stability of the power system, and better match generation to demand for electricity. The BESS usage can be allocated into 8 categories:

- Electric energy time-shift (arbitrage) is purchasing inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so that the stored energy can be discharged to used or sold at a later time when the price or costs are high during peak hour [12, 13].

- Electric supply capacity: Large-scale battery storage systems are well suited to serve as capacity reserves as they can discharge during peak hours, displacing peak generators and deferring further investment in peaking plants., could be used to defer or reduce the need to buy new central station generation capacity or purchasing capacity in the wholesale electricity marketplace [12, 13].

- Regulation: Regulation is one of the ancillary services for which storage is especially well suited. An imbalance between the power supply and the power demand can lead to a dip or a rise in grid frequency beyond the specified limits. Utility-scale battery storage systems can provide frequency regulation services [12, 13].

- Spinning, non-spinning, and supplemental reserves or Operating Reserves: The operation of an electric grid requires reserve capacity that can be called on when some portion of the normal electric supply resources unexpectedly become unavailable. There are various categories of operating reserves that function on different timescales, all of which are needed to ensure grid reliability [12, 13].

- Voltage support: Normally, designated power plants are used to generate reactive power (expressed in VAr) to offset reactance in the grid [12, 13].

- Black start: In the event of grid failure, large generators need an external source of electricity to perform key functions before they can begin generating electricity for the grid. Storage systems provide an active reserve of power and energy within the grid and can be used to energize transmission and distribution lines and provide station power to bring power plants online after a catastrophic failure of the grid [12, 13].

- Load Leveling/Load Shifting: Load leveling is characterized by power output that generally changes as often as every several minutes. When solar photovoltaic (PV) penetration, starts to increase, the shape of the load curve changes dramatically into the so-called solar duck curve. large-scale battery storage is to deploy centralized batteries in a district to store the surplus energy generated [12, 13].

- Transmission upgrade deferral: Transmission upgrade deferral involves delaying utility investments in transmission system upgrades, by Deploying BESS can help defer or circumvent the need for new grid investments by meeting peak demand [12, 13].

- Transmission congestion relief: Transmission congestion occurs when energy from dispatched power plants cannot be delivered to all or some loads because of the power flow through the transmission network may exceed the load-carrying capacity of transmission networks [12, 13].

BESS has potential to provide services that can ensure reliability and stability of power systems. According to the document [10], in 2016 the US utility scale battery storage was the most deployed for operating reserve and ancillary services such as frequency response and regulation with 550 MWh of installed capacity. While only 110 MWh was used for other purposes e.g. arbitrage, and RE curtailment. Furthermore, the document [5] states that the global trend tends to install energy storage on power systems for ancillary services than to install energy storage for other applications such as peaking capacity, etc. Among all types of ancillary service, there are three types of service that are the most popular for battery use:

- **Operating reserves**

The operation of generation systems requires reserve capacity that can be called on when some portion of the normal electric supply resources unexpectedly become unavailable. There are various categories of operating reserves i.e. spinning, non-spinning, and supplemental reserves that function on different timescales, all of which are needed to ensure grid reliability [12, 13].

- **Load leveling/load shifting**

Load following is characterized by power output that generally changes as often as every several minutes. When solar photovoltaic (PV) penetration, starts to increase, the shape of the load curve changes dramatically into the so-called solar duck curve. large-scale battery storage is to deploy centralized batteries in a district to store the surplus energy generated [10, 13].

2.3.2 Battery energy storage system characteristics

For designing BESS, installation cost must be considered so BESS characteristics significantly affect the BESS installation cost such as if power systems need the BESS that can serve large amount of energy in a short period of time, the system operator should design the BESS to be large installation capacity and slow energy serve or small installation capacity and fast energy serve. This section provides information about BESS characteristics which is essential for designing BESS. In general, the characteristics consisting of 7 parameters.

- **Rated power capacity or Available power**

Rated power capacity or Available power is the parameter that indicates the total maximum power that can be discharged from energy storages. The parameter is presented in kilowatts (kW) or megawatts (MW) [12, 13, 42].

- **Energy capacity or storage capacity**

Energy capacity or storage capacity is the maximum amount of energy that can be stored in energy storages. The parameter is presented in kilowatt-hours (kWh) or megawatt-hours (MWh) used for sized according to power storage capacity (in MWh). However, it does not mean that all of the energy can be discharged. The depth of discharge limits the discharged energy. the depth of discharge represents the limit of discharge depth (minimum-charge state).: renewable integration, peak shaving and load leveling, and microgrids. For any application, maximizing the depth of discharge minimizes the required energy storage capacity. [12, 13, 42]

- **State of charge**

State of charge, expressed as a percentage, represents the battery’s present level of charge and ranges from completely discharged to fully charged. The state of charge influences a battery’s ability to provide energy or ancillary services to the grid at any given time. [12]

- **Storage duration**

Storage duration is the amount of time storage can discharge at its power capacity before depleting its energy capacity. Storage durations relate to C-rate or autonomy of BESS which the ratio between the energy capacity (restorable energy) and maximum discharge power. For example, a battery with 1 MW of power capacity and 4 MWh of usable energy capacity will have a storage duration of four hours. The C-rate or autonomy of a system depends on the type of storage and the type of application. [12, 42]

- **Cycle life/lifetime/Durability**

Cycle life/lifetime/Durability is the amount of time or cycles a BESS can provide regular charging and discharging before failure or significant degradation. The lifetime of a BESS depends on many factors, including charge and discharge cycling, depth of discharge, and environmental conditions. The parameter is expressed as the maximum number of cycles N (one cycle corresponds to one charge and one discharge). [12, 13, 42]

- **Self-discharge**

Self-discharge occurs when the battery's energy is reduced through internal chemical reactions, or the portion of the initially stored energy has dissipated over a given amount of non-use time. [12, 42]

- **Round-trip efficiency**

Round-trip efficiency, measured as a percentage, is a ratio between released energy and stored energy. Round-Trip Efficiency: Round-trip efficiency takes into consideration energy losses from power conversions associated with operating the energy storage system. [12, 13, 42]

Chapter 3

Impacts of variable renewable energy on power generation systems

Renewable technologies' intermittency and unpredictability (particularly wind) necessitate more system reserves as well as flexible backup plants. According to numerous studies, 1 MW of conventional energy backup capacity is now required for every MW of renewable energy. Given the importance of these plants in meeting demand in the event of fluctuations in intermittent source production patterns, while also promoting renewable technologies, it is critical to ensure market conditions that encourage investments in traditional backup generation and provide a balanced energy mix in terms of sources, flexibility, and geographical distribution of plants. This chapter provides basic knowledge about the impacts of VRE i.e., the day-ahead planning impact, the regulation impact, and the reliability impacts.

3.1 Day-ahead planning impacts

In a power system, scheduling is the process of arranging generation to meet daily and peak power demands. This frequently entails estimating daily demand and planning what generation will fulfill that need at a coarse level while maintaining enough reserve margins. Because scheduling is so closely linked to projections of generation output and availability, forecasting variable renewable resources is crucial in systems with extremely high VRE levels.

The increasing penetration of renewable energy sources in power systems has brought new challenges to power system operation and planning. Among renewable sources, VRE sources such as wind and solar photovoltaic (PV) have received significant attention due to their intermittent and uncertain nature. The variability and uncertainty of VRE sources result in challenges for power system operators, including uncertainty in scheduling, ramping and balancing reserves, and curtailment of excess power. Day-ahead planning is an essential step in power system operation that aims to schedule power generation and dispatch resources to meet the forecasted load and reserve requirements. In this context, the integration of VRE sources in day-ahead planning requires a comprehensive analysis of the impacts of VRE sources on power system operation.

The integration of VRE sources in day-ahead planning can have various impacts on power system operation. One of the primary impacts is the increased uncertainty in scheduling due to the variability and uncertainty of VRE sources. This uncertainty can lead to sub-optimal scheduling and dispatching of conventional generators and may result in higher costs and reduced efficiency. Several studies have proposed different methods to handle the uncertainty of VRE sources in day-ahead planning. For example, stochastic optimization and scenario-based methods have been proposed to consider the uncertainty of VRE sources and provide more robust and reliable schedules.

Solar adoption is increasing, which makes balancing supply and demand on the grid challenging for utilities. This is because as the sun sets and PV contributes less, there is a larger requirement for power producers to quickly ramp up energy output. Another difficulty with extensive solar adoption is the possibility that PV would produce more energy than can be utilized at any given time, a phenomenon known as over-generation. As a result, system operators restrict PV output, reducing the technology's economic and environmental benefits. When curtailment happens on a regular basis throughout the year, it has minimal impact on the advantages of PV, but it can have a significant impact when PV is used more frequently.

For instance, [43] developed a day-ahead wind power uncertainty management framework that considers power system balancing operation. The proposed framework incorporates a multi-stage decision-making process that considers wind power forecasting errors, balancing operation costs, and power system constraints. The results of the study show that the proposed framework can effectively manage wind power uncertainties and reduce the impact of wind power forecasting errors on power system operation.

Another impact of VRE sources on day-ahead planning is the need for additional ramping and balancing reserves. The variability and uncertainty of VRE sources can cause significant variations in power output, which requires additional reserves to maintain system stability. This requirement for additional reserves can result in higher operating costs and reduced efficiency. Several studies have proposed different methods to estimate and schedule ramping and balancing reserves to ensure the reliability and stability of the system.

[44] proposed a probabilistic day-ahead scheduling method for wind power using two-stage stochastic programming. The proposed method considers the uncertainty of wind power generation, transmission system constraints, and market prices. The results of the study show that the proposed method can reduce the impact of wind power uncertainty on power system operation and improve the reliability and efficiency of the power system.

In addition to scheduling and reserves, the integration of VRE sources in day-ahead planning can also affect the power system's market operation. The variability and uncertainty of VRE sources can result in curtailment of excess power, which can have negative impacts on the market's competitiveness and efficiency. Several studies have proposed different methods to reduce curtailment of VRE sources, including the use of energy storage systems, demand response, and curtailment forecasting.

While the general public is just now becoming aware of these concerns, the Solar Energy Technologies Office (SETO) of the US Department of Energy has been at the forefront of exploring answers for years. The majority of SETO's systems integration subprogram-funded initiatives are geared at supporting grid operators in coping with the duck curve's problems.

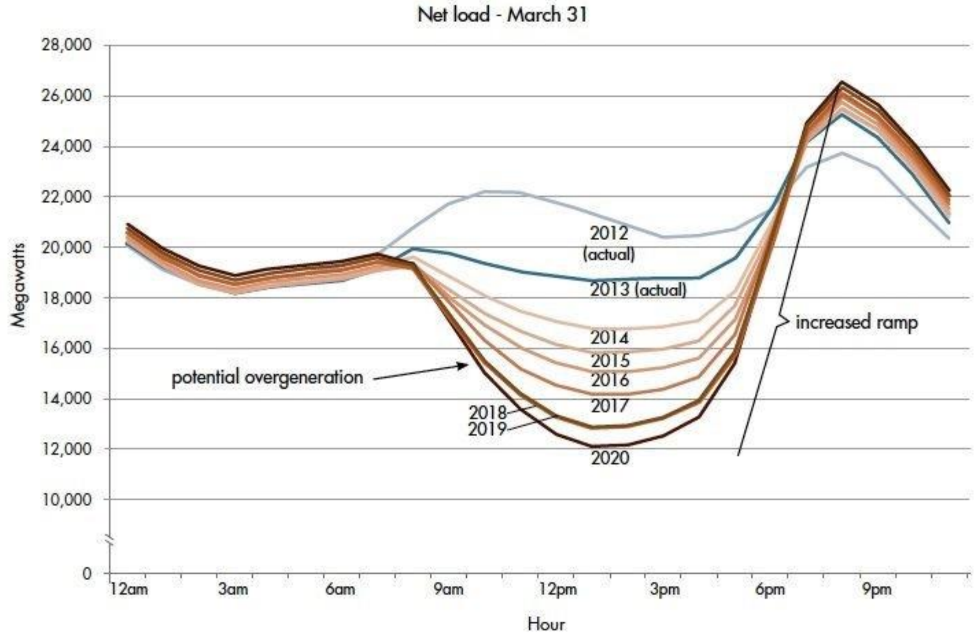

Figure 17 The example of duck curves.

Combining solar and storage technology might reduce, if not eliminate, over-generation. Curtailment isn't necessary since excess energy may be stored and utilised during peak electricity demand. SETO launched a number of programs in 2016 that paired academics with utilities to look at how storage may make it easier for utilities to rely on solar energy to meet customer demands around the clock. This research will enable utilities to integrate even more solar energy into the grid while also solving the problems they face in doing so.

In 2012, SETO launched a research project to help utilities, grid operators, and solar power plant owners better predict when, where, and how much solar energy will be generated. With more precise solar power estimates, forecasts help utilities and electric system operators better understand generation patterns and effectively manage solar resources. Thanks to its machine-learning technology, IBM, for example, witnessed a 30 percent boost in prediction accuracy. However, as the amount of solar energy generation connected to our electric system increases, greater precision in forecasting will be necessary.

There are several techniques to solve the duck curve. The lessons learned from SETO's initiatives will be critical in boosting grid flexibility and addressing over-generation challenges as solar extends across the country. According to the Energy Information Administration, installed PV will quadruple by 2030, perhaps shifting the duck curve outside of California. Because of new and improved technologies, PV will be able to provide on-demand capacity and fulfill a bigger percentage of overall power demand. [45]

The integration of VRE sources in day-ahead planning is essential for achieving a reliable, efficient, and sustainable power system operation. The variability and uncertainty of VRE sources require a comprehensive analysis of the impacts on power system operation and the development of new methods to handle the challenges. The use of stochastic optimization, scenario-based methods, and other techniques can

3.2 Reliability impact

Load following occurs throughout the day in the range of minutes to hours in a power system. To satisfy the load, the power from generation is gradually raised or lowered (or additional generation is brought on/offline) to match the natural increase or drop in demand over hours. Generators often offer this service with quick ramping capabilities or the capacity to switch on and off in tens of minutes. VREs are not normally intended to follow load unless they are linked with some sort of energy storage since they provide electricity when renewable resources are available. When using ultra-high levels of VRE in power systems, it's important to pay close attention to the entire net load once VRE is taken into consideration. The new ramping requirements may differ significantly from the initial system requirements in some circumstances.

Balancing power has different characteristics, classifications, and terminology in different power systems. In most power systems, various forms of balancing power, or balancing power products, are used at the same time since there are multiple causes of imbalances with varying characteristics. Balancing power types can be classified in a number of ways:

- purpose (operating/non-event v. contingency/event reserve)
- state of supplying power plant (spinning v. stand-by reserve)
- target system (synchronous system v. balancing area)
- response time (fast v. slow)
- activation frequency (direct/continuously v. scheduled)
- way of activation (manual v. automatic)
- positive, negative, or both (upward v. downward v. symmetric)

Balancing power is referred to as "control power" in the UCTE, and there are three types: main control, secondary control, and tertiary control. They differ in terms of purpose, reaction time, and activation method.

In roughly 30 seconds, primary control power (PC) may be fully deployed. It is triggered by locally recorded frequency variation rather than TSOs since it is a shared resource inside the UCTE. At the power plant level, activation is accomplished via turbine-governor control. PC is engaged proportionally to frequency variation from 50 Hz to maximal activation at 200 mHz. It's optimized to compensate for imbalances and minimize frequency dropouts (but not restored). The mechanism is not activated by small oscillations below 10 Hz (dead band). PC stands for symmetric spinning reserve, which is utilized to keep the synchronous system balanced. It's quick, it's automatic, and it's simple., and symmetric. It's intended to be a contingency reserve (0), but it's also utilized for operational imbalances.

Within 5 minutes of activation, secondary control power (SC) must be available. TSOs use an automated generation control (AGC) signal that is updated every few seconds to turn it on automatically and centrally. SC is used to re-balance the appropriate balancing region and restore nominal frequency, such that at steady-state, imbalances are replaced by SC from the same balancing area. Some standby hydro plants may generate SC, although synchronized thermal generators are the most common source. As a result, it's an automated reserve with direct activation that balances both the synchronous system and the balancing area up and down; it's also a spinning reserve to a considerable extent.

SC is gradually replaced with tertiary control power (TC), often known as minute reserve. It may be turned on immediately or in 15-minute intervals. TSO employees make the choice to activate SC depending on the present and planned deployment of SC. Standby generators provide the majority of the TC. More technical information on the three forms of balancing power may be found in UCTE and Rebours et al [46].

3.2.1 The expected energy not supplied

Due to VRE's continued cost reduction and environmental protection pressures, Many countries/regions are planning to integrate high wind and PV penetration. Unlike most power plants, the power generation of VRE cannot be controlled by changing the amount of fuel burned or water flow rate. the power generation of VRE is dependent on weather conditions, both sunlight and wind, which are unstable, so having more VREs in the electrical system will make the overall power generation system more 'intermittency'.

Since VRE has become more involved in the power generation system, power plants that able to provide reserve capacity (dispatchable power plant) are probably less committed to the power generation system because the power plants cannot generate electricity less than the minimum generation limit [47]. This contrasts with the increased requirement for reserve capacity due to fluctuations in renewable energy. Thus, VRE penetration affects power system reliability.

In September 2016, a windstorm caused power outages across South Australia for hours to days. After that incident, researchers stated that such incidents could be avoided if the power system did not have so much VRE. In addition, by analyzing the power outage data from ERCOT, it was found that wind power outages caused the incident. Because even in extreme cold there are refrigeration systems in coal-fired power plants and natural gas pipelines. But fossil power plants can still operate normally.

The expected energy not supplied (EENS) is usually used as the index to illustrate power system reliability [48]. This index depends on the total failures probability of all generators in the system which can be calculated by created Capacity Outage Probability Table (COPT). If EENS is high, the system has a high probability that total power generation cannot support the electricity demand, contributing to the poor system reliability. EENS is used in calculation of expected outage costs by multiplying it with value of loss load (VOLL) which refers to the costs per energy not supplied as shown in equation

$$C_{outage} = EENS \times VOLL$$

Value of Lost Load (VOLL) is the cost of energy not supplied. VOLL should reflect the real cost of outages for system users. The average consumer loss determines it to an insufficient kWh, or the value the customer wishes to be paid to avoid a peak load. VOLL is vary significantly depending on geographic factors, differences in the nature of load composition, the type of consumers that are affected and their level of dependency on electricity, differences in reliability standards, the time of year, and the duration of the outage. VOLL is normally high [49] because it reflects the opportunity costs of customers when electricity is deficient. Thus, system operators should allocate adequate reserve capacity to support EENS in order to avoid the high expected outage costs. However, the reserve capacity requirement contributes to higher overall generator operating costs.

3.2.2 Spinning Reserve

In this topic will be discussed. "Meaning of Reserve Capacity Ready to Pay" and "Guidelines for Determination of Reserve Capacity Ready to Pay" in foreign countries to be used as a guideline for analyzing the impact of reserve capacity ready to pay in Thailand.

- **Definition**

1) The North American Electric Reliability Corporation (NREL)

Reserve capacity that is ready to supply for the growing demand for electricity. From a power plant connected to the electrical system and not operating at full rated load, refer to "Operating manual, NREL, 2004" [50].

2) Energy Efficiency & Renewable Energy (EERE)

Reserve capacity that can meet the electricity demand of the power plant that is running. which must respond and increase the power generation as soon as the command and can respond fully in less than 10 minutes, including reserve capacity for power plant failures, according to "Electric Market and Utility Operation Terminology, EERE, 2011" [51].

