# THE POWER QUALITY AND STABILITY IMPROVEMENT OF WIND POWER PLANT CONNECTED WITH MEDIUM VOLTAGE DISTRIBUTION NETWORK

RATTAPORN NGOENMEESRI

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Doctor of Philosophy in Applied Physics - (Type 1.1)
2024

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By Rattaporn Ngoenmeesri

has been approved by the Graduate School as partial fulfillment of the requirements for the Doctor of Philosophy in Applied Physics - (Type 1.1) of Naresuan University

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| **Title** | THE POWER QUALITY AND STABILITY IMPROVEMENT OF WIND POWER PLANT CONNECTED WITH MEDIUM VOLTAGE DISTRIBUTION NETWORK |
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## ABSTRACT

Thailand has continuously increased its installation of wind power plants, as the country has the potential for good wind energy, especially in the southern and north-eastern regions. Additionally, the support from the Ministry of Energy has led to an increase in the installation of wind power generation systems in accordance with the Alternative Energy Development Plan. However, the wind power generation system has limitations in terms of installation space, particularly for large-scale wind power plants that are connected to the distribution system. In Thailand, wind power plants are installed in remote areas such as mountains or coastal regions because of the potential for good wind energy and the relatively low demand for electricity. Consequently, when wind power plants operate, there will be a significant amount of electricity injected into the distribution system, causing problems with power quality such as overvoltage, voltage fluctuations, and voltage dips, resulting in feeder trips and plant shutdowns. These power quality issues have a significant impact on electricity consumers in the affected feeders, particularly if there are factories, shops, or important government facilities in the area. Frequent power outages can cause public dissatisfaction, damage to electrical equipment, and other problems. According to the literature review, integration of energy storage systems (ESS) with high-variability wind power plants can significantly improve system stability, maintain power quality, and enable the management and scheduling of power output. because

ESS can perform several functions, such as power quality and UPS, bridging power, and energy management.

In this study, an operational 8 MW wind farm (Nakhon Ratchasima province) faces severe annual feeder trips of 146 times, which is not permissible according to the manufacturers. The feeder trips are mostly attributed to the high grid voltage caused by the low load demand. The Battery Energy Storage System (BESS) is developed to minimize the feeder trip using DigSILENT. The simulation results conclude that the optimal value for a 5 MWh BESS and the State of Charge (SOC) value were set to be between 20% and 100%. The energy storage system could charge and discharge to adjust the voltage in the Provincial Electricity Authority distribution system throughout the day, demonstrating zero feeder trips. To ensure stable wind farm operation, the BESS is capable of supplying voltage to the grid without any feeder trips. The energy storage system can maintain and improve the power quality in the distribution system. It can manage the electricity generated by the wind turbines and keep the voltage in the distribution system within the standard specified by the Provincial Electricity Authority. When the data is analyzed, it is found that the wind power plant can generate 2.41% more electricity without the energy storage system.

We conducted an economic analysis of a 5 MWh energy storage system in conjunction with an 8 MW wind power plant. The results showed that the payback period would be shorter and the return on investment would be higher if the cost of the energy storage system was lower. The installation of the energy storage system increased the wind power plant's revenue by 2,825,000 THB per year, bringing the Internal Rate of Return (IRR) to 7.76% for the original wind power plant and 9.03% for the wind power plant with the energy storage system. We found that the wind power plant with the energy storage system had a shorter payback period (PB) due to its increased revenue, which helped the plant operate at full efficiency and significantly reduced plant trips. However, we conducted a sensitivity analysis to determine the appropriate price for the integration of the energy storage system into the system. The findings indicated that the optimal investment cost ratio for energy storage systems is about 67%, equivalent to 10,000 THB/kWh. Implementing this strategy would lead to a payback time of under 10 years and raise the internal rate of return (IRR) to 14.54%, resulting in a benefit-cost ratio (BCR) of 1.45.

The study found that the BESS alone did not provide the economic benefits. Integrating with a wind farm boosts energy generation and reduces the feeder trip period, thereby improving the BESS's return on investment. Installation of an energy storage system can solve tripping problems, improve power quality, increase wind power plant efficiency, and enhance power stability. It can also act as a backup system, providing backup power during power outages and adjusting voltage and reactive power. This reduces maintenance and management costs, reduces wind turbine damage risk, and increases electricity generation efficiency.

# ACKNOWLEDGEMENTS

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Rattaporn Ngoenmeesri

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# CHAPTER I
# INTRODUCTION

## 1.1 Background and Significance of the Study

The proportion of electricity production from renewable energy has been increasing globally as a response to the wake-up call from the energy crisis and environmental problems caused by the use of fossil fuels, leading to global warming resulting from the annual increase in greenhouse gas emissions. Therefore, the world has adopted policies to reduce the use of fossil fuels and increase the use of renewable energy, which is a technology that uses clean energy without adverse effects on the environment. Thailand has responded to the global trend by implementing the Alternative Energy Development Plan (AEDP) for 2018-2037 [1] to set the framework and direction for the country's development of renewable energy, focusing on environmental sustainability and promoting electricity production from renewable energy sources. The PDP 2024 aims to increase the proportion of renewable energy to 51% by 2037, and wind energy is one of the renewable energy sources with a continuously increasing installation rate, as shown in Figure 1.

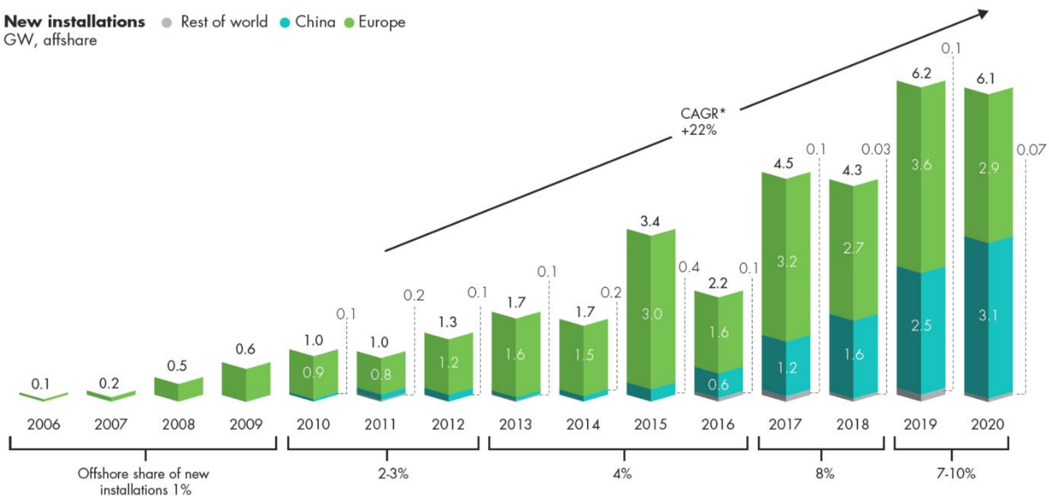



Figure 1 Global Offshore Wind Growth, 2006-2020. Source: GWEC (2021)

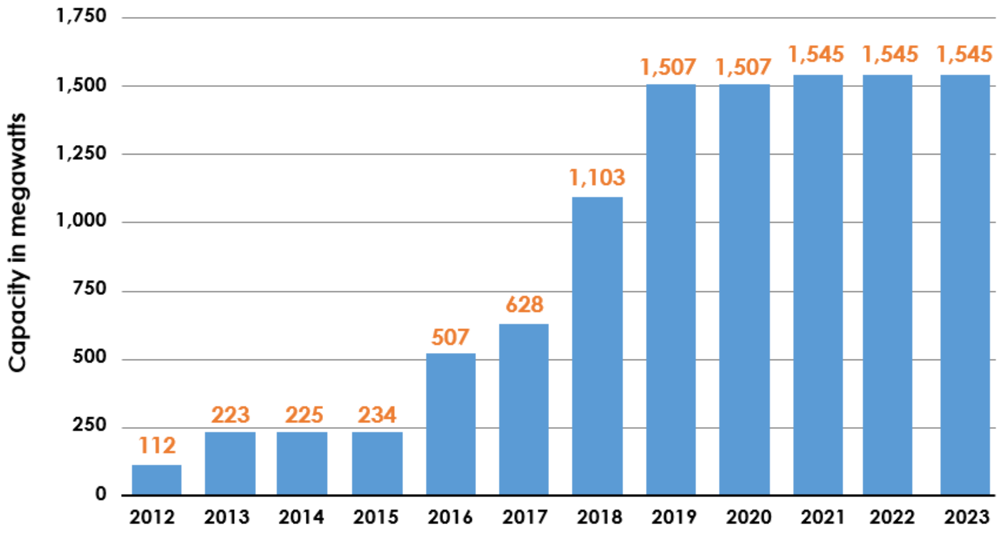
Over the next few decades, offshore wind power is expected to continue to grow at a rate that is ten times faster than before. According to the Global Wind Energy Council (GWEC) [2], the installed offshore wind capacity is expected to increase by a factor of seven during this decade, with a projected capacity of 270 GW by 2030. The GWEC anticipates a significant increase in the annual installation of new offshore wind projects, more than tripling in the next five years from 6.1 GW/year in 2020 to over 20 GW/year in 2025, which will increase its global share of new installations from 6.5% to 20%. The GWEC also thinks this trend will continue, with the number of new installations doubling again in the second half of the decade and reaching 40 GW/year by 2030.