3) Union for the Coordination of the Transmission of Electricity (UCTE)

Tertiary reserve capacity from pumped-back hydroelectric power plants gas turbine power plant and thermal power plants that the machine is not running at full capacity And must be able to use the reserve power within 15 minutes, controlled by the electric transmission system operator. (Transmission System Operator: TSO) Reference from "UCTE Operation Handbook, UCTE, 2004" [52].

4) British Electricity International

The power generation that can be increased from a power plant that is not running at full capacity and can supply backup power within 5 minutes, refer to "Modern power station practice: incorporating modern power system practice, B. E. International, 1991" [53].

5) California Independent System Operator Corporation

The reserve capacity of the power plant that is running. and ready to pay to meet the electricity demand within 10 minutes, which independent electrical operators use. (Independence System Operator: ISO) to maintain a constant power system frequency during emergencies and unforeseen changes in power demand, according to "Spinning Reserve due SC, CISO Corporation" [54].

6) Indian Electricity Grid Code (IEGC)

Reserve capacity of a power plant that is running and not running at full capacity which is ready to increase production capacity in a short period To follow the result of capacity allocation (Economic Dispatch) or to support the sudden drop in power system frequency Refer to “Indian Electricity Grid Code, IEGC, 2002” [55].

7) Eric Hirst and Brendan Kirby, Unbundling Generation and Transmission Services for Competitive Electricity Markets

The reserve capacity of the power plant that is operating the power supply. and can increase the power generation immediately to cope with the interruption It can accelerate the generation of electricity to reach the maximum installed capacity within 10 minutes, according to “Unbundling Generation and Transmission Services for Competitive Electricity Markets, E. Hirst, 1998” [46].

8) Electricity Generation Authority of Thailand

Reserve power from the power plant that is running or can order to increase the power supply as soon as the system needs it. which by standard must be 800 – 1,600 MW or at least more than the largest power plant capacity. to support if there is a failure at a large thermal power plant, for example, with a capacity of 800 MW The National Power System Control Center can instantly increase the power supply to prevent problems with power cuts or blackouts. Which may spread until the power outage in a wide area (Blackout), according to the “Communication Department of the Electricity Generating Authority of Thailand, 2013” [56].

The reserve capacity during the power generation process (Operating Reserve) can be divided into different groups. according to the following criteria (Frequency Control)

Primary Frequency Control Reserve responds to noise and stops changes in power system frequency. To maintain the power system frequency within the specified range to maintain the stability of the power system. It is the reserve power from the power plant that is running. This is automatically controlled by the power plant's control system (Governor), which must respond to interference in seconds. with a term used to call such as Frequency Response Reserve

Secondary Frequency Control Reserve maintains Area Control Error and adjusts frequencies outside the specified range back to normal or 50 Hz for Thailand. It is the reserve power from the power plant that is running. which is automatically controlled by the automatic frequency control system, which can respond within several seconds. The term used to call it is Regulating Reserve.

Tertiary Frequency Control Reserve maintains the stability of the power system during Unit Commitment and Economic Dispatch. can start running quickly which is automatically controlled or not automatically from the electrical system operator There are many types of reserve capacity in this group. Divided by sources of reserve capacity such as Spinning Reserve, Synchronous Reserve, Non-Spinning

Reserve, Quick Start Reserve or divided by function of reserve capacity. such as Ramping Reserve, Load Following Reserve, Supplemental Reserve, or divided by the duration of response such as Ten-Minute Reserve, Thirty-Minute Reserve, if the reserve capacity is classified as Tertiary Frequency Control Reserve according to the function of the reserve capacity. Can be divided into 3 types as follows:

Ramping Reserve acts as a response to unexpected disturbances that occur over a long period of time, such as power plant failures. and the continuous decline in power generation from renewable energy power generation systems. which can respond within minutes to hours can be divided into

- Forecast Error Reserve serves to accommodate errors arising from the demand for electricity or the power generated from renewable power generation systems that are inaccurate from the forecast values. It is the reserve power that comes from the power plant that is running.
- Contingency Reserve serves to replace unexpected decreases in power generation, such as power plant failures. and the continuous decline in power generation from renewable energy power generation systems. It is the reserve power that comes from a power plant that is running or a power plant that can start up quickly.
- Load Following Reserve or Dispatch Reserve adjusts the power generation capacity of the power system according to the trend of electricity demand. When the electrical system operator expects the demand for electricity to increase. The reserve capacity is Load Following Reserve to be prepared to supply power to the increasing demand for electricity. If the remaining reserve capacity is lower than the specified threshold The electrical system operator may operate additional power plants to increase backup power and pay for potential failures. Load Following Reserve is the reserve power that comes from a power plant that is running or a power plant that can start operating. machine fast which can respond within minutes

Supplemental Reserve or Replacement Reserve serves to adjust the power generation of power plants that are ordered to supply different types of reserve power. returned to the level it was before it was ordered to supply reserve power. To prepare for the next call to supply backup capacity, for example when a power plant failure occurs. A running power plant uses reserve power to maintain the stability of the power system. A running power plant uses reserve power to maintain the stability of the power system. Then, slow or low-cost power plants will be ordered to run to increase the power generation. In order for power plants that have already supplied reserve power to reduce their power generation in order to prepare reserve capacity to prepare for new disruptions that may occur and to allocate new production power to make the power system have lower power generation costs which can respond within minutes.

The response time of the reserve power in the frequency control of the power system can be summarized as shown in Figure 18 [57]. However, different countries and power distribution zones determine different names and definitions of reserves as shown in Table 4 [58].

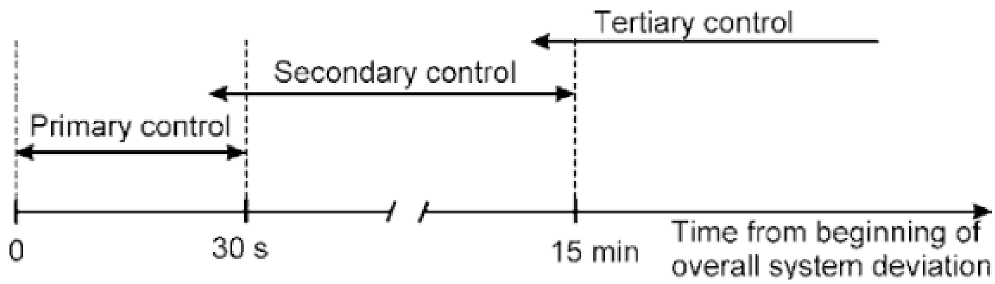

Figure 18 Operating reserve timeframe.

Table 4 Reserve definitions by countries.

Area	Primary Frequency Control Reserve	Secondary Frequency Control Reserve	Tertiary Frequency Control Reserve
ENTSO-E	Frequency Response Reserve	Regulating Reserve	Load Following Reserve Supplemental Reserve
Spain	Frequency Response Reserve	Regulating Reserve	Deviation Reserve Load Following Reserve
Ireland	Operating Reserve	Regulating Reserve	Replacement Reserve Contingency Reserve
CAISO	-	Regulation Reserve Regulation Up Reserve Regulation Down Reserve	Spinning Reserve Non-Spinning Reserve
NYISO	-	Regulation Reserve	10-Minute Spinning Reserve 10-Minute Non-Synchronized Reserve 30-Minute Spinning Reserve 30-Minute Non-Synchronized Reserve
PJM	-	Regulation Reserve	Contingency Reserve Synchronous Reserve Quick Start Reserve Supplemental Reserve

Where ENTSO-E means European Network of Transmission System Operators.
CAISO means California Independent System Operator.
NYISO means New York Independent System Operator.
PJM means Pennsylvania Jersey Maryland.

- **Spinning reserve requirement**

The Spinning Reserve Requirement is the pre-defined reserve capacity of the system. To have enough back-up capacity to supply for unprepared power system failures which is part of the allocation of production capacity where the reserve capacity is set to be paid as a value that depends on the characteristics of each power system, such as the installed capacity of the power plant. the highest electricity demand, etc. Therefore, each country will set the reserve capacity and supply differently, as shown in Table 5 where UCTE means Union for the Coordination of the Transmission of Electricity and PJM means Pennsylvania Jersey Maryland [59].

Table 5 Spinning reserve determining by countries.

Area	Spinning reserve requirement
Australia and New Zealand	$\left(10P_d^{max}+150^2\right)^{0.5}-150 \quad \max\left(u_i^t P_i^t\right)$
UCTE	$\left(10P_d^{max}+150^2\right)^{0.5}-150$
Yukon (Canada)	$max\left(u_i^t P_i^{max}\right)+10\% \times P_d^{max}$
South PJM	$max\left(u_i^t P_i^{max}\right)$
Western PJM	$1.5\% \times P_d^{max}$
Spain	between $3\left(P_d^{max}\right)^{0.5}$ and $6\left(P_d^{max}\right)^{0.5}$
France	same as UCTE and with at least 500 MW
Belgium	same as UCTE and with at least 460 MW
Netherlands	same as UCTE and with at least 300 MW
California	$50\% \max\left(5\%P_{hydro}+7\%P_{other\ generation}, P_{largest\ contingency}\right)+P_{non-firm\ import}$

When	u_i^t	is	The status of the power plant i at time t If it is equal to 1 it means the plant has been put into operation. If it is equal to 0, it means the plant has not been put into operation.
	P_i^t	is	The power that is defined to be produced by the power plant at i at time t (MW)
	P_d^{max}	is	The maximum demand for electricity (MW)
	P_i^{max}	is	The maximum power generation capacity of the power plant i (MW)
	P_{hydro}	is	Electricity produced by hydroelectric power generation systems (MW)
	$P_{other\ generation}$	is	Electricity that is not produced by hydroelectric power generation systems (MW)
	$P_{largest\ contingency}$	is	Power Dissipation in the Most Severe Failure (MW)
	$P_{non-firm\ import}$	is	The power produced by a type of power plant non – firm (MW)

From Table 5, it can be found that the determination of reserve capacity in the country and in various power distribution zones There are different ways to define:

Australia, New Zealand and PJM South set reserve capacity to be supplied from the power plant's maximum capacity. Australia and New Zealand set the standby capacity equal to the power generated by the power plant generating the most electricity at that time. For South PJM, the standby capacity is set equal to the installed capacity of the largest power plant in operation.

- UTCE, PJM, Western and Spain designate standby capacity as a function of the highest electricity demand.
- Yukon (Canada) sets standby capacity from the sum of the installed capacity of the largest power plants in operation and 10% of peak demand.
- France, Belgium, and the Netherlands determine their reserve capacity according to the same UTCE basis, and reserve capacity must be at least a certain constant.

California defines standby capacity based on the type of power plant generating power and the most severe power failure. And California considers power generated from non-firm renewable power generation systems such as solar and wind power generation systems. should be used to determine the reserve capacity and pay

The definition of standby power is largely determined based on the experience of each power distribution zone, and the terms used to refer to standby power in each power distribution zone have similar and different parts. It will be discussed in the next section.

Chapter 4

Proposed method to determine the optimal daily operation schedule of grid-scale BESS

High VRE penetration changes the shape of residual demand curves. The operations of conventional generators require fast ramping and frequent start-ups and shutdowns, leading to increased operating costs of generators during the day. A grid-scale BESS mitigates the negative impacts on a power system's reliability in different applications, such as spinning reserve, ramp-rate, firm-capacity, and frequency-regulation services. This section describes the proposed mathematical model to solve the problem. The method is de-signed to determine optimal sizing and the optimal daily-operation schedule of a grid-scale BESS to compensate for the negative impacts of VRE. The method can be used to select the BESS application that can operate most cost effectively in a given scenario. The method minimizes power-generation-system costs, BESS operation and installation costs, and the cost of EENS.

The Multi-application Battery Energy Storage System Unit Commitment (MB-UC) approach is used to determine the optimal operation schedule for BESS. MB-UC, solved through mixed-integer linear programming, provides a framework for optimizing BESS utilization and its integration into the power system. This approach considers the BESS as a flexible resource that can be charged and discharged to meet changing demand and supply conditions. The MB-UC optimization problem minimizes the operational cost of the power system while satisfying constraints such as demand, generation capacity, transmission capacity, and environmental regulations.

This paper presents a BESS model for two main applications: as a spinning reserve, and for load leveling/shifting of variable renewable energy (VRE). The BESS is operated as one of the two applications in a given period, with each application designed to be used within different time frames. For example, load leveling/shifting is usually planned a day ahead, load leveling/shifting is not planned intra-day, and spinning reserve is planned throughout the day regardless of the time frame [60, 61]. The limitation of the BESS model is defined with the following assumptions:

1. There is no BESS ramp-rate limitation. For example, a BESS can instantly discharge from not producing power to maximum power.
2. A BESS has losses from the associated power conversions. This method considered only losses that occur from the round-trip efficiency.
3. The operation cost of a BESS in this method included the charged-energy cost and the degradation cost of a BESS.
4. The installation cost of a BESS in this method included the power-installation cost and the rated energy-installation cost.
5. The method assumed electrical systems with a centralized structure, so a BESS was considered a utility asset.

In conclusion, the integration of BESS into the unit commitment optimization problem through the MB-UC approach is crucial for the future development of the power industry and the integration of renewable energy sources. MB-UC provides a framework for optimally utilizing BESS to provide various services to the power system while considering the impact on the operational cost and constraints of the system.

Thus, the method is divided into two stages differentiated by the considered time frame. The first stage is day-ahead unit commitment. This stage intends to convey the commitment start-up or shutdown status of generators on the considered day with a time resolution of 1 h. The second stage is intra-day economic dispatch, considering the day-ahead unit commitment decisions from the first stage. Detailed explanations of the two stages are provided in the following subsections.

4.1 First-Stage: Unit Commitment Problem

The objective function of the first stage is to find the optimal daily schedule of generators, and the operation schedule of a BESS. The objective function considers BESS operating costs, power-generation-reliability constants, and BESS installation costs. The objective function is shown as Equation (1).

$$Min \sum_{t=1}^{24}\left[\sum_{k=1}^{n}\left(u_{k,t}(C_{k,t}P_{k,t}\right)+u_{k,t}S_{k,t}\right] \tag{1}$$

where

$u_{k,t}$ is the status of power plant k (0 or 1)

$C_{k,t}$ is the fuel cost of power plant k ($/kWh)

$P_{k,t}$ is the output of power plant k (kW)

$S_{k,t}$ is the start-up cost of power plant k ($)

$C_{outage,t}$ is the expected outage cost ($/kWh)

The UPC is solved by considering the generator limit, the power system, and the BESS constraints as follows:

4.1.1. Generator-Limit Constraints

As mentioned in the previous sections, VRE integration requires more power-system flexibility. Conventional generators (i.e., thermal generators) provide flexibility because they have considerable mechanical inertia. However, conventional generation is limited in terms of power-system flexibility, depending on the power plants' configuration. This paper is focused on three main factors: rated power capacity (maximum power and the minimum power limit), ramp rate, and minimum up/downtime.

4.1.1.1. Rated Power Capacity or Available Power Constraints

The maximum power limit ($P_{\max,k}$) is the amount of power that a generator can produce when running at full capacity. The minimum power limit ($P_{\min,k}$) is the minimum amount of power that a generator must supply if it is committed. The boiler thermal components are stabilized at the minimum design-operating temperature. $P_{\max,k}$ and $P_{\min,k}$ are typically measured in megawatts (MW). The rated power-capacity constraints are shown in Equation (3):

$$P_{\min,k} \le u_{k,t} P_{k,t} \le P_{\max,k} \tag{2}$$

4.1.1.2. Ramp rate constraints

Ramp rate constraints refer to the maximum rate at which a power generation unit can increase or decrease its output to meet changes in demand on the power grid. These constraints are imposed to ensure that power generation units can respond quickly and smoothly to changes in demand, while also preventing damage to the power generation units and maintaining the stability and reliability of the power system.

Ramp rate constraints are typically set based on the technical characteristics of the power generation unit, such as its size and the type of fuel it uses. For example, coal-fired power plants typically have lower ramp rates than natural gas-fired power plants, due to the longer start-up and shutdown times required for coal-fired power plants.

Ramp rate constraints are typically enforced by the grid operator, who monitors the power system in real-time and adjusts the output of individual power generation units as needed to maintain the power balance. This is typically done using automatic generation control (AGC) algorithms, which adjust the output of individual power generation units to match changes in demand.

Failure to adhere to ramp rate constraints may result in power system instability and blackouts. It is imperative for power system operators to consistently monitor and enforce these constraints in order to preserve the stability, reliability, and integrity of the power system and its power generation units.

Ramp-rate constraints are the limitations of changing the power output of a generator within the considered periods. Ramp-rate constraints can be separated into three conditions. The first one is when generator k is in a start-up state, where the ramp rate of generator k must be less than $RR_{startup,k}$. The second condition is when the generator is in a shutdown state, where the ramp rate of generator k must be less than $RR_{shutdown,k}$. The last condition is when generator k is in an operating state (not in a start-up or a shutdown state), where the RR of generator k must be less than $RR_{up,k}$ and $RR_{down,k}$. Note that ramp rates are constants, depending on the configuration of the generator.

$$\left|P_{k,t}-P_{k,t-1}\right| \le \begin{cases} RR_{startup,k} & \text{if } t>\tau \text{ and } u_{k,t}-u_{k,t-\tau}=1 \\ RR_{shutdown,k} & \text{if } t>\tau \text{ and } u_{k,t}-u_{k,t-\tau}=-1 \\ RR_{up,k}, RR_{down,k} & \text{if } u_{k,t}-u_{k,t-\tau}=0 \end{cases} \tag{3}$$

Where

$RR_{startup,k}$	is start up ramp rate of power plant k (MW/min)
$RR_{shutdown,k}$	is shutdown ramp rate of power plant k (MW/min)
$RR_{up,k}$	is ramp rate up of power plant k (MW/min)
$RR_{down,k}$	is ramp rate down of power plant k (MW/min)

4.1.1.3. Minimum uptime, downtime constraints

Minimum uptime and downtime constraints refer to the minimum amount of time that a power generation unit must be online or offline, respectively, to ensure the reliable and efficient operation of the power system. These constraints are typically imposed by the grid operator to ensure that the power system has sufficient generation capacity to meet the demand for electricity, while also allowing for necessary maintenance and repairs to be performed on power generation units.

Minimum uptime constraints are imposed to ensure that power generation units are available to meet the demand for electricity. This is particularly important for units that are critical to maintaining the stability and reliability of the power system, such as those providing spinning reserves or voltage support. Minimum uptime constraints are typically set based on the capacity of the power generation unit and the expected demand for electricity.

On the other hand, downtime constraints are imposed to ensure that power generation units are taken offline for maintenance and repairs as needed. Downtime constraints are typically set based on the expected lifespan of the power generation unit and the cost of maintenance and repairs.

Violations of minimum uptime and downtime constraints can lead to system instability and blackouts. Therefore, it is essential for power system operators to continuously monitor and enforce minimum uptime and downtime constraints to maintain the reliability and efficiency of the power system.

In summary, Minimum uptime and downtime constraints are imposed by the grid operator to ensure that the power system has sufficient generation capacity to meet the demand for electricity and also to allow for necessary maintenance and repairs to be performed on power generation units. These constraints are critical for maintaining the stability and reliability of the power system and ensuring the efficient operation of the power generation units. In general, conventional power plants are unable to start up or shut down within frequent intervals. Minimum uptime is the minimum operating time before the generator is able to shut down. Minimum down time is the minimum shutdown time before the generator is able to start up. The constraints are illustrated in Equation (4).

$$u_{k,t} \neq \begin{cases} 1 & \text{if } u_{k,t-1} = 0 \text{ and } \sum_{t-downtime}^{t-1} u_k \leq 0 \\ 0 & \text{if } u_{k,t-1} = 1 \text{ and } \sum_{t-uptime}^{t-1} u_k \leq uptime \end{cases} \tag{4}$$

Where

downtime	is minimum uptime (hours)
uptime	is minimum downtime (hours)

In Equation (4), minimum uptime and downtime constraints are used to limit changes in a power plant's status. If power plant k is running for a period that is less than the minimum uptime, then u_k cannot be changed from 1 to 0. If power plant k has not stopped operating for a period that is greater than the minimum downtime, the u_k cannot be changed from 0 to 1.

4.1.2. Power-System Operational Constraints

A power-generation system is composed of conventional generators, VRE, energy storage, and electricity demand. All the elements have relationships with each other. In this stage, the day-ahead time frame is considered. The constraints are associated with the relationship (i.e., power balance and spinning reserve). These constraints are also considered in the second stage, except for the constraints in Equation (8).

4.1.2.1. Power-Balance Constraints

Power balance constraints refer to the requirement that the total power generated by all power generation units in a power system must be equal to the total power consumed by all loads at any given time. This requirement is crucial for ensuring the stability and reliability of the power system.

Power balance constraints are typically enforced by the grid operator, who monitors the power system in real-time and adjusts the output of individual power generation units as needed to maintain the power balance. This is typically done using automatic generation control (AGC) algorithms, which adjust the output of individual power generation units to match changes in demand.

Violations of power balance constraints can lead to system instability and blackouts. Therefore, it is essential for power system operators to continuously monitor and enforce power balance constraints to maintain the reliability and stability of the power system.

In summary, Power balance constraints refer to the requirement that the total power generated by all power generation units in a power system must be equal to the total power consumed by all loads at any given time. It is a crucial requirement for ensuring the stability and reliability of the power system and is typically enforced by the grid operator using AGC algorithms to match changes in demand. Ensuring power balance constraints is essential for maintaining a stable and reliable power supply. In this paper, Power balance is measured in a 1 h period. The demand in each period must be equal to the scheduled conventional power generation plus the grid-scale BESS' charge/discharge power, as shown in Equation (5). A BESS can assist the generation system in responding to the demand, which corresponds to the load-following application, according to this equation.

$$P_{d,net,t} = \sum_{k=1}^{n} P_{k,t} + P_{BESS,t} \quad (5)$$

Where

$P_{BESS,t}$ is output power of BESS (MW)

4.1.2.1. Spinning-Reserve Constraints

Spinning reserve is a type of ancillary service that refers to the ability of a power generation unit to quickly increase its output to meet unexpected changes in demand on the power grid. Spinning reserve is typically provided by synchronous generators, such as coal, natural gas, or hydroelectric power plants, that are already online and synchronized with the power grid.

In order to provide spinning reserve, the power generation unit must be able to increase its output within a short period of time, typically within 15 minutes. This is achieved by maintaining a certain amount of generating capacity offline, but ready to be brought online quickly if needed.

The use of spinning reserve is crucial for maintaining the stability and reliability of the power grid. It helps to ensure that the demand for electricity can be met even in the event of unexpected changes, such as the sudden loss of a large generator.

Spinning reserve is typically provided by power generation units under contract to the grid operator, and the cost of providing spinning reserve is typically passed on to consumers through their electricity bills.

spinning reserve is a vital ancillary service that helps to maintain the stability and reliability of the power grid by providing the ability to quickly increase power generation output in response to unexpected changes in demand. It is typically provided by synchronous generators that are already online and synchronized with the grid and is essential for maintaining a reliable and stable power supply.

In this paper, both spinning reserves from power plants and batteries are simultaneously prepared to support the fluctuation of VRE, including the possibility of a power plant failure situation.

$$SR_{k,t} = \min\left\{(P_{\max,k,t} - P_{k,t}), \tau R_{up,k,t}\right\} \quad (7)$$

$$SR_{BESS} = \min\left\{(P_{\max,BESS} - P_{BESS,t}), \tau RR_{BESS}\right\} \quad (8)$$

$$SR_{BESS,t} + \sum_{1}^{n} SR_{n,t} \geq SR_{Requirement} \quad (9)$$

Where

SR_k is spinning reserve of power plant k (MW)

SR_{BESS} is spinning reserve of BESS (MW)

τ is time available to ramp up (min)

Spinning reserve provided from a generator can be calculated from two conditions. The first condition is when the maximum power limit of a power plant minus the power generation of the plant is less than the ramp rate of the plant; the spinning reserve of a power plant is calculated by the maximum power limit of the plant minus the power generation. The second condition is when the maximum power limit of a power plant minus the power generation of the plant is more than the ramp rate of the plant; the spinning reserve of a power plant is equal to the ramp rate of the plant. The spinning reserve of BESS is calculated in the same way as generators, as shown in Equations (6) and (7), respectively. The summation of the spinning reserve provided from generators and BESS must be more than or equal to the spinning reserve requirement of the system, as shown in Equation (8). Based on this equation, BESS will be able to assist the generation system to operate as a spinning reserve.

4.1.3 BESS constraints

Previous studies have indicated that it is feasible to utilize unit commitment (UC) simulation to model the operation of a battery energy storage system (BESS). The process of unit commitment is the scheduling of power generation units to meet the demand for electricity over a specified time horizon. A BESS can be represented as a generator unit within the UC simulation, with its own distinct constraints, including maximum charging and discharging rates, energy capacity, and state of charge (SOC) limits. The UC algorithm can subsequently optimize the operation of the BESS in conjunction with other generator units, with the goal of minimizing the cost of electricity while adhering to demand and reliability constraints.

The power from BESS is limited by its installed capacity, as shown in Equation (10). Thus, a BESS has more flexibility than conventional power plants. Equations (11)– (16) show the BESS operation and installation costs. In Equation (11), the BESS installation cost can be separated into two parts, consisting of the rated power installation cost and the rated energy installation cost. The rated power installation ($\mathrm{BESS}_{installed,power}$) is the maximum power supplied by a BESS throughout the unit-commitment horizon (*T*), as shown in Equation (12). The rated energy installation ($\mathrm{BESS}_{installed,energy}$) is the maximum cumulative energy charged and discharged by a BESS throughout the unit-commitment horizon (*T*), as shown in Equation (13).

The operational cost of a BESS system in a single day can be determined by calculating the number of cycles used during that period. The number of cycles is obtained by summing the absolute power of the BESS in each time period and dividing by two, as the BESS power includes both charging and discharging. The resulting value is then divided by four to adjust the time period calculation from 15-minute intervals to one-hour intervals, and divided by the total energy that can be utilized according to the installation power. Once the number of cycles used in a single day is determined, the operating cost of the BESS system for that day can be calculated by multiplying the number of cycles by the total cost of the BESS system, and then dividing by the total cycle life of the system. Based on the information provided in Chapter 5, the total cycle life is set to be equal to 5,000 cycles. The BESS operation cost depends on BESS usage, as shown in Equation (14)-(15) shows a method to calculate BESS usage.

$$-P_{\max,BESS} \le P_{BESS,t} \le P_{\max,BESS} \tag{10}$$

$$C_{BESS,installtion} = (\text{BESS}_{installed,power} \times C_{BESS,power}) + (\text{BESS}_{installed,energy} \times C_{BESS,energy}) \tag{11}$$

$$\max\{DOD_{BESS,t} \quad \forall t \in T\} = 0.8 \tag{12}$$

$$(\text{1-DOD}_{\max}) \times \text{BESS}_{installed,energy} = \min\{E_{BESS,t} \quad \forall t \in T\} \tag{13}$$

$$\text{BESS}_{usage,cycle} = \frac{\sum_{t=1}^{n} \left| P_{BESS,t} \right|}{2 \times 4 \times 0.8 \times \text{BESS}_{installed,energy}} \tag{14}$$

$$C_{BESS,operation} = \frac{\text{BESS}_{usage,cycle} \times C_{BESS,installation}}{\text{BESS}_{total,cycle}} \tag{15}$$

$$\sum_{t=1}^{n} P_{BESS,t} = 0 \tag{16}$$

The equation (16), which assumes the sum of BESS power at all times equals zero and that BESS energy returns to its installed capacity at the end of the day, is a critical constraint in the optimization problem of unit commitment. This equation guarantees that the BESS energy storage capacity is fully charged at the conclusion of each day and is straightforward to simplify, necessitating this assumption.

Without this assumption, additional scenarios would need to be examined, as the BESS's energy at the beginning of different days would yield varying analysis results. Consequently, this assumption enables more efficient and effective operation of the BESS within the power system and streamlines the optimization problem, making it easier to resolve.

Where

$P_{\max,BESS}$	is maximum output of BESS (MW)
$C_{BESS,installtion}$	is total installation cost of BESS (Baht/MWh)
$BESS_{installed,power}$	is capacity of BESS (MW)
$C_{BESS,power}$	is power installation cost (Baht/MW)
$BESS_{installed,energy}$	is energy installation cost (MWh)
$C_{BESS,energy}$	is power installation capacity (Baht/MWh)
$C_{BESS,operation}$	is operation cost (Baht/MWh)
$BESS_{usage,cycle}$	is BESS cycle used (%)
$BESS_{degradation,cycle}$	is BESS degradation cost per cycle (%)
$BESS_{energy,cycle}$	is BESS total energy per cycle (MWh)
DOD	is Depth of Discharge (%)

It's important to note that these findings are based on the usage of pre-installed BESS. The cost of BESS installation has not been factored into these results.

4.2 Second Stage: The Economic Dispatch Problem

The objective function of this stage is to minimize the generator, BESS operation, and outage costs of the system. In this stage, the intra-day economic dispatch is solved by considering the status of each generator and BESS, which are the day-ahead results from the first stage. This stage enables the consideration of system regulation to mitigate the uncertainty of renewable energy. The resolution time of the economic dispatch problem is 15 min.

$$Min \ \sum_{t=1}^{96}\left[\sum_{k=1}^{n}\left(u_{k,t}(C_{k,t}P_{k,t}\right)+u_{k,t}S_{k,t}+C_{outage,t}\right] \tag{17}$$

In this thesis, a conceptual approach for multi-stage unit commitment with a 15-minute time resolution is presented. This choice balances computational efficiency, power system dynamics representation, and model simplification. Utilizing a 15-minute time resolution allows for the sufficient capture of the essential dynamics of the power system while keeping computational requirements manageable.

As technology advances, more efficient optimization models may enable finer simulations with resolutions such as minutes or seconds, providing improved insights and optimization of power systems. In the future, with enhanced computational capabilities or more resource-efficient techniques, these more detailed simulations could be achieved, further enhancing the understanding and optimization of power systems and ultimately leading to better decision-making in the sector.

4.2.1. Uncertainty of Renewable Energy Constraints and electricity demand

Uncertainty of electricity demand refers to the unpredictability or variability in the amount of electricity that consumers will require at any given time. This uncertainty can be influenced by various factors such as weather conditions, economic activity, technological changes, energy efficiency measures, and consumer behavior.

Effective demand forecasting is critical to manage this uncertainty. Accurate predictions allow energy providers to balance supply and demand efficiently, reducing the need for expensive and potentially environmentally damaging 'peak' power plants. However, despite sophisticated forecasting models, there will always be some degree of uncertainty due to the inherent variability and unpredictability of many influencing factors.

This uncertainty can pose significant challenges for power system operation and planning. For example, if demand is overestimated, there could be excess generation, leading to wasted resources and economic inefficiency. On the other hand, if demand is underestimated, there might not be enough capacity to meet the demand, leading to power outages and customer dissatisfaction.

Therefore, to deal with this uncertainty, power systems often have measures in place such as maintaining reserve capacity and implementing demand response programs. Furthermore, the increasing integration of renewable energy sources and the use of advanced technologies such as energy storage and smart grids are providing new strategies to manage demand uncertainty.

The integration of renewable energy sources, such as solar and wind power, into the power system can introduce significant uncertainty in the power generation output. This uncertainty can create challenges for maintaining the power balance and ensuring the stability and reliability of the power system.

The uncertainty in the power generation output of renewable energy sources can be caused by a variety of factors, such as weather conditions, the availability of solar or wind resources, and the performance of the renewable energy equipment.

This uncertainty can make it difficult to predict the amount of power that will be generated by renewable energy sources and to plan for changes in demand.

To manage the uncertainty of renewable energy, power system operators can use forecasting techniques to predict the power generation output of renewable energy sources and to plan for changes in demand. Additionally, power system operators can use energy storage systems, such as battery energy storage systems (BESS), to store excess renewable energy when it is available and to release it when it is needed to meet changes in demand.

Power system operators can also use control strategies such as demand response, to encourage consumers to adjust their energy consumption in response to changes in the availability of renewable energy.

the integration of renewable energy sources into the power system can introduce significant uncertainty in the power generation output, creating challenges for maintaining the power balance and ensuring the stability and reliability of the power system. To manage this uncertainty, power system operators can use forecasting techniques, energy storage systems and control strategies to balance the system. The uncertainty of renewable energy is the error between the predicted output power and the actual output power of renewable-energy generation. In this paper, the expected power-generation profiles are set to be the average power production based on the historical statistics in 2021. The actual output-power profiles are based on the VRE-generation profile, which depends on weather conditions.

$$P_{uncertainty,t} = (P_{VRE,Prediction,t} - P_{VRE,Actual,t}) + (P_{load,Prediction,t} - P_{load,Actual,t}) \tag{18}$$

4.2.2. EENS Constraints

Expected outage cost can be calculated depending on spinning reserve, Failure Outage Rate (FOR) of power plants, and Value of Loss Load (VOLL). In addition, EENS is the energy that is expected to be not supplied due to the power plant failures and can be calculated by the following equation.

$$C_{outage} = EENS \times VOLL \tag{19}$$

$$EENS = \sum_{e=1}^{n_e} f_e E_e \tag{20}$$

$$E_e = 0.5 \times \left[\sum_{j=1}^{m} P_{j,e} + P_{uncerainty,e} - \left(\sum_{k=1}^{n} SR_{k,e} - \sum_{j=1}^{m} SR_{j,e} \right) - SR_{BESS,e} \right] \tag{21}$$

Equation (19) shows that the EENS can be calculated by summation of energy not supplied in every situation that has the potential to cause a power outage. Equation (20) shows that the energy not supplied in each situation e can be calculated by summation of power generation of outage power plant in situation e , the uncertainty of VRE in situation e and the spinning reserve remaining in the power system in situation e .

Damage incurred in the event of a power outage (VOLL) is the average cost incurred to a power user in the event of a power outage. It is set to be equal to 54.6 baht per kilowatt hour, referring to “T. L. GROUP, 2016” [62]. Expected Energy Not

Supplied is a type of reliability index, meaning that the expected power is insufficient to meet the demand from the event that the power generation in the system is less than the expected energy demand. This can be calculated by creating a Capacity Outage Probability Table (COPT) together with a Load Duration Curve as shown in Figure 19

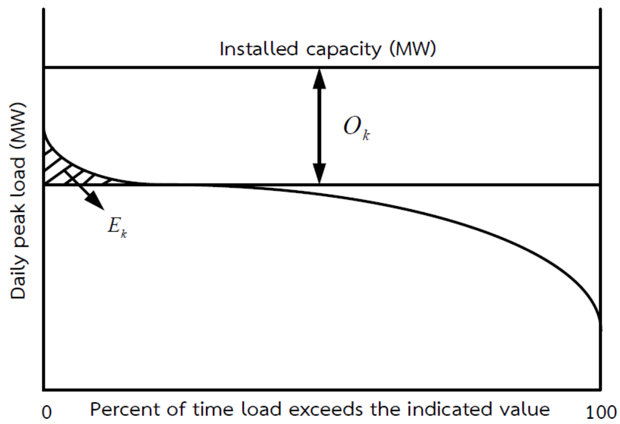

Figure 19 The energy not supplied when the system loses O_k.

from Figure 19, when the power system loses power O_k, the shaded area E_t represents the electrical power that the electricity demand is not supplied. This is because the electricity demand is higher than the capacity that the system can produce. The probability of this happening is equal to f_t can calculate the value EENS as shown in equation (21)

where N is the total number of COPT states, the $EENS$ value in this section is used to estimate reserve capacity availability. If there is a large reserve capacity ready to supply, it will result in a low $EENS$ value. E_e can be calculated as shown in equation (22). The spinning reserve calculation is shown as equation (23).

$$E_t = \sum_{j=1}^{m} P_j + P_{uncertainty,t} - \left(\sum_{k=1}^{n} SR_k - \sum_{j=1}^{m} SR_j \right) \tag{22}$$

$$SR_k = u_k \times min\{P_{max,k} - P_k, \tau R_{up,k}\} \tag{23}$$

When

SR_k	is	The spinning reserve of the power plant at k (MW)
u_k	is	The status of the power plant k (0 or 1)
$P_{max,k}$	is	The Maximum output of the power plant k (MW)
P_k	is	output power of the power plant k (MW)
τ	is	time available to ramp up (min)
$R_{up,k}$	is	ramp rate of the power plant k (MW/min)
$P_{uncertainty}, t$	is	the uncertainty of renewable energy power generation (MW) of time t
P_j	is	the output power of power plant failure at event t

		(MW)
SR_j	is	The spinning reserve of the outage power plant (MW)
n	is	number of statistics committed power plants
m	is	Number of outage power plants

From equation (22), the spinning reserve can be calculated in two cases: the case where the remaining capacity after generator power allocation is greater than the capacity to increase capacity in 15 minutes and the case. The remaining capacity after generator power allocation is less. The ability to increase capacity in 15 minutes with standby capacity is always equal to the smaller value. The calculation format can be displayed as Figure 20.

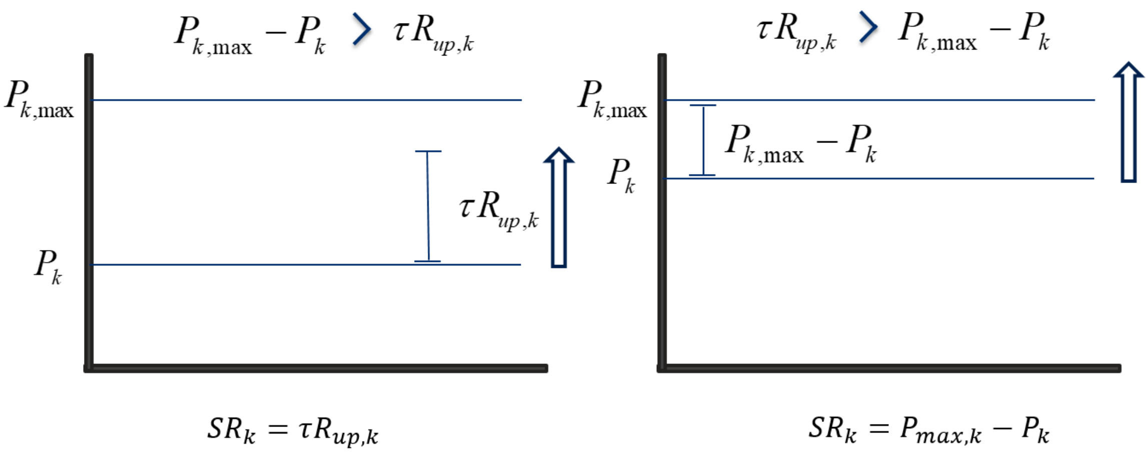

Figure 20 The calculation of spinning reserve.