Thailand has supported the use of renewable energy, leading to an increase in its usage. Currently, the draft of the Power Development Plan (PDP 2024–2037) includes an additional 15% increase in the proportion of renewable energy usage, from the previous 36% to 51%. This has resulted in increased investment in electricity generation from renewable energy, especially wind energy. Currently, Thailand has consistently increased its wind power plant installation because the country has the potential for excellent wind energy, especially in the southern and north-eastern regions. Additionally, the support from the Ministry of Energy has led to an increase in the installation of wind power generation systems in accordance with the Power Development Plan. The plan aims to achieve a target installation of up to 9,339 MW of wind power by 2037, as shown in Figure 2. The Thailand wind energy market is expected to grow more than 4.98% during the forecast period of 2020–2025 [3]. The market is expected to experience significant growth due to rising energy demand, an increasing share of renewables in the power generation mix, and efforts to reduce reliance on fossil fuel-based power generation.


Figure 2 The Power Development Plan (PDP 2024-2037)

Thailand is increasing its wind energy installations, with more than 1.5 GW of wind power plants already installed by 2023. This is because Thailand has high-potential wind energy areas scattered throughout the country, such as the northeastern, central, and southern regions. Most of these areas are located in the central highlands and along the coastline. Thailand's total wind energy potential ranges between 13 - 17 GW. The total capacity of wind energy in Thailand will reach approximately 1.5

thousand megawatts. This marks a significant increase compared to the total capacity of wind energy in 2012, which was around 112 megawatts, as shown in Figure 3.




**Source:** https://www.statista.com/statistics/1006126/thailand-total-wind-energy-capacity

Figure 3 Total wind energy capacity in Thailand from 2012 to 2023

Wind turbines are devices that convert the wind's kinetic energy into electrical energy. They are a significant source of renewable energy and play a critical role in reducing our reliance on fossil fuels. The work of wind turbines is Wind turbines have blades attached to a rotor. The blades are shaped like airfoils and are designed to capture the energy in the wind. When the wind blows, it causes the blades to rotate. The blades rotate, which sets the rotor in motion. A shaft connects the rotor to the turbine's center. As the blades turn, the shaft rotates. The shaft is connected to a gearbox that increases the speed of rotation. The gearbox converts the slow rotational speed of the blades into a faster speed that is required by the generator. At the end of the shaft, there is a generator. The generator is the component of the turbine that converts the mechanical energy of the rotor into electrical energy. The generator consists of a rotor and a stator. The rotor is a rotating electromagnet, while the stator is a stationary electromagnet. When the rotor spins, it induces current in the stator, which produces electricity. The wind turbine has a control system that monitors wind speed and direction. If the wind is too strong or too weak, the control system adjusts the pitch angle of the blades to optimize energy production. The pitch angle is the angle at which the blades are set relative to the wind. If the wind is too strong, the control system will reduce the pitch angle to prevent the blades from spinning too fast. If the wind is too weak, the control system will increase the pitch angle to allow the blades to capture more energy. Most wind power plants are connected to distribution or transmission lines with a voltage of 22 kV or 115 kV, managed by PEA (Provincial Electricity Authority).