The spinning reserve can be calculated after allocating capacity by using unit commitment. The spinning reserve is then used to calculate EENS. The EENS calculation method in this dissertation is based on the State Selection method based on "A. Bellinton, 1984". The principle of this method is to calculate the likelihood of power plant failure. By ignoring the events that are less likely to occur, in this case, only the failures of no more than two power plants at the same time (N-2) will be considered according to the calculation example as shown in Table 6. Based on the above information, the probability of a power plant failure in various ways can be calculated as shown in Table 7.

Table 6 Example of power plants reliability calculation.

Power plants	Probability of failures	Probability of not failures
G1	0.05	0.95
G2	0.1	0.9
G3	0.2	0.8

Table 7 The example of probability of failure calculation.

The fail power plants	Probability of failures

The fail power plants	Probability of failures
G1	(0.05)(0.9)(0.8) = 0.036
G2	(0.95)(0.1)(0.8) = 0.076
G3	(0.95)(0.9)(0.2) = 0.171
G1 and G2	(0.05)(0.1)(0.8) = 0.004
G1 and G3	(0.05)(0.9)(0.2) = 0.009
G2 and G3	(0.95)(0.1)(0.2) = 0.019

The computational result of the above example is the probability of failure in each case, which can calculate the power that cannot be supplied in the event of a power plant failure. It can be estimated from the following example.

The set of power plants committed to serving the net electricity demand is equal to 120 MW. However, during the period that forecasted electricity demand and power generated from renewable power generation systems are inaccurate, the actual net electricity demand was 10 MW higher than the forecasted value based on the power allocation. It will have power generation capacity and reserve capacity ready to distribute the mismatched power, as shown in Table 8.

Table 8 The example of power allocation and spinning reserve.

Power plants	Committed power (MW)	Spinning reserve (MW/15 min.)
G1	70	30
G2	30	10
G3	20	10

If the G1 power plant fails, the G2 and G3 power plants will use their spinning reserve and supplied power to increase the power generation and reduce the power that cannot be supplied as shown in Table 9.

Table 9 The example of the power and reserve allocation if a power plant fails.

Power plants	Allocated power (MW)
G1 (fail)	0
G2	30 + 10 = 40
G3	20 + 10 = 30

The net electricity demand is 120 MW. Due to the failure of the G1 power plant, the G2 and G3 power plants can supply a total of 70 MW of electricity. However, the actual net demand is 10 MW higher than the forecast value, which means the system electricity loses 10 MW of spinning reserve to accommodate demand deviations net of forecast values. Therefore, the available power will be equals to 60 MW (70 minuses 10). The net demand is equal to 120 MW, so that the power that cannot be supplied is 60 MW (120 minuses 60). This makes it possible to calculate EENS from equation (19), where the calculated EENS values are used to calculate the expected damage in the event of a power outage from equation (20).

4.3 Flow Chart

The Multi-Application Unit Commitment (MB-UC) scenario is a crucial aspect of determining the optimal operation schedule of a Battery Energy Storage System (BESS) in a power-generation system. The MB-UC scenario involves the integration of the BESS into the power-generation system to provide multiple applications, including spinning reserve and load leveling/shifting. The MB-UC scenario offers several benefits compared to conventional generator unit commitment and single-application BESS scenarios, such as improved cost-effectiveness and increased system flexibility.

To demonstrate the benefits of the MB-UC scenario, it is essential to perform a detailed simulation of the power-generation system, taking into account various factors such as the penetration level of Variable Renewable Energy (VRE) sources, the size of the BESS installation, and the availability of conventional power generation units. The simulation results can be used to evaluate the total cost, outage cost, startup cost, energy production, energy storage, dispatchability, and dispatch efficiency of the power-generation system.

To ensure the accuracy and reliability of the simulation results, it is important to follow a standardized and systematic procedure for optimizing the dispatch of the power-generation system. A flow chart can be used to outline the steps involved in the optimization process, including the selection of a mathematical model, the optimization of dispatch using the selected model, and the calculation of dispatchability and dispatch efficiency. The flow chart of the methods presented in sections 4.1 and 4.2 can be shown in Figure 21.

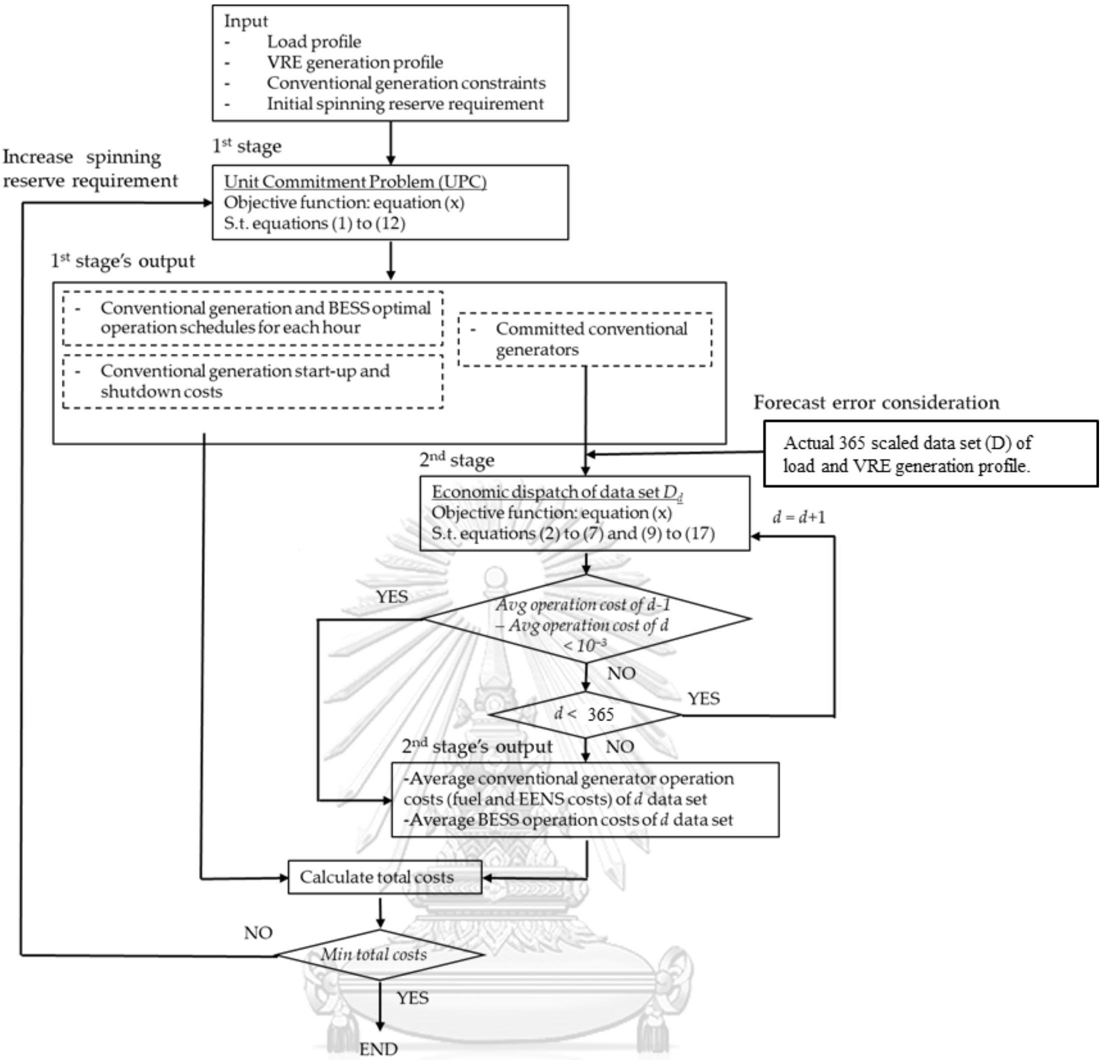

Figure 21 Flow chart

Chapter 5
Data and Assumptions of Power Generation System and BESS Modeling

The data and assumptions used in this dissertation are essential for understanding the current state of Thailand's power generation system and simulating the performance of the proposed battery energy storage system (BESS) and unit commitment strategies. This section provides information about the data used in evaluating the BESS operation schedule consisting of conventional power plants and electricity demand data. This dissertation used Thailand’s power system as the test system. The data includes information on the configuration of the power system, the generation profiles, and the characteristics of the power plants. The data is collected from various sources such as government agencies, power companies and publicly available data sets. The assumptions made in this dissertation are clearly stated and justified and are chosen based on the research question and the available data. The data and assumptions play a crucial role in modeling and simulating the performance of the BESS and unit commitment strategies and are essential for understanding the potential benefits and costs of integrating a BESS into Thailand's power generation system.

This chapter provides an overview of the data and assumptions used in modeling the power system and BESS for the analysis conducted in this study. The chapter is divided into four sections, each of which discusses the data and assumptions used for a particular aspect of the modeling process. These sections are:

- Thailand’s Power Generation System Data - This section provides an overview of the data used to model the power generation system in Thailand. The data includes information on the types of power generation units used, their capacities, and their operational characteristics.
- Electricity Demand Data - This section discusses the data used to model the electricity demand in Thailand.
- BESS Data - This section provides an overview of the data used to model the BESS in the power system. This includes information on the BESS capacity, efficiency, and discharge characteristics.
- Simulation Scenarios - This section outlines the different simulation scenarios that were developed to analyze the performance of the power system with and without BESS. Each scenario represents a different combination of power generation units, BESS configurations, and operational parameters.

Overall, this chapter provides a comprehensive overview of the data and assumptions used in modeling the power system and BESS for the analysis conducted in this study. The information presented in this chapter is crucial for understanding the results and conclusions presented in later chapters.

5.1 Thailand’s Power Generation System data

Thailand's power generation system is a complex and dynamic system that is responsible for producing and distributing electricity to the population. The data associated with Thailand's power generation system includes information on the various power generation units that make up the system, such as the type of generation technology used, the capacity of each unit, and the fuel source. It also includes information on the power transmission and distribution infrastructure, as well as data on the demand for electricity and the costs associated with generating and distributing power.

The data associated with Thailand's power generation system is collected and managed by various government agencies and private companies. This data is used to monitor and analyze the performance of the power system and to make decisions about the operation and expansion of the system.

In recent years, Thailand's power generation system has undergone significant changes, with an increasing emphasis on renewable energy sources, such as solar and wind power, and the use of advanced technologies, such as battery energy storage systems (BESS). This has resulted in an increase in the amount of data available and the need for sophisticated methods for analyzing and utilizing this data.

Thailand's power generation system data includes information on power generation units, power transmission and distribution infrastructure, demand for electricity and costs associated with generating and distributing power. It is collected and managed by various government agencies and private companies and is used to monitor and analyze the performance of the power system and to make decisions about the operation and expansion of the system. With the This subsection addresses Thailand’s power generation system modified data for modeling the test system and understanding the principle of Thailand’s power system. The data consists of the configuration of Thailand’s power system along with the generation profiles.

The number of power plants and installed capacity in each generation type, which is obtained from the conventional power plants in May 2021 according to [63], are listed in Table 10. The example of the conventional power plants is provided by [63] and shown in Table 11 and Table 12. The data consists of contracted capacity, ramp rate, failure outage rate, and minimum output.

Table 10 The number of power plants on each type and power plant capacity

Power Plant Types	Number of Power Plants	Installed Capacity (MW)
Gas turbine	8	336
Thermal	25	8,567
Combined cycle	34	20,398

Table 11 Dispatchable generation technical data I

Name	FOR	Pmin	Pmax	Ramp rate
BPK-C5	0.0199772	710.00	410.00	375.00
BPK-S	0.0199772	1386.00	840.00	1050.00
CHN-C1	0.0142694	710.00	410.00	300.00
CHN-S	0.0028539	766.00	464.00	390.00
EPEC-S1	0.0085616	350.00	200.00	112.50

Name	FOR	Pmin	Pmax	Ramp rate
GLOW-S	0.0085616	713.00	420.00	225.00
GNS-C	0.0085616	1600.00	928.00	900.00
GPG-C	0.0085616	1468.00	828.00	600.00
GPS-C1	0.0085616	700.00	350.00	225.00
GSRC-S	0.0085616	2500.00	1500.00	900.00
GUT-C	0.0114155	1600.00	928.00	900.00
KN-S	0.0085616	930.00	540.00	450.00
NB-C1	0.0085616	670.00	430.00	450.00
NB-S	0.0085616	828.00	508.00	495.00
NPO-C	0.0085616	650.00	360.00	480.00
RB-C	0.0085616	2041.00	1470.00	405.00
RPCL-C	0.0085616	1400.00	980.00	960.00
SB-C	0.0085616	1290.00	885.00	750.00
SB-S	0.0085616	1220.00	740.00	750.00
WN-C	0.0085616	1436.00	790.00	915.00
BLCP-T	0.0085616	1346.50	322.00	270.00
BPK-T-1-2	0.0085616	1051.00	560.00	150.00
BPK-T-3-4	0.0085616	1152.00	560.00	150.00
GOC-T1	0.0085616	660.00	210.00	180.00
HSA-T	0.0085616	1473.00	858.00	702.00
KA-T1	0.0114155	315.00	85.00	51.00
MM-T1	0.0114155	600.00	180.00	180.00
MM-T-8-13	0.0142694	1620.00	972.00	225.00

Table 12 Dispatchable generation technical data II

Name	Cost	Start	Min up	Min down
BPK-C5	1.6242	2178.14	1.00	1.00
BPK-S	1.4899	190.36	1.00	1.00
CHN-C1	1.6208	1255.25	1.00	1.00
CHN-S	1.5545	4013.74	1.00	1.00
EPEC-S1	1.5814	1958.12	4.00	2.00
GLOW-S	1.6899	712.91	4.00	2.00
GNS-C	1.5762	742.90	1.00	1.00
GPG-C	1.6318	3660.34	2.00	1.00
GPS-C1	1.5888	2278.35	1.00	2.00
GSRC-S	1.1564	358.37	1.00	2.00
GUT-C	1.5762	1485.80	1.00	1.00
KN-S	1.5048	2295.29	1.00	1.00
NB-C1	1.7568	1517.00	1.00	1.00
NB-S	1.6823	4240.11	2.00	1.00
NPO-C	1.1552	1778.27	5.00	4.00
RB-C	1.7829	2457.92	2.00	5.00
RPCL-C	1.7987	1233.74	1.00	2.00

Name	Cost	Start	Min up	Min down
SB-C	1.6284	1568.59	1.00	2.00
SB-S	1.5697	433.20	1.00	1.00
WN-C	1.5887	1203.71	1.00	1.00
BLCP-T	0.9967	2401.66	2.00	4.00
BPK-T-1-2	3.3112	1250.23	24.00	24.00
BPK-T-3-4	2.1882	858.34	24.00	24.00
GOC-T1	1.0553	3156.94	2.00	4.00
HSA-T	0.7073	6224.40	5.00	2.00
KA-T1	4.3539	2446.82	24.00	4.00
MM-T1	0.5853	0.00	2.00	2.00
MM-T-8-13	0.6667	0.00	24.00	24.00

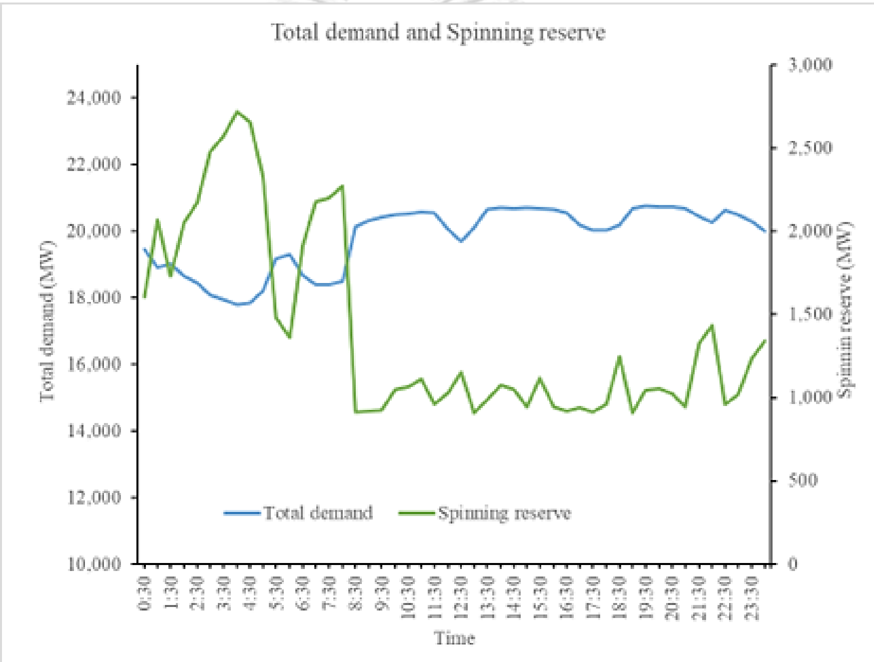

Figure 22 Power profile of Conventional power plants (Net demand) and Total demand of EGAT's power generation.

Hydroelectric power generation is a form of electricity generation that utilizes the kinetic energy of falling water to generate electricity. It is considered a clean and renewable energy source, as it does not require the use of fossil fuels. The capacity of hydroelectric power generation is limited by the availability of water, which is typically regulated by the Royal Irrigation Department.

In this thesis, the hydroelectric power generation system of the country is modeled based on historical operating data, including energy production per day and maximum capacity. This historical data is collected from various sources such as government agencies and power companies. The data is used to understand the current state of the hydroelectric power generation system and to simulate its performance under different scenarios.

It should be noted that the hydroelectric power generation systems from other countries may have different contractual limitations and operating patterns, which have been neglected in this thesis. Instead, the operation pattern is based on statistical data. This approach allows for a simplified representation of the system and its components, and allows researchers to focus on specific aspects of the system without being overwhelmed by the complexity of the entire system.

For micro hydro power, the operation data is based on historical data, and the capacity cannot be allocated. Researchers requested information from the Electricity Generating Authority of Thailand (EGAT) to be used as an example of hydroelectric power generation system operation. The data is used to understand the current state of the micro hydropower system and to simulate its performance under different scenarios. Researchers requested information from EGAT, an example of the operation of the hydroelectric power generation system is shown in Figure 23.

In conclusion, the data and assumptions used in this thesis are essential for understanding the current state of Thailand's hydroelectric power generation system and simulating the performance of the proposed hydroelectric power generation system. The data includes information on the configuration of the power system, the generation profiles, and the characteristics of the power plants. The assumptions made in this dissertation are clearly stated and justified and are chosen based on the research question and the available data. The data and assumptions play a crucial role in modeling and simulating the performance of the hydroelectric power generation system and are essential for understanding.

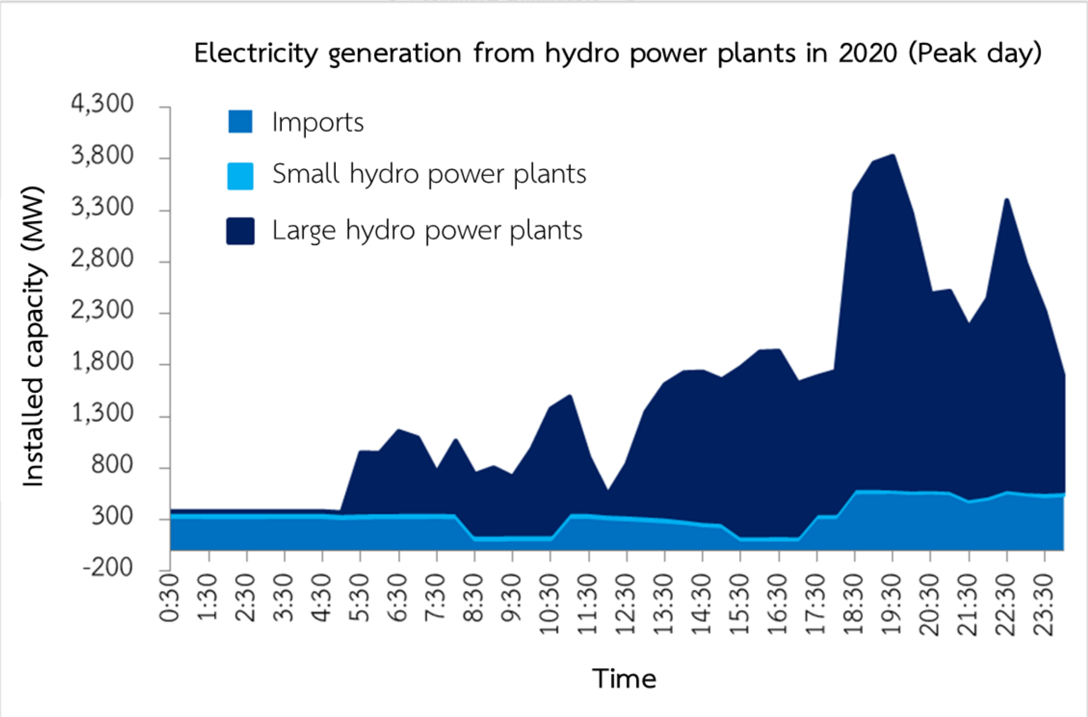

Figure 23 Hydro power plants' generation profile. [63]

For the contracted power generation system, High-Voltage Direct Current (HVDC) will require a form of production. According to the production data from statistics, it is observed that the system may not operate at all due to the high cost of fuel per unit when used to allocate production capacity. However, unlike the statistical data that indicates that the production capacity has been ordered, it is assumed that the reason for this discrepancy is due to contract restrictions. These contract restrictions may include limitations on the operation of the system during certain times, or limitations on the capacity that can be used for power generation. In order to accurately model and simulate the performance of the contracted power generation system, it is important to take into account these contract restrictions and their impact on the system's operation. Additionally, it is important to consider alternative methods for allocating production capacity, such as using renewable energy sources or energy storage systems, to mitigate the impact of high fuel costs on the system's operation.

- **Firm renewable energy power plants**

The firm renewable energy power plants group is an important segment of the power generation system as it is composed of power plants that have firm contracts, such as Small Power Producer (SPP) and cogeneration power plants. These power plants are known to be less flexible in terms of responding to changes in demand as compared to other types of power plants. However, they are still critical in ensuring a steady and reliable supply of electricity to the grid.

EGAT, or the Electricity Generating Authority of Thailand, is responsible for ordering power plants in advance. However, since these power plants do not play a significant role in meeting the changing demand for electricity, their operation is based on historical data. The researchers requested information from EGAT to better understand the operation of these power plants.

An example of a firm operating system for renewable energy generation systems is shown in Figure 23. This figure provides a visual representation of the historical data used to understand the behavior of these power plants. It is essential to consider the data for firm renewable energy power plants when simulating the power generation system and analyzing the performance of the system. This is because their contribution to the power generation system is significant, and their operation is unique as compared to other types of power plants.

Furthermore, the firm renewable energy power plants are considered as a clean and sustainable source of energy. They produce electricity with low emissions and have a minimal impact on the environment. Additionally, the firm renewable energy power plants have contracts that ensure a stable flow of energy to the grid and help to diversify the power generation system. Therefore, it is important to consider the data of the firm renewable energy power plants when performing analysis and simulation of the power generation system, BESS, and Unit commitment to ensure the integrity and reliability of the power system.

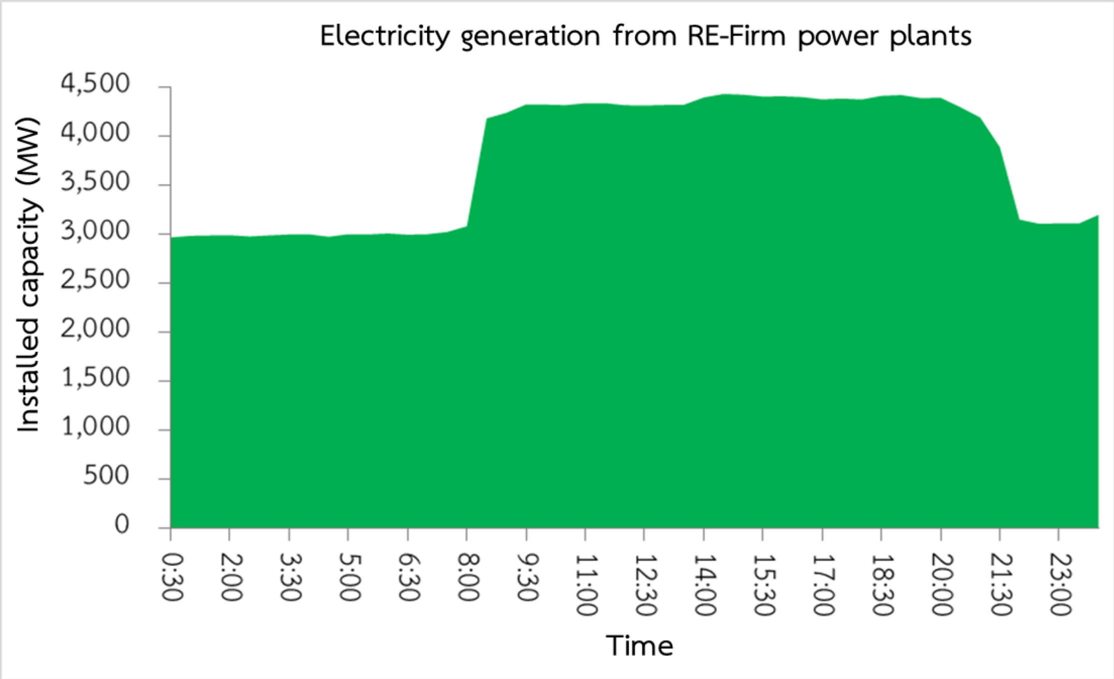

Figure 24 RE-firm power plants' generation profile. [63]

- **Variable renewable energy power plants**

Variable renewable energy power plants, such as solar and wind power generation systems, introduce significant uncertainty in the power generation output due to their dependence on environmental conditions. These power plants are unable to control the amount of power they generate and as a result, the power system must have the ability to withstand the fluctuations of renewable power generation. For example, when clouds rapidly obscure a solar power generation system, the power produced is reduced rapidly and the running power plant must be able to accelerate its operation to replace the power that the solar power generation system cannot produce. This requires the power system to have sufficient backup power and supply to sustain the uncertainty of the renewable power generation system.

To model the uncertainty of renewable energy power generation systems in this thesis, historical power generation data with a resolution of 30 minutes is used to create models of solar and wind power generation systems in various provinces of Thailand. The data is used to find the standard deviation of solar and wind power generation systems, which is used to calculate the effect on the spinning reserve. Sample data is used to calculate the standard deviation as shown in Figure 24 and Figure 25.

It is important to note that the integration of renewable energy sources into the power system can create challenges for maintaining the power balance and ensuring the stability and reliability of the power system. To manage this uncertainty, power system operators can use forecasting techniques to predict the power generation output of renewable energy sources and to plan for changes in demand. Additionally, power system operators can use energy storage systems, such as battery energy storage systems (BESS), to store excess renewable energy when it is available and to release it when it is needed to meet changes in demand. Power system operators can also use control strategies such as demand response, to encourage consumers to adjust their energy consumption in response to changes in the availability of renewable energy.

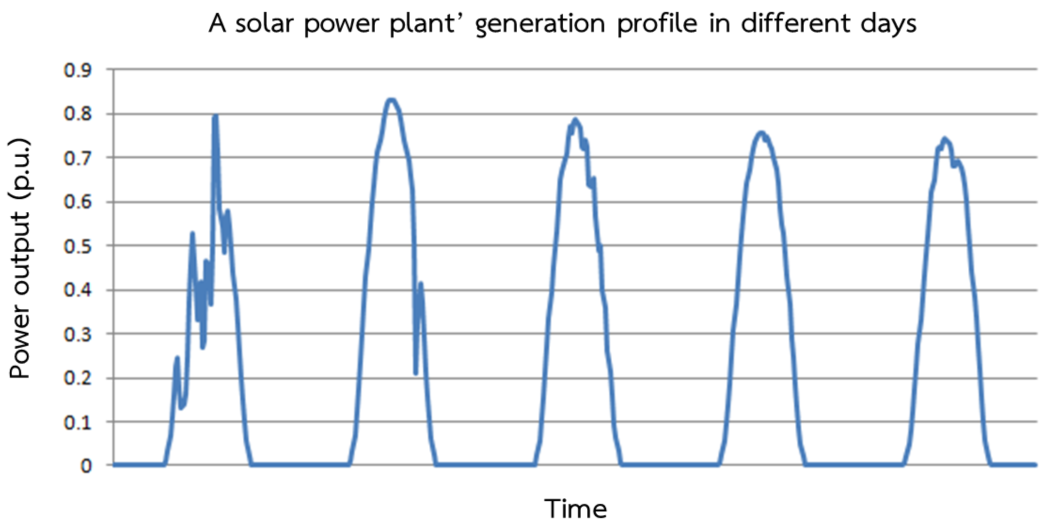

Figure 25 Solar power plants' generation profile. [63]

Solar power plants rely on the availability of sunlight to generate electricity, making their power generation output highly dependent on weather conditions. As a result, the generation profile of solar power plants can be highly variable, with significant fluctuations in output depending on factors such as cloud cover, time of day, and season.

To accurately model the generation profile of solar power plants, it is necessary to take into account the specific characteristics of the solar resource at the location of the power plant. This includes factors such as the solar irradiance, which is the amount of solar energy received per unit area, and the solar insolation, which is the amount of solar energy received per unit time.

In addition to the solar resource, other factors such as the type and efficiency of the solar panels, the orientation and tilt of the solar panels, and the performance of the power plant's electrical equipment can also have an impact on the generation profile of a solar power plant.

To accurately model the generation profile of solar power plants, it is necessary to have access to high-resolution solar resource data, as well as detailed information about the power plant's technical specifications and performance. In this thesis, data on the solar resource and power plant performance is collected from various sources such as the National Renewable Energy Laboratory (NREL), and the Electricity Generating Authority of Thailand (EGAT) and used to create detailed models of the solar power generation system. These models are then used to simulate the power plant's generation profile under various weather conditions and to analyze the impact of different factors on the power plant's performance.

Furthermore, the data is used to evaluate the operation and performance of solar power plants in the context of the larger power system, taking into account factors such as the operation of other power plants, changes in electricity demand, and the integration of renewable energy sources. This allows for a comprehensive understanding of the challenges and opportunities associated with the integration of solar power into the power system, and to identify strategies for optimizing the performance of solar power plants.

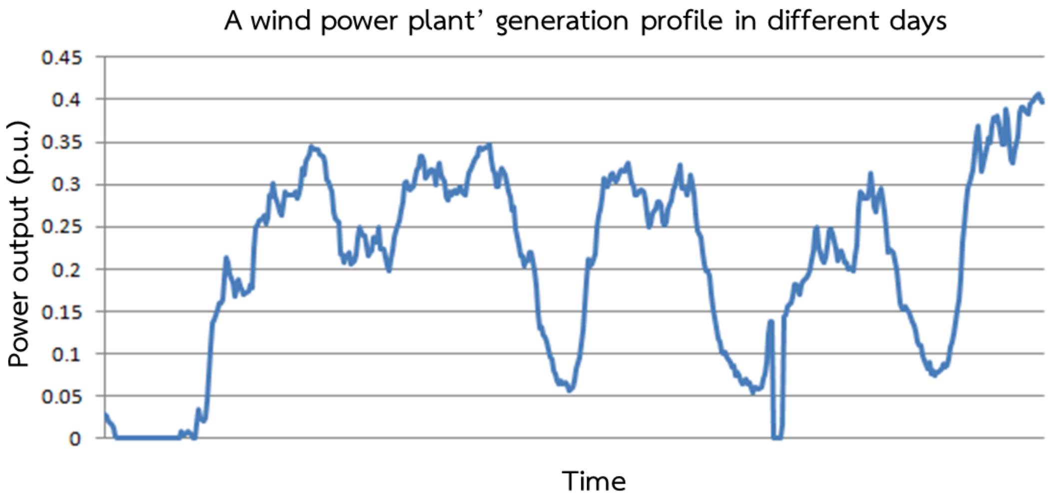

Figure 26 Wind power plants' generation profile. [63]

The generation profile of wind power plants is a crucial aspect of understanding the behavior and performance of wind power systems. It refers to the pattern of power production over time, which is influenced by various factors such as wind speed, wind direction, and turbine design. The generation profile of wind power plants is typically characterized by its variability, as the wind speed and direction can change rapidly and unpredictably. This variability can create challenges for maintaining the power balance and ensuring the stability and reliability of the power system.

To manage the variability of wind power generation, power system operators can use forecasting techniques to predict the power generation output of wind power plants and to plan for changes in demand. Additionally, power system operators can use energy storage systems, such as battery energy storage systems (BESS), to store excess wind power when it is available and to release it when it is needed to meet changes in demand.

Power system operators can also use control strategies such as demand response, to encourage consumers to adjust their energy consumption in response to changes in the availability of wind power. In addition, the use of advanced monitoring and control systems can also help to optimize the performance of wind power plants and to improve the integration of wind power into the power system.

It is important to note that wind power generation is heavily dependent on the weather conditions, specifically the wind speed and direction. Therefore, the generation profile of wind power plants is highly dependent on the location of the power plant, and the data for the generation profile must be accurate and up to date to ensure the proper planning and operation of the power system.

5.2 Electricity Demand Data

Electricity demand data plays a crucial role in the unit commitment process of power generation systems. It is used to predict the amount of electricity that will be required at specific times and to plan for changes in demand. This data is typically collected and analyzed over a period of time to identify patterns and trends in electricity consumption.

In this thesis, the conventional dispatchable electricity demand data of Thailand in 2019 is used to evaluate the unit commitment process. The data includes the total electricity demand, as well as the output power of various power generation sources such as Small Power Producers (SPP), Very Small Power Producers (VSPP), hydro power plants of the Electricity Generating Authority of Thailand (EGAT), and power exchange on High Voltage Direct Current (HVDC) link between Thailand and Malaysia.

To obtain a clear picture of the net demand, the total electricity demand is subtracted from the output power of these various sources. The net demand is illustrated in Figure 27 and can be calculated using equation 16. This data is critical in determining the optimal operation schedule for power plants and ensuring that the power system can meet the changing demand for electricity.

It is important to note that this data is based on historical information and may not accurately reflect the current demand for electricity. Furthermore, the demand for electricity can be affected by various factors such as weather conditions, economic conditions, and changes in population. Therefore, it is essential to regularly update and analyze the electricity demand data to ensure that the power system can meet the changing demand for electricity.

$$P_{dispatch,t} = P_{System,t} - P_{SPP,t} - P_{VSPP,t} - P_{Hydro,t} - P_{HVDC,t} \tag{16}$$

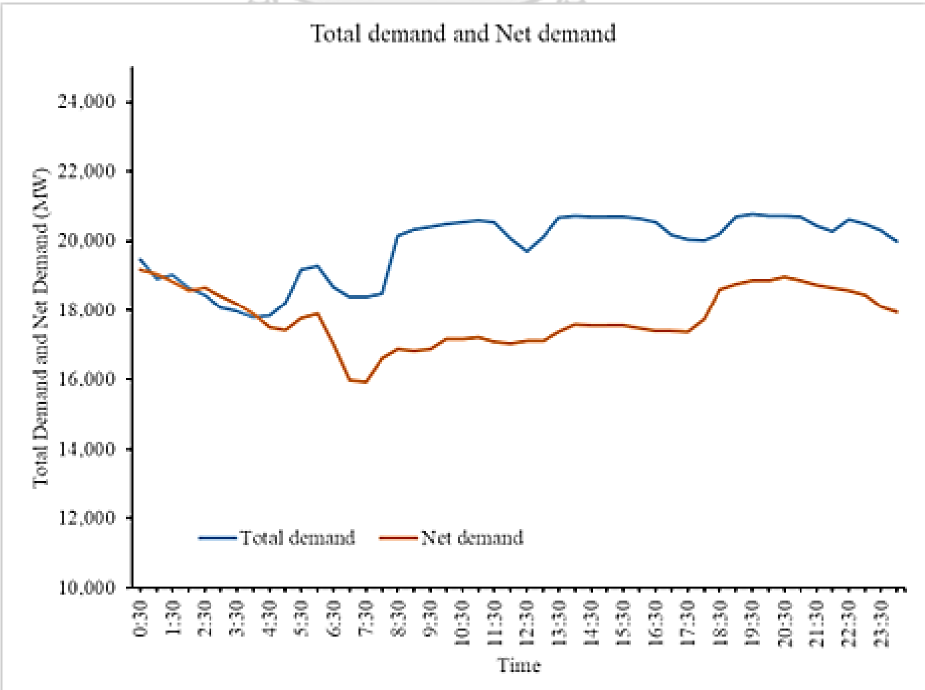

Figure 27 Net demand (MW) [63]

To ensure that simulation results are accurate and representative, it is important to select a day that is representative of typical demand and renewable energy generation patterns in the system being studied. It is recommended to choose a day that is not significantly different from the average conditions in the system. Simulating multiple days and averaging the results is ideal, with each day representing different seasons or weather patterns to capture variations in demand and renewable energy generation throughout the year. If simulating multiple days is not feasible due to time or resource constraints, a single day can be selected based on the average demand and renewable energy generation profile using historical data for the system. The purpose of selecting a representative day is to ensure that simulation results are robust and representative of typical demand and renewable energy generation patterns in the system, allowing for the identification of optimal BESS operation in response to varying demand and renewable energy generation under the most common operating conditions.

One possible reference to support this approach is a paper [64]. In this paper, the authors propose a methodology for modeling energy storage systems that incorporates enhanced representative days and system states. This methodology is designed to better represent the variability and uncertainty of renewable energy sources and provide more accurate analysis for energy storage investment decisions.

These articles [65, 66] emphasize the importance of choosing a representative day for unit commitment simulations, which is essential for ensuring that simulation results are accurate and representative of typical operating conditions in the system. They also provide different approaches for selecting a representative day, such as selecting a day that represents average demand and renewable energy generation patterns or using statistical techniques to create synthetic representative days. Overall, these journal articles support the use of a representative day approach for simulating the operation of battery energy storage systems in renewable energy systems.

Using peak days and holidays in addition to an average day can provide a more comprehensive understanding of the performance of a renewable energy system with battery energy storage. Peak days often have much higher demand for energy than an average day, which can stress the system in a different way and reveal potential issues that may not be present on an average day. For example, if the battery energy storage system is not able to meet the peak demand on a peak day, it may indicate that the system is undersized or that additional system upgrades are needed.

Similarly, holidays can have different energy demand and renewable energy generation patterns than an average day, depending on factors such as weather, traffic patterns, and business operations. By including holidays in the simulation, the system's ability to handle these variations can be evaluated, which can help to identify potential areas for improvement.

Several studies have highlighted the benefits of using peak and holiday scenarios in addition to average days for simulating energy systems. In a dissertation [67] This dissertation investigates unit commitment programming for optimal generation unit scheduling with renewable energy sources and energy storage. It also incorporates the use of flexible alternating current transmission system (FACTS) devices for transfer line security. The model uses a robust optimization method, allowing for uncertainty in parameter values to be defined in certain intervals, and the model is then solved for the worst-case scenario. The proposed model generates sufficient information for hourly unit bidding curves and is tested under different scenarios, including two specific days of peak load and low load.