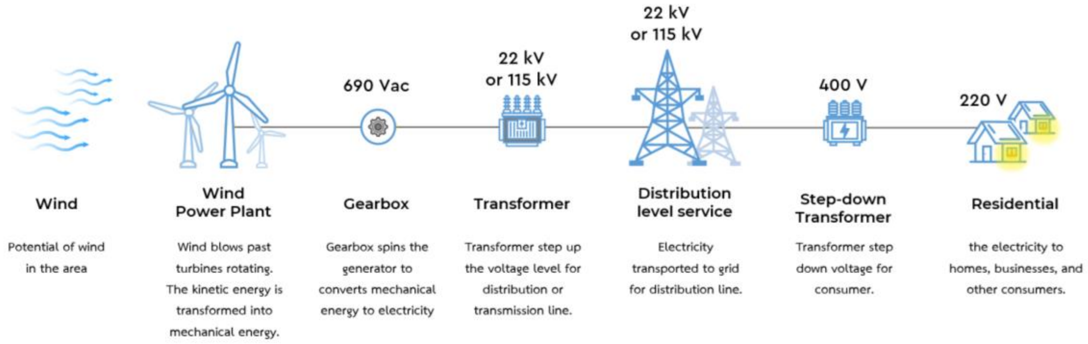



Figure 4 Wind power plant work

The wind power generation system has limitations in terms of installation space, particularly for large-scale wind power plants that are connected to the distribution system. In Thailand, wind power plants are installed in remote areas such as mountains or coastal regions because of the potential for good wind energy and the relatively low demand for electricity. Consequently, when wind power plants operate, there will be a significant amount of electricity injected into the distribution system, causing problems with power quality such as overvoltage, voltage fluctuations, and voltage dips, resulting in feeder trips and plant shutdowns. These power quality issues have a significant impact on electricity consumers in the affected feeders, particularly if there are factories, shops, or important government facilities in the area. Frequent power outages can cause public dissatisfaction, damage to electrical equipment, and other problems. The study targets the Wind Energy Development Co., Ltd., Wind Farm SubPlu 1, as shown in Figure 5. An 8 MW commercial-scale wind power plant is located in Huaybong subdistrict, Dankhuntoth district, Nakhon Ratchasima province. The plant has four 2 MW wind turbines of the Doubly Fed Induction Generation (DFIG) type, by Gamesa Company.

Figure 5 An 8 MW wind farm SubPlu 1, Nakhon Ratchasima province

This wind power plant is connected to the 22 kV distribution line of the Provincial Electricity Authority (PEA). The wind power plant has entered into a 10-year maintenance and management contract with the wind turbine manufacturer. However, if the number of plant trips exceeds 52 times per year, the warranty will be void. Data collection shows that this power plant experiences 146 plant trips per year. As a result, the warranty for this wind power plant has already expired, as illustrated in Figure 6.

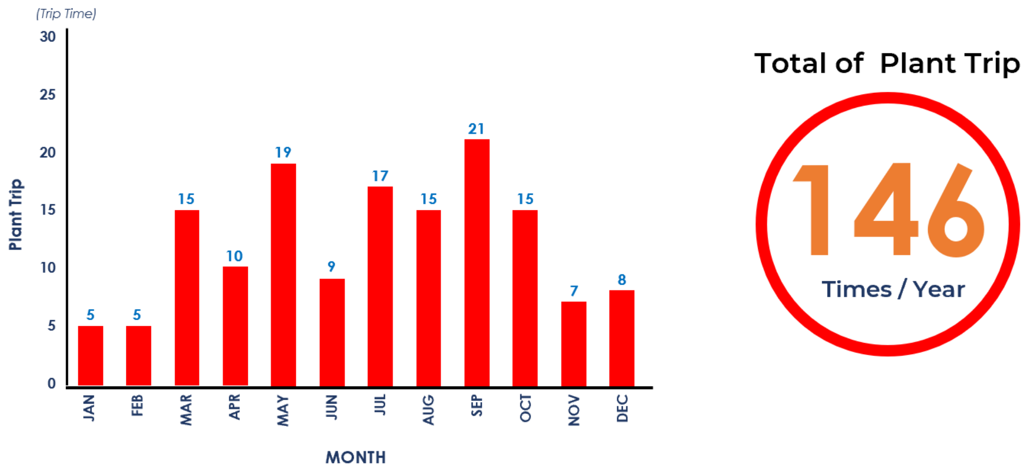



Figure 6 The data of plant trips

The wind power plant trip will cause the wind