In summary, while an average day can provide a good starting point for simulation studies of renewable energy systems with battery energy storage, adding peak days and holidays can help to reveal potential system vulnerabilities and ensure that the system is robust enough to handle a wide range of operating conditions.

5.3 BESS Data

BESS is widely used in power systems and industries. This paper examines the use of Li-ion batteries with BESS because they have received attention from the industry due to their small size, high energy density, long life cycle, lack of memory effect, lack of pollution, low self-discharging, and high comprehensive efficiency. Additionally, the cost of Li-ion batteries continues to drop due to technology development and material innovation [68].

Li-ion batteries store 150–250 watt-hours per kilogram (kg) and can store 1.5–2 times more energy than Na–S batteries and two to three times more than redox-flow batteries. Li-ion batteries have the highest charge and discharge efficiency (about 95%), followed by lead-storage batteries (around 60%–70%) and redox-flow batteries (approximately 70%–75%). [12].

This thesis used the estimated current costs for a 60 MW BESS with storage durations of 2, 4, 6, 8 and 10 h using thorough NREL cost models. The costs were shown in terms of energy capacity (USD/kWh) and power capacity (USD/kW) [69]. The main disadvantages of large-scale utility batteries are their short cycling times and high maintenance costs. Since a battery's lifetime depends on the discharge depth, many batteries do not completely discharge. Therefore, in this paper, it is necessary to consider the system's cost effectiveness by evaluating the characteristics and essential parameters of the battery. The BESS characteristics consist of the cycle life/lifetime/durability, and the State of charge. The BESS costs and characteristics are shown in Table 13.

Table 13 Battery energy storage characteristics

BESS Characteristics	Value	Ref
Rated power capacity or Available power ($/kW)	275	[8]
Energy capacity or storage capacity ($/kWh)	250	[8]
Cycle life/lifetime/Durability (Cycle)	5,000	[72]
State of charge (%)	80	[72]
round-trip efficiency (%)	90	[72]
Maintenance cost (%/year)	2.5	[8]
C-rate	1	-
Ratio of kW and kWh	1	-

Regarding the determination of BESS size for simulation purposes, this dissertation utilizes a comparison between the BESS size of foreign countries and the peak load of each respective country. The International Renewable Energy Agency (IRENA) [70] has reported on the energy storage capacity of selected countries, providing information on the installed capacity (in megawatts, MW) and energy capacity (in megawatt-hours, MWh) of energy storage systems in each country.

- United States: 883 MW/1,236 MWh
- China: 1,476 MW/1,048 MWh
- Japan: 242 MW/467 MWh
- Germany: 197 MW/236 MWh
- South Korea: 156 MW/175 MWh
- Australia: 96 MW/129 MWh
- United Kingdom: 96 MW/90 MWh
- Canada: 49 MW/212 MWh
- Italy: 49 MW/56 MWh
- France: 34 MW/41 MWh

The "World Energy Outlook 2020" report, published by the International Energy Agency (IEA) [71], provides valuable data on peak electricity demand in several countries. These numbers indicate the highest amount of electricity consumed during a specific period, which is important to understand when considering the energy storage requirements for a given country. In the report, peak demand figures are provided for the summer and winter seasons, reflecting the different seasonal energy consumption patterns in different regions. The report includes data on a range of countries, such as the United States, China, Japan, Germany, South Korea, Australia, United Kingdom, Canada, Italy, and France. By analyzing peak demand in these countries, we can gain insight into the energy storage requirements necessary to ensure reliable and efficient operation of the power grid during times of high demand.

- United States peak demand: 741 GW (summer)
- China peak demand: 1,801 GW (summer)
- Japan peak demand: 180 GW (summer)
- Germany peak demand: 82 GW (winter)
- South Korea peak demand: 90 GW (summer)
- Australia peak demand: 26 GW (summer)
- United Kingdom peak demand: 54 GW (winter)
- Canada peak demand: 25 GW (winter)
- Italy peak demand: 57 GW (summer)
- France peak demand: 90 GW (winter)

Using the data above, we can estimate the percentage of BESS size compared to peak load for each country. Here are the results:

- United States: 0.12%
- China: 0.08%
- Japan: 0.26%
- Germany: 0.24%
- South Korea: 0.17%
- Australia: 0.50%

- United Kingdom: 0.17%
- Canada: 0.85%
- Italy: 0.10%
- France: 0.05%

Note that these percentages are rough estimates and do not take into account the specific requirements of each country's power system.

Based on the average percentage of BESS size as a percentage of peak load in multiple countries (ranging from 0.08% to 0.85%), selecting a BESS size of 100, 200, or 300 MWh for unit commitment simulation in Thailand's generation system would be reasonable. This approach aligns with the general trend in other countries where BESS installations have been deployed and can help ensure that the simulation accurately captures the system's performance and identifies the optimal operation of the BESS in response to the varying demand and renewable energy generation. With Thailand's peak load of 32,254.5 MW in 2022, a BESS size of 100, 200, or 300 MWh would represent 0.31%, 0.62%, or 0.93% of the peak load, respectively.

5.4 Simulation scenarios

As the use of battery energy storage systems (BESS) in power systems continues to grow, the importance of simulation scenarios cannot be overstated. These simulations are crucial to understanding the potential impacts and benefits of BESS on unit commitment and power generation. They allow for the optimal scheduling of BESS, ensuring that the system is being utilized in the most efficient and cost-effective manner possible. This is critical for the successful integration of BESS into power systems, as it enables the identification of any potential issues or challenges that may arise, and facilitates the development of effective strategies for addressing these issues and optimizing BESS performance.

The integration of battery energy storage systems (BESS) into power systems is becoming increasingly prevalent and their potential impacts and benefits cannot be overstated. To accurately simulate scenarios for BESS integration, a wide range of factors must be considered, such as renewable energy sources, BESS capacity and power output, power consumption patterns, and economic and regulatory environments. By doing so, a comprehensive and realistic simulation scenario can be created that accurately reflects the complex interactions between these different elements. Additionally, the social and economic impacts of BESS must also be evaluated to identify potential barriers to adoption and develop strategies for addressing these challenges.

When proposing simulation scenarios, it is important to take a wide range of factors into account. These include the availability and reliability of renewable energy sources, the capacity and power output of BESS, the load demand and patterns of power consumption, and the economic and regulatory environment in which the BESS is being operated. By considering all of these factors, it is possible to create comprehensive and realistic simulation scenarios that accurately reflect the complex interactions between these different elements.

In this paper, the MB-UC method is proposed to determine the optimal operation schedule of BESS. The simulation scenarios demonstrate the benefits of integrating BESS and allow for the comparison of single and multi-application operations. Furthermore, the cost-effectiveness of BESS among different variable renewable energy penetration levels is also demonstrated. The dissertation cases are divided into five scenarios to showcase the potential benefits of BESS integration.

Case 1: Conventional generator unit commitment (C-UC)

The scope of case 1 is as follows:

- There is no BESS installed in the power-generation system.

Case 2: Single BESS application (spinning reserve) unit commitment (SB(SR)-UC)

The scope of case 2 is as follows:

- The BESS participates in unit commitment and economic dispatch as a spinning reserve (single application).
- The BESS cannot participate in power balancing.

- The BESS cannot participate in power balancing with a 15 min time resolution.

Case 3: Single BESS application (load leveling/shifting) unit commitment (SB(LL/S)-UC)

The scope of case 3 is as follows:

- The BESS participates in unit commitment and economic dispatch as load leveling/shifting (single application).
- The BESS cannot participate in power balancing with a 15 min time resolution.
- The BESS is not able to provide a spinning reserve.

Case 4: Multi-Application Unit Commitment (MB-UC)

The scope of case 4 is as follows:

- The BESS participates in unit commitment and economic dispatch and can operate as a spinning reserve, and for load leveling/shifting (multi-application).
- In a considered period, the BESS is operated as the most cost effective application among the two applications.

Chapter 6
Result and discussion

In this chapter, preliminary test results are presented and discussed. The results of this analysis are the result of combining the mathematical models discussed in Chapter 4 with the information already mentioned in Chapter 5, and they can be divided into 5 sections:

- Case 1: Conventional generator unit commitment (C-UC)
- Case 2: Single BESS application (spinning reserve) unit commitment (SB(SR)-UC)
- Case 3: Single BESS application (load leveling/shifting) unit commitment (SB(LL/S)-UC)
- Case 4: multi-application BESS (MB-UC)

In this study, an analytical model was developed to investigate the use of battery energy storage systems (BESS) in unit commitment (UC) programs. The model was divided into five distinct cases, with the first four representing the original analytical model and the fifth case representing a new analysis presented in this dissertation.

The approach assumes electrical systems with a liberalized structure. In this model, the unit commitment problem (UCP) is addressed and solved using mixed-integer linear programming (MILP), a MATLAB optimization technique. The UCP, represented as a mixed-integer linear function, is resolved by employing the "Intlinprog" MILP optimization tool within MATLAB.

In the first case, conventional generator unit commitment (C-UC) was used as a baseline for comparison. The second case involved the use of a single BESS for spinning reserve (SB(SR)-UC) in UC programs. The third case explored the use of a single BESS for load leveling/shifting (SB(LL/S)-UC) in UC programs

The final case involved the use of a multi-application BESS (MB-UC) in UC programs. In this case, the BESS was used for all two applications: spinning reserve, and load leveling/shifting.

Through the analysis of these cases, it was found that the use of a BESS in UC programs can be highly effective in improving the overall performance of the system. The MB-UC approach was found to provide the most optimal results in terms of cost reduction, efficiency, and reliability. The results of this study have significant implications for the future design and implementation of energy storage systems in power systems.

6.1 Case 1: Conventional generator unit commitment (C-UC)

Conventional generator unit commitment (C-UC) refers to the process of determining which power generation units to turn on, turn off or keep running in order to meet the demand for electricity over a certain time period while considering factors such as cost, reliability, and environmental regulations. In a C-UC approach, only conventional power generation units such as coal or gas power plants are considered as sources of power generation. The objective is to find the optimal schedule of these conventional generation units to meet the forecasted electricity demand while minimizing the operating cost of the power system.

The present study aimed to evaluate the impact of adjusting spinning reserve requirements on unit commitments in a power-generation system. In order to achieve this goal, a detailed simulation was performed, incorporating various variables such as fuel cost, startup cost, operation cost, expected energy not supplied (EENS), and total cost. The simulation results were analyzed using a standardized and systematic optimization procedure, as outlined in the flow chart presented in Chapter 4.

The results of our analysis demonstrate the complex relationship between spinning reserve requirements and unit commitments in the power-generation system. By considering various variables such as fuel cost, startup cost, operation cost, expected energy not supplied (EENS), and total cost, we were able to gain a comprehensive understanding of the impact of adjusting spinning reserve requirements on unit commitments. The results of our analysis can be clearly demonstrated in Table 14, which presents a summary of the simulation results and highlights the key findings of the study."

Table 14 The impact of adjusting spinning reserve requirements on unit commitments.

SR req	Fuel cost (Baht)	Startup cost (Baht)	Operation cost (Baht)	EENS (Baht)	Total cost (Baht)
500	686,113,141	1,297,414.14	687,410,555	2,890,314	690,300,868
550	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
600	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
650	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
700	686,714,458	1,757,631.68	688,472,089	1,813,763	690,285,852
750	686,654,418	1,757,631.68	688,412,050	1,894,869	690,306,919
800	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
850	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
900	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
950	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
1,000	686,710,750	1,757,631.68	688,468,382	1,817,227	690,285,609
1,050	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
1,100	686,715,129	1,757,631.68	688,472,761	1,828,620	690,301,381
1,150	686,841,170	1,757,631.68	688,598,802	1,643,180	690,241,982
1,200	686,849,805	1,757,631.68	688,607,437	1,640,474	690,247,911
1,250	687,538,470	1,757,631.68	689,296,101	1,391,040	690,687,142
1,300	687,102,557	2,592,879.30	689,695,436	1,236,357	690,931,793
1,350	687,138,139	2,592,879.30	689,731,018	1,182,338	690,913,356
1,400	687,054,376	2,592,879.30	689,647,255	1,277,196	690,924,452
1,450	687,110,059	2,592,879.30	689,702,938	1,195,202	690,898,140
1,500	687,073,644	2,592,879.30	689,666,523	1,252,737	690,919,260
1,550	687,863,532	1,757,631.68	689,621,164	886,580	690,507,743

SR req	Fuel cost (Baht)	Startup cost (Baht)	Operation cost (Baht)	EENS (Baht)	Total cost (Baht)
1,600	687,123,843	2,592,879.30	689,716,723	1,191,348	690,908,071
1,650	687,865,350	1,757,631.68	689,622,981	882,872	690,505,853
1,700	687,821,625	1,757,631.68	689,579,257	947,069	690,526,326
1,750	687,867,310	1,757,631.68	689,624,942	892,900	690,517,842
1,800	687,821,625	1,757,631.68	689,579,257	947,069	690,526,326
1,850	687,948,548	1,757,631.68	689,706,180	839,859	690,546,038
1,900	687,951,600	1,757,631.68	689,709,232	831,460	690,540,692
1,950	688,552,268	4,203,979.30	692,756,247	799,573	693,555,820
2,000	688,947,461	3,830,898.19	692,778,359	796,028	693,574,387

Note: SR req is spinning reserve requirement

The results of our analysis reveal that increasing the spinning reserve requirement leads to a higher operating cost. This is due to the power-generation system having to reserve capacity for spinning reserve and dispatch it, which results in an increase in the sum of fuel cost and startup cost. As a result of these increased costs, the operation becomes less cost-effective.

Contrarily, increasing the spinning reserve requirement leads to a reduction in the expected energy not supplied (EENS), which ultimately decreases the total cost. However, when the spinning reserve requirement exceeds 1,150 MW, the total cost begins to increase instead of decrease. This observation highlights the importance of finding the optimal spinning reserve requirement, as it can minimize the total cost. To visualize the results of our analysis, Figure 28 displays the correlation between the spinning reserve requirement, total cost, and operation cost.

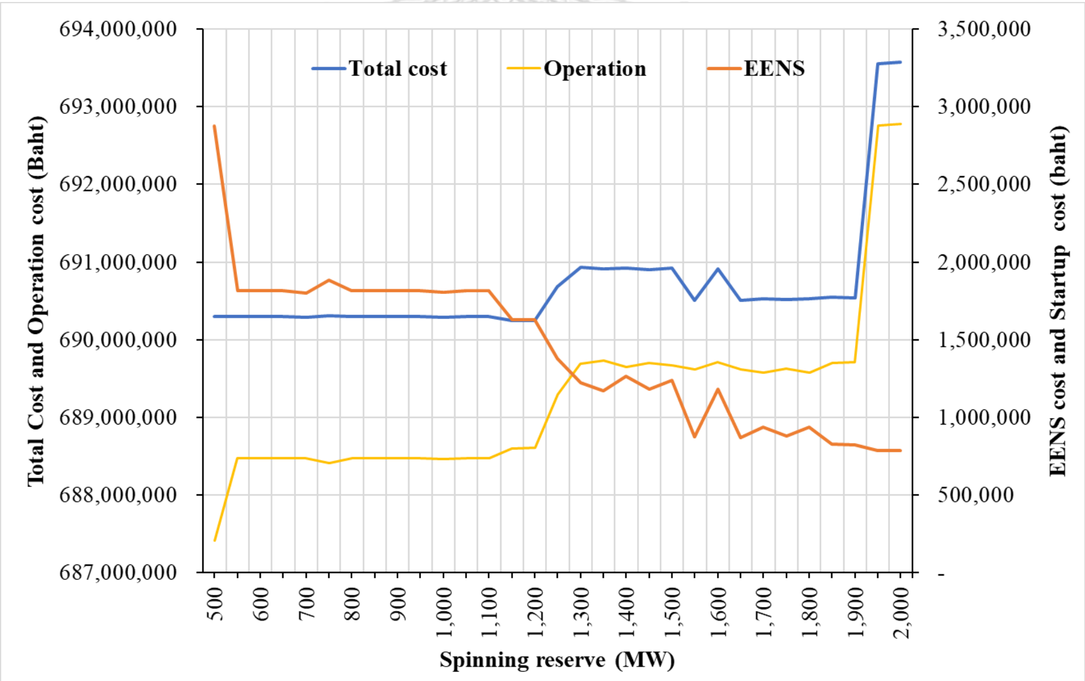

Figure 28 the correlation between the spinning reserve requirement, total cost, and operation cost.

Based on the above test results, it is evident that the spinning reserve requirement plays a crucial role in the power-generation system. In the next step of our analysis, we will delve into the details of the test results obtained when using the Conventional Generator Unit Commitment (C-UC) method with the power generation system in Thailand. This will allow us to compare the results with the case where the Battery Energy Storage System (BESS) is used in other scenarios.

In essence, the "expected energy outage cost" is a theoretical estimation used as an evaluative metric in power system reliability and economic studies, rather than an actual, payable cost. It serves as a crucial parameter in understanding the potential economic implications of power outages, which can, in turn, guide necessary investments and strategic decisions. By effectively gauging the risks and impacts associated with power disruptions, stakeholders can optimize their strategies towards improving grid resilience and minimizing economic losses. Therefore, even though operators or customers do not directly bear this cost, its analysis remains pivotal in facilitating economically efficient and robust power system operations.

The comprehensive analysis of the conventional generator unit commitment (C-UC) method in Thailand's power generation system has been conducted to assess its impact on various cost components, including fuel cost, startup cost, expected energy not supplied (EENS) cost, total cost, and the range of spinning reserve. Additionally, the dispatch efficiency of the system was also analyzed. The results of this scenario simulation are displayed in Table 15, providing a clear and concise representation of the findings.

Table 15 summary results of case 1: C-UC

Load	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	Total cost (Baht)	Spinning reserve range (MW)	Dispatch efficiency (%)	Average cost (kWh/Baht)
Typical workday	686,841,170	1,757,632	1,643,180	690,241,982	868 - 1,721	87.75%	1.3296
Typical holiday	535,869,463	462,167	1,542,045	535,873,675	1,254 - 1,449	86.81%	1.2540
Peak day	753,919,858	0	679,339	754,599,196	1,407 - 1,841	94.08%	1.3551

The results presented in this scenario simulation were obtained by testing the power generation model of the VRE with actual values of 365, as described in Chapter 4. The generator operation results were calculated based on the spinning reserve requirement of 365 formats.

The C-UC approach does not consider the integration of batteries or other energy storage systems in the power generation mix. As a result, it may not be well-suited for power systems with high penetrations of renewable energy sources that have varying and uncertain output. In such systems, the integration of energy storage can play an important role in providing stability and improving the reliability and cost-effectiveness of the power system.

6.2 Case 2: Single BESS Application (Spinning Reserve) Unit Commitment (SB(SR)-UC).

The scenario of Single BESS Application (Spinning Reserve) Unit Commitment (SB(SR)-UC) involves the use of a Battery Energy Storage System (BESS) as a spinning reserve in the power system. The BESS is integrated into the unit commitment and economic dispatch optimization and operates solely to provide spinning reserve services to maintain stability and prevent power outages in the system. In this scenario, the BESS does not participate in other applications such as load following, or power balancing.

Table 16 Summary results of case 2: SB(SR)-UC Typical workday

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh	686,714,587	1,757,632	1,316,902	149,829	689,938,950	303,032
200 MW / 200 MWh	686,546,597	1,757,632	1,071,779	299,658	689,675,666	566,316
300 MW / 300 MWh	686,263,885	1,757,632	1,018,556	449,486	689,489,559	752,423
400 MW / 400 MWh	686,119,103	1,757,632	877,122	599,315	689,353,172	888,809
500 MW / 500 MWh	685,985,358	1,757,632	759,376	749,144	689,244,576	997,406
600 MW / 600 MWh	685,844,714	1,757,632	678,838	898,973	689,180,157	1,061,825
700 MW / 700 MWh	685,656,019	1,757,632	632,529	1,048,801	689,094,981	1,147,001
800 MW / 800 MWh	685,510,753	1,757,632	569,329	1,198,630	689,036,343	1,205,638
900 MW / 900 MWh	685,367,592	1,757,632	519,237	1,348,459	688,992,919	1,249,063
1,000 MW / 1,000 MWh	685,250,153	1,757,632	461,086	1,498,288	688,967,158	1,274,824
1,100 MW / 1,100 MWh	685,159,232	1,757,632	402,825	1,648,116	688,967,806	1,274,176
1,200 MW / 1,200 MWh	685,093,311	1,757,632	352,065	1,797,945	689,000,953	1,241,029
1,300 MW / 1,300 MWh	685,039,002	1,757,632	309,304	1,947,774	689,053,712	1,188,270
1,400 MW / 1,400 MWh	685,064,158	1,757,632	259,369	2,097,603	689,178,762	1,063,220
1,500 MW / 1,500 MWh	685,009,092	1,757,632	228,015	2,247,432	689,242,170	999,812

Table 17 Summary results of case 2: SB(SR)-UC Typical Holiday

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh	533,833,232	462,167	1,145,219	149,829	535,590,447	283,229
200 MW / 200 MWh	533,833,232	462,167	1,145,219	299,658	535,378,243	495,432
300 MW / 300 MWh	533,371,572	462,167	1,066,541	449,486	535,349,766	523,909
400 MW / 400 MWh	533,196,514	462,167	905,062	599,315	535,163,058	710,617
500 MW / 500 MWh	533,005,956	462,167	812,810	749,144	535,030,076	843,600
600 MW / 600 MWh	531,587,527	1,193,553	1,123,710	898,973	534,803,762	1,069,913
700 MW / 700 MWh	531,403,696	1,193,553	981,355	1,048,801	534,627,406	1,246,270
800 MW / 800 MWh	531,249,894	1,193,553	845,024	1,198,630	534,487,101	1,386,575
900 MW / 900 MWh	531,015,284	462,167	1,074,395	1,348,459	533,900,304	1,973,371
1,000 MW / 1,000 MWh	530,977,919	462,167	893,464	1,498,288	533,831,837	2,041,838
1,100 MW / 1,100 MWh	530,960,106	1,193,553	725,121	1,648,116	533,795,510	2,078,165
1,200 MW / 1,200 MWh	530,919,303	1,193,553	603,466	1,797,945	533,782,881	2,090,795

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
1,300 MW / 1,300 MWh	530,879,083	1,193,553	502,041	1,947,774	533,791,065	2,082,611
1,400 MW / 1,400 MWh	530,851,484	1,193,553	403,467	2,097,603	533,814,721	2,058,955
1,500 MW / 1,500 MWh	530,815,960	1,193,553	328,188	2,247,432	533,853,746	2,019,929

Table 18 Summary results of case 2: SB(SR)-UC Typical Peak day

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh	753,693,525	-	649,004	149,829	754,492,358	106,839
200 MW / 200 MWh	750,656,406	1,295,465	2,029,818	299,658	754,281,347	317,849
300 MW / 300 MWh	750,480,880	1,295,465	1,713,565	449,486	753,939,396	659,800
400 MW / 400 MWh	750,327,214	1,295,465	1,429,089	599,315	753,650,400	948,796
500 MW / 500 MWh	750,120,737	1,295,465	1,233,744	749,144	753,399,091	1,200,106
600 MW / 600 MWh	749,775,986	1,295,465	1,177,334	898,973	753,147,759	1,451,438
700 MW / 700 MWh	749,555,012	1,295,465	947,307	1,048,801	752,846,585	1,752,611
800 MW / 800 MWh	749,342,828	1,295,465	836,001	1,198,630	752,672,925	1,926,272
900 MW / 900 MWh	749,111,151	1,295,465	806,986	1,348,459	752,562,061	2,037,135
1,000 MW / 1,000 MWh	748,933,076	1,295,465	755,982	1,498,288	752,482,811	2,116,385
1,100 MW / 1,100 MWh	748,831,062	1,295,465	598,306	1,648,116	752,372,950	2,226,246
1,200 MW / 1,200 MWh	749,002,973	1,295,465	515,564	1,797,945	752,611,948	1,987,249
1,300 MW / 1,300 MWh	748,721,917	1,295,465	471,146	1,947,774	752,436,302	2,162,895
1,400 MW / 1,400 MWh	748,700,016	1,295,465	411,258	2,097,603	752,504,342	2,094,854
1,500 MW / 1,500 MWh	748,700,016	1,295,465	411,258	2,247,432	752,654,171	1,945,025

The installation of a Battery Energy Storage System (BESS) as a spinning reserve can have a significant impact on reducing the overall cost of electricity generation. Spinning reserve refers to the additional capacity that is reserved by power generating units to quickly respond to any sudden changes in demand. The reserve capacity acts as a safety net for the power generation system, ensuring that the system is able to meet the changing demand for electricity.

Traditionally, spinning reserve has been provided by conventional power generation units, such as gas and coal-fired power plants. However, the use of BESS as a spinning reserve offers several advantages over conventional power generation units. Firstly, BESS is able to respond to changes in demand much faster than conventional power generation units, which allows it to provide spinning reserve more effectively. Secondly, BESS has lower operating costs compared to conventional power generation units, which means that the cost of providing spinning reserve is lower when BESS is used.

In addition to providing spinning reserve, BESS can also be used for load leveling/shifting. This multi-application capability of BESS makes it a more cost-effective solution compared to conventional power generation units, which are typically only capable of providing one application. By reducing the cost of providing spinning reserve and offering additional applications, BESS can help to reduce the overall cost of electricity generation.

In conclusion, the installation of BESS as a spinning reserve can have a significant impact on reducing the overall cost of electricity generation. By providing spinning reserve more effectively and offering additional applications, BESS can help to minimize the cost of electricity generation, making it a more cost-effective solution compared to conventional power generation units.

6.3 Case 3: Single BESS Application (Load leveling/shifting) Unit Commitment (SB(LL/S)-UC)

Single BESS Application (Load leveling/shifting) Unit Commitment (SB(LL/S)-UC) refers to a scenario where the Battery Energy Storage System (BESS) is only used for load following and ramping up in the power system. In this scenario, the BESS is integrated into the unit commitment and economic dispatch optimization problem and is used to follow changes in the load demand and ramp up its power output to meet the changes in the load demand. Load leveling/shifting refers to the ability of a power system to continuously adjust its power output to match changes in the load demand.

In the SB(LL/S)-UC scenario, the BESS is not used for other applications such as spinning reserve, or power balancing. It is only used for load following and ramping up.

Table 19 Summary results of case 3: SB(LL/S)-UC Typical workday

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh						
200 MW / 200 MWh						
300 MW / 300 MWh						
400 MW / 400 MWh						
500 MW / 500 MWh	685,848,286	1,757,632	1,642,446	773,207	690,021,570	220,411
600 MW / 600 MWh	685,773,857	1,297,414	1,699,416	998,394	689,769,082	472,900
700 MW / 700 MWh	685,854,690	1,297,414	1,604,989	1,072,863	689,829,956	412,026
800 MW / 800 MWh	685,841,170	1,297,414	1,188,856	1,566,130	689,893,570	348,412
900 MW / 900 MWh	684,840,192	1,297,414	1,577,629	2,398,459	690,113,693	128,289
1,000 MW / 1,000 MWh						
1,100 MW / 1,100 MWh						
1,200 MW / 1,200 MWh						
1,300 MW / 1,300 MWh						
1,400 MW / 1,400 MWh						
1,500 MW / 1,500 MWh						

Table 20 Summary results of case 3: SB(LL/S)-UC Typical Holiday

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh						
200 MW / 200 MWh						
300 MW / 300 MWh						
400 MW / 400 MWh						
500 MW / 500 MWh						
600 MW / 600 MWh						
700 MW / 700 MWh						
800 MW / 800 MWh	532,508,763	462,167	1,463,184	1,216,407	535,650,521	223,155
900 MW / 900 MWh	531,904,657	462,167	1,481,477	1,366,236	535,214,537	659,138
1,000 MW / 1,000 MWh	531,890,254	462,167	1,475,563	1,516,065	535,344,050	529,626
1,100 MW / 1,100 MWh	531,879,682	462,167	1,533,935	1,665,893	535,541,677	331,998
1,200 MW / 1,200 MWh	531,905,579	462,167	1,466,845	1,815,722	535,650,313	223,363
1,300 MW / 1,300 MWh						
1,400 MW / 1,400 MWh						
1,500 MW / 1,500 MWh						

Table 21 Summary results of case 3: SB(LL/S)-UC Typical Peak day

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh						
200 MW / 200 MWh						
300 MW / 300 MWh						
400 MW / 400 MWh						
500 MW / 500 MWh						
600 MW / 600 MWh						
700 MW / 700 MWh						
800 MW / 800 MWh	751,915,262	0	681,413	1,769,568	754,366,243	232,954
900 MW / 900 MWh	751,927,785	0	682,202	1,503,772	754,113,759	485,437
1,000 MW / 1,000 MWh	751,916,393	0	671,426	1,653,601	754,241,419	357,777
1,100 MW / 1,100 MWh	751,917,142	0	678,047	1,803,429	754,398,617	200,579
1,200 MW / 1,200 MWh	751,913,232	0	631,235	1,953,258	754,497,725	101,472
1,300 MW / 1,300 MWh						
1,400 MW / 1,400 MWh						
1,500 MW / 1,500 MWh						

The integration of a Battery Energy Storage System (BESS) for load leveling/shifting purposes has the potential to lower the total cost of electricity production. This is achieved by allowing the power generation system to adapt to changes in demand by ramping up or down as necessary. BESS can store excess energy during periods of surplus generation and release stored energy during periods of deficit, supporting the load leveling/shifting process.

However, it is important to note that the use of BESS for load leveling/shifting is not as impactful as using BESS for spinning reserve. Spinning reserve, as additional capacity kept on standby, provides a more immediate response to unexpected changes in demand and plays a critical role in maintaining the stability of the power generation system.

The analysis indicated that the incorporation of Battery Energy Storage Systems (BESS) of specific capacities might not be economically advantageous. This was observed in certain scenarios where the total system cost with BESS surpassed that of Case 1, where BESS was not utilized. The primary advantage derived from using BESS stemmed from its influence on the unit commitment model of the power generation system, specifically in minimizing startup and shutdown costs. However, it's important to note that these benefits may not always compensate for the additional expenditure associated with BESS integration. Therefore, careful evaluation of BESS size and application is vital in ensuring its cost-effectiveness.

Despite this, the integration of BESS for load leveling/shifting still serves as a useful solution. By allowing the power generation system to adapt to changes in demand, it reduces the overall cost of electricity production.

Overall, the integration of BESS for load leveling/shifting purposes can have a positive impact on reducing the total cost of electricity production. However, it is less effective compared to using BESS for spinning reserve, which provides a more immediate response and plays a critical role in maintaining stability.

6.4 Case 4: Multi-Application Unit Commitment (MB-UC)

MB-UC refers to a scenario where the Battery Energy Storage System (BESS) is used for multiple applications in the power system. In this scenario, the BESS is integrated into the unit commitment and economic dispatch optimization problem and is used for multiple applications such as spinning reserve and load leveling/shifting.

Table 22 the result of case 5: MB-UC Typical workday

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh	686,714,587	1,757,632	1,316,902	149,829	689,938,950	303,032
200 MW / 200 MWh	686,546,597	1,757,632	1,071,779	299,658	689,675,666	566,316
300 MW / 300 MWh	686,263,885	1,757,632	1,018,556	449,486	689,489,559	752,423
400 MW / 400 MWh	685,621,649	1,297,414	1,403,929	599,315	689,267,932	974,049
500 MW / 500 MWh	685,481,266	1,297,414	1,234,727	1,094,769	689,108,177	1,133,805
600 MW / 600 MWh	685,405,354	1,297,414	987,606	1,017,098	688,934,972	1,061,825
700 MW / 700 MWh	685,145,951	1,297,414	1,151,424	1,166,926	688,761,715	1,480,266
800 MW / 800 MWh	685,044,876	1,297,414	970,527	1,316,755	688,629,572	1,612,410
900 MW / 900 MWh	684,948,716	1,297,414	770,161	1,466,584	688,482,876	1,759,106
1,000 MW / 1,000 MWh	684,857,069	1,297,414	632,488	1,616,413	688,403,384	1,838,598
1,100 MW / 1,100 MWh	684,787,330	1,297,414	503,351	1,766,241	688,354,336	1,887,645
1,200 MW / 1,200 MWh	684,698,273	1,297,414	438,430	1,916,070	688,350,187	1,891,795
1,300 MW / 1,300 MWh	684,609,612	1,297,414	399,708	2,065,899	688,372,633	1,869,349
1,400 MW / 1,400 MWh	684,607,688	1,297,414	342,210	2,215,728	688,463,039	1,778,943
1,500 MW / 1,500 MWh	684,153,548	1,297,414	342,355	2,422,432	688,500,743	1,741,239

Table 23 the result of case 5: MB-UC Typical Holiday

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh	533,833,232	462,167	1,145,219	149,829	535,590,447	283,229
200 MW / 200 MWh	533,770,344	462,167	846,075	299,658	535,378,243	495,432
300 MW / 300 MWh	533,606,378	462,167	777,036	467,264	535,312,843	560,832
400 MW / 400 MWh	533,196,514	462,167	905,062	599,315	535,163,058	710,617
500 MW / 500 MWh	533,005,956	462,167	812,810	749,144	535,030,076	843,600
600 MW / 600 MWh	531,587,527	1,193,553	1,123,710	898,973	534,803,762	1,069,913
700 MW / 700 MWh	531,403,696	1,193,553	981,355	1,048,801	534,627,406	1,246,270
800 MW / 800 MWh	531,076,574	1,193,553	845,024	1,280,143	534,429,041	1,444,634
900 MW / 900 MWh	531,015,284	462,167	1,074,395	1,348,459	533,900,304	1,973,371
1,000 MW / 1,000 MWh	530,977,919	462,167	893,464	1,498,288	533,831,837	2,041,838
1,100 MW / 1,100 MWh	530,960,106	1,193,553	725,121	1,648,116	533,795,510	2,078,165
1,200 MW / 1,200 MWh	530,919,303	1,193,553	603,466	1,797,945	533,782,881	2,090,795
1,300 MW / 1,300 MWh	530,879,083	1,193,553	502,041	1,947,774	533,791,065	2,082,611
1,400 MW / 1,400 MWh	530,851,484	1,193,553	403,467	2,097,603	533,814,721	2,058,955
1,500 MW / 1,500 MWh	530,815,960	1,193,553	328,188	2,247,432	533,853,746	2,019,929

Table 24 the result of case 5: MB-UC Typical Peak day

BESS size (MWh)	Fuel cost (Baht)	Startup cost (Baht)	EENS (Baht)	BESS cost (Baht)	Total cost (Baht)	Profit (Baht)
100 MW / 100 MWh	753,693,525	-	649,004	149,829	754,492,358	106,839
200 MW / 200 MWh	750,656,406	1,295,465	2,029,818	299,658	754,281,347	317,849
300 MW / 300 MWh	750,480,880	1,295,465	1,713,565	449,486	753,939,396	659,800
400 MW / 400 MWh	750,327,214	1,295,465	1,429,089	599,315	753,650,400	948,796
500 MW / 500 MWh	750,120,737	1,295,465	1,233,744	749,144	753,399,091	1,200,106
600 MW / 600 MWh	749,738,993	1,295,465	1,099,473	949,285	753,083,216	1,515,980
700 MW / 700 MWh	749,555,012	1,295,465	947,307	1,048,801	752,846,585	1,752,611
800 MW / 800 MWh	748,982,163	1,295,465	1,170,339	1,944,568	752,097,069	2,502,127
900 MW / 900 MWh	748,840,568	-	929,112	1,656,896	751,426,576	3,172,620
1,000 MW / 1,000 MWh	748,694,962	-	755,982	3,502,038	750,954,066	3,645,130
1,100 MW / 1,100 MWh	748,493,849	-	755,620	1,737,804	750,987,273	3,611,924
1,200 MW / 1,200 MWh	748,400,831	-	631,235	1,797,945	750,919,699	3,679,497
1,300 MW / 1,300 MWh	748,320,056	-	523,784	1,949,962	750,829,769	3,769,428
1,400 MW / 1,400 MWh	748,292,074	-	411,258	2,099,790	750,882,250	3,716,947
1,500 MW / 1,500 MWh	748,276,423	-	411,258	2,249,619	750,945,820	3,653,376

In MB-UC, the BESS has the ability to switch between different applications depending on the needs of the power system, making it a more flexible and versatile solution compared to the single-application scenarios. This ability to switch between different applications also enables the BESS to provide multiple services to the power system, increasing the overall value it can provide. The findings indicate that not all sizes of Battery Energy Storage Systems (BESS) can effectively perform multiple applications. The results underscore the necessity for a sufficiently large BESS capacity. This capacity is critical to facilitate changes in unit commitment, thereby reducing startup and shutdown costs when the BESS operates independently. It also enables the BESS to perform multiple applications, such as providing spinning reserves and engaging in load leveling or load shifting activities.

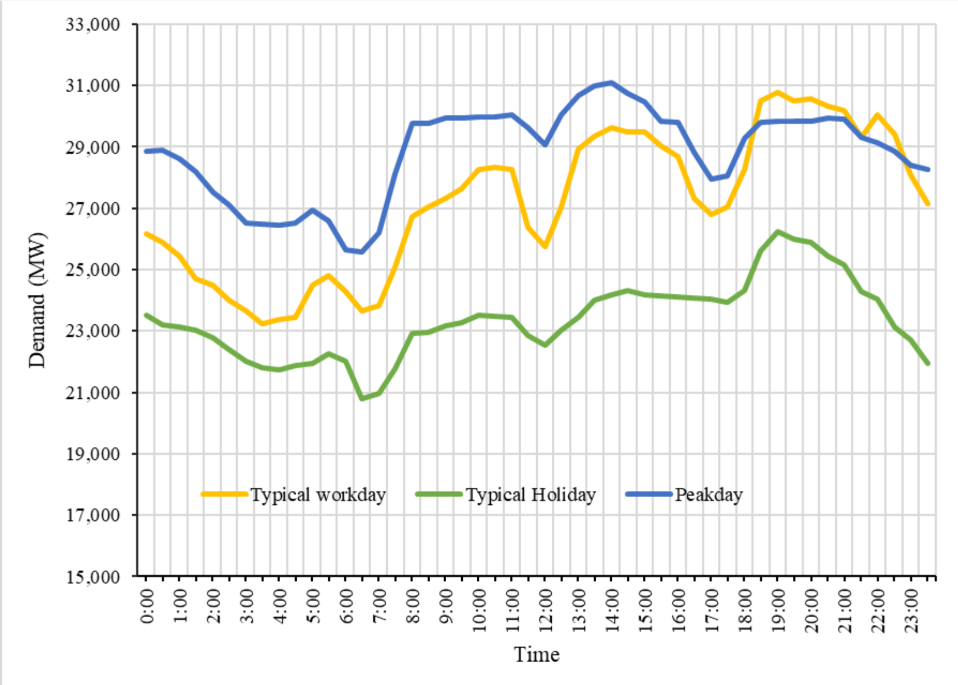

Figure 29 Total power generation profiles,

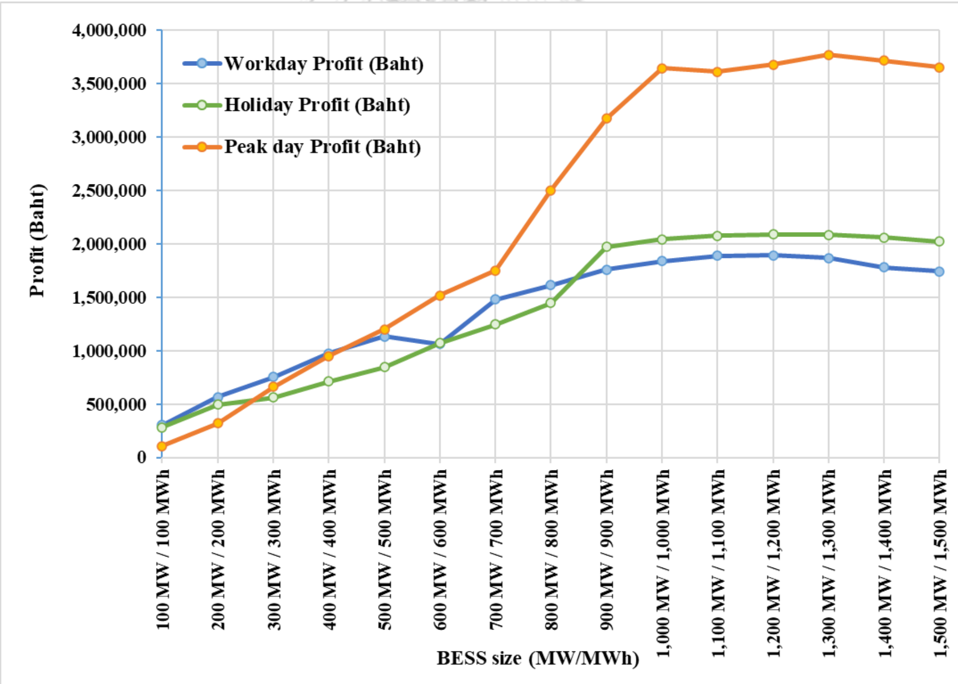

Figure 30 Total Profit

The study found that the MB-UC method was the most effective approach for determining the optimal operation schedule of BESS, as it demonstrated the highest level of cost effectiveness and reliability when compared to the other three case scenarios. This highlights the importance of considering a wide range of technical and economic factors when proposing simulation scenarios for the integration of BESS into power systems and underscores the potential benefits of using advanced simulation methods for optimizing the performance and efficiency of these systems. The study tested different BESS sizes, from 100 MW/100 MWh to 1,500 MW/1,500 MWh. It was found that the more BESS was used for different purposes, the more profitable it became. However, when the BESS size surpassed a certain point, the benefits or returns started to diminish. In scenarios representing typical workdays and holidays, a BESS size of 1200 MW/1200 MWh offered the best value, providing the highest returns. Conversely, on peak usage days, a BESS capacity of 1300 MW/1300 MWh proved to be the most efficient.

It's important to note that these findings are based on the usage of pre-installed BESS. The cost of BESS installation has not been factored into these results.

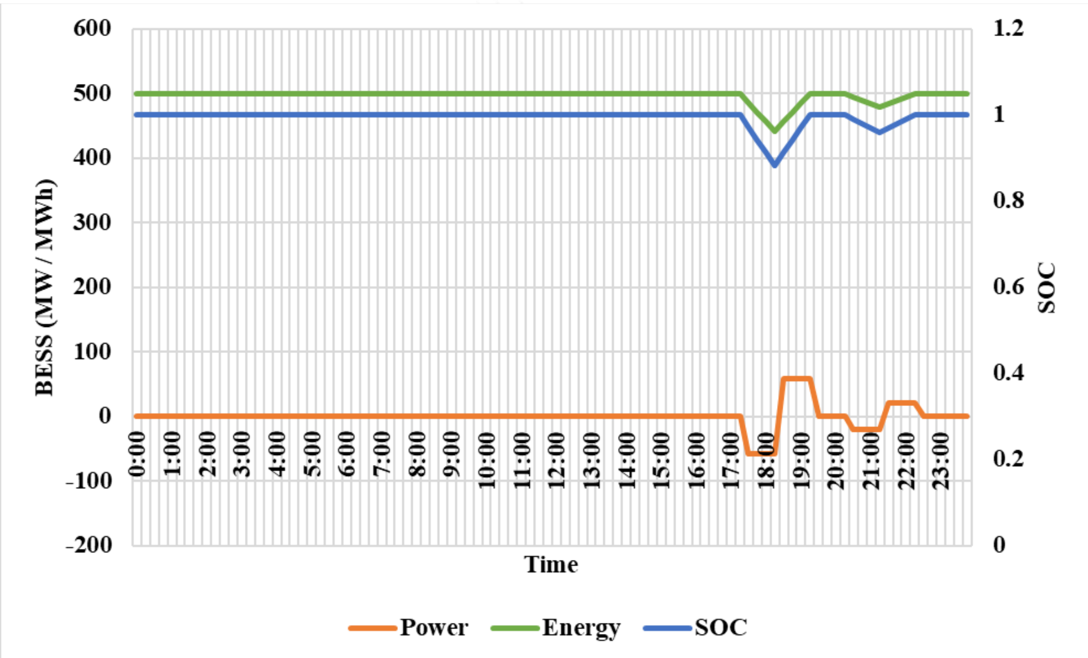

Figure 31 Workday BESS operation schedules.

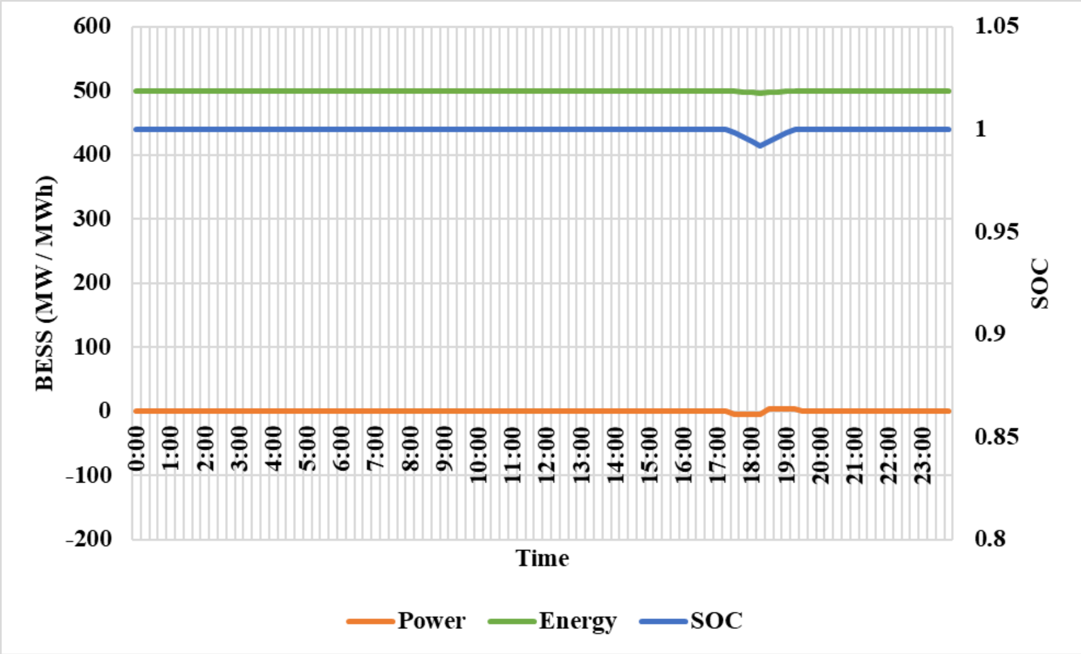

Figure 32 Holiday BESS operation schedules.

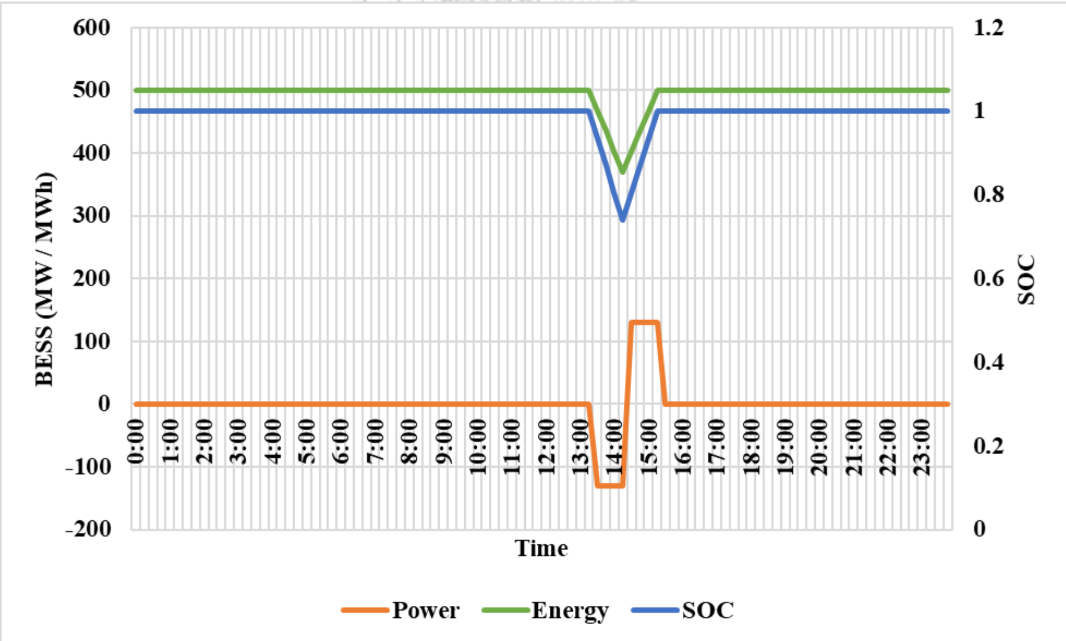

Figure 33 Peak day BESS operation schedules.

Figure 29 to Figure 33 illustrate example of how Battery Energy Storage Systems (BESS) are operated in both stages of a power generation system. The results indicate that BESS is most frequently operated as a spinning reserve, which acts as additional capacity reserved by power generating units to quickly respond to any sudden changes in demand, ensuring the system can meet the changing demand for electricity. The use of BESS as a spinning reserve offers several advantages over conventional power generation units, including faster response times and lower operating costs, which makes it a more cost-effective solution for power generation systems.

In addition to spinning reserve, BESS can also be operated for load leveling/load shifting purposes, but this is limited to specific periods during the day. Specifically, between 17:00 PM and 22:00 PM at workday and between 17:00 PM and 18:00 PM at workday holiday and between 13:00 PM and 16:00 PM at, BESS is operated as load leveling/load shifting.

The results presented in these figures highlight the versatility and flexibility of BESS in power systems. The use of BESS as a spinning reserve and load leveling/shifting can all have a positive impact on reducing the overall cost of electricity generation, depending on the specific needs and constraints of the power generation system. This underscores the importance of considering a wide range of technical and economic factors when proposing simulation scenarios for the integration of BESS into power systems, and the potential benefits of using advanced simulation methods for optimizing the performance and efficiency of these systems.

6.5 Discussion

The integration of battery energy storage systems (BESS) into power generation systems has the potential to significantly reduce the overall cost of electricity generation. BESS can be utilized for different applications, such as spinning reserve and load leveling/shifting, each of which can contribute to the overall efficiency of the system.

Based on the findings of this study, BESS as a spinning reserve is the most effective application in reducing the cost of electricity generation. By providing spinning reserve more effectively and at a lower cost compared to conventional power generation units, BESS can offer a more efficient solution. However, the integration of BESS as load leveling/shifting can also have a positive impact on reducing the cost of electricity production.

It is important to note that while the use of BESS for load leveling/shifting can contribute to the overall efficiency of the system, BESS as a spinning reserve is more critical to the stability of the power generation system. This is because spinning reserve provides a more immediate response to changes in demand, compared to load leveling/shifting which may respond over longer time frames. In the context of the power generation system, spinning reserve is considered a higher priority application compared to load leveling/shifting.

To determine the optimal operation schedule of BESS, this study proposes the Multi-Battery Unit Commitment (MB-UC) method. The MB-UC method offers the most cost-effective and reliable solution compared to the other three case scenarios. This highlights the importance of considering a wide range of technical and economic factors when proposing simulation scenarios for the integration of BESS into power systems. By utilizing advanced simulation methods such as the MB-UC, it is possible to optimize the performance and efficiency of BESS, and ultimately reduce the cost of electricity generation.

Based on the analysis of the data, it has been found that the use of Battery Energy Storage Systems (BESS) in the context of the Peak day provides the greatest benefit, with an estimated value of approximately 3.7 million baht per day. This contrasts with the benefits of BESS during workdays and holidays, which have been found to be similar, with an estimated value of 2 million baht per day. The analysis indicates that the greatest potential for cost savings and optimization is achieved through the implementation of BESS during workdays. It is therefore recommended that further consideration be given to the implementation of BESS during workdays in order to achieve the greatest benefits and optimize the use of this technology.

This analysis primarily serves as a parameter evaluation of Thailand's power generation system, highlighting that any deviations in parameter tuning can lead to varying outcomes. For instance, if the Value of Lost Load (VOLL) is doubled or tripled, a relatively minimal increase in total system cost, about 0.5%, is observed. However, the outage cost in the optimal solution exhibits a more pronounced response, swelling by a factor of three and four, respectively. Furthermore, modest augmentations in fuel costs, specifically by 10% and 20%, can trigger a rise in the fuel component of the optimal solution by 9% and 18%, respectively. This suggests that even minor tweaks in input parameters can have a disproportionate influence on the composition of the system's cost profile.

In conclusion, the integration of BESS into power generation systems offers a range of benefits that can contribute to the overall efficiency and cost-effectiveness of the system. By providing spinning reserve more effectively and offering additional applications such as load leveling/shifting, BESS can help to minimize the cost of electricity generation, making it a more cost-effective solution compared to conventional power generation units. The MB-UC method provides a reliable and cost-effective approach to determine the optimal operation schedule of BESS, highlighting the potential benefits of using advanced simulation methods to optimize the performance and efficiency of these systems.

Chapter 7

Conclusion

The increasing penetration of Variable Renewable Energy (VRE) in power systems is changing the shape of residual demand curves, resulting in mismatches between electricity demand and power generation. These mismatches are causing a greater value of Expected Energy Not Supplied (EENS), which is the possibility of electricity outages. These outages involve an expected outage cost, which is one of the critical components of power generation costs. The impact of VRE on power systems' reliability is a concern for many countries, including Thailand, and results in a need for energy storage solutions such as the Battery Energy Storage System (BESS).

BESS is a popular energy storage technology for addressing the VRE impact due to its fast response characteristics and continuously decreasing installation cost. BESS can be used to operate in different applications, such as spinning reserve, ramp rate, firm capacity, and frequency regulation services. Behind The Meter (BTM) BESS primarily aims at customer benefits such as electricity bill saving and demand-side management. On the other hand, utility scale BESS is more popular in providing ancillary services to maintain reliable operation of the power system and support the VRE impact.

There are plans to install more utility scale BESS in many countries, including the United States. However, overinvestment in BESS can lead to high system costs, which burdens customers. Therefore, determining the optimal sizing and daily operation schedule of grid-scale BESS is crucial. The method must be able to trade-off between the operating costs, the power generation reliability constants, the avoided expected outage cost, and the installation cost of BESS. Additionally, the method needs to be able to select the most cost-effective application of BESS to operate during.

BESS can operate in spinning reserve and load leveling/shifting depending on the most cost-effective solution. The installation of BESS as a spinning reserve can reduce the overall cost of electricity generation significantly. BESS can operate as load leveling/shifting during a specific period, but it is less effective than using BESS as a spinning reserve. The optimal daily operation schedule of grid-scale BESS is crucial for achieving the cost-effective and efficient operation of power systems. By selecting the most cost-effective application of BESS and considering a wide range of technical and economic factors, the installation of BESS can provide a range of benefits, from improving power system stability to reducing the cost of electricity generation.

The integration of BESS into power systems has become increasingly important as the world transitions towards a more sustainable and renewable energy future. As such, the development of accurate and effective simulation scenarios for the operation of BESS in power systems has become a critical issue. This is where the five scenarios, including C-UC, SB(SR)-UC, SB(LL/S)-UC, and MB-UC, come into play. Each scenario has its own strengths and weaknesses and must be carefully considered based on the specific needs and constraints of the power generation system.

Starting with the conventional generator unit commitment (C-UC) scenario, it represents the traditional approach to power generation and does not take into account the benefits that BESS can offer. On the other hand, the Single BESS Application (Spinning Reserve) Unit Commitment (SB(SR)-UC) scenario is characterized by the BESS only being used as a spinning reserve. In this scenario, the BESS is integrated into the unit commitment and economic dispatch optimization problem, and its sole purpose is to provide spinning reserve services to the power system.

The Multi-Battery Unit Commitment (MB-UC) scenario allows the BESS to participate in unit commitment and economic dispatch as a spinning reserve, for load leveling/shifting. In this scenario, the BESS can be operated as any of the two applications, depending on which is the most cost-effective. Based on the results, the MB-UC method was found to be the most effective approach for determining the optimal operation schedule of BESS, as it demonstrated the highest level of cost-effectiveness and reliability when compared to the other three case scenarios.

Comparing the performance of these different scenarios, it becomes clear that BESS can provide a range of benefits, from improving power system stability to reducing the cost of electricity generation. However, the choice of scenario will ultimately depend on the specific needs and constraints of the power generation system, and each scenario should be carefully considered based on those specific needs. BESS are a valuable asset in power systems due to their ability to store and release energy on demand. The benefits of BESS have been extensively studied in the literature, and it has been shown that the utilization of BESS can result in significant cost savings and system improvements.

In this study, the benefits of BESS were evaluated in the context of different days, including workday, holiday, and peak day. The results showed that the highest benefits were obtained during a typical peak day, where the BESS provided approximately 3.7 million baht per day in cost savings. This is a significant amount compared to the other days, where the benefits were similar at 2 million baht per day.

The higher benefits obtained during workdays can be attributed to the higher load demands and increased variability in demand patterns, which make it more challenging to manage the power system. The BESS can be used to address these challenges by providing load shifting and peak shaving services, which help to reduce system costs and improve reliability. In contrast, the benefits of BESS during holidays and workdays were relatively lower due to the lower demand and more predictable load patterns. However, it is still important to consider the use of BESS during these periods to maintain system stability and to provide backup power in case of outages or other system disruptions.

The appropriate installation size for Battery Energy Storage Systems (BESS) in Thailand is estimated to be around 1200 - 1300 MW/MWh. It is important to note, however, that any changes in parameters, such as cost or the Value of Lost Load (VOLL), may lead to different outcomes from those presented in this study. The scope of this analysis is confined to the examination of BESS operation schedule assuming that BESS is already installed in the system. The determination of optimal BESS installation sizes is not considered in this study.

Overall, the results of this study highlight the importance of considering the specific characteristics of different days when evaluating the benefits of BESS. By doing so, system operators can make more informed decisions regarding the optimal deployment of BESS in power systems, which can result in significant cost savings and improved system performance and each scenario has its own strengths and weaknesses, the choice of scenario should ultimately depend on the specific needs and constraints of the power generation system, with the MB-UC approach offering the most cost-effective and flexible solution.

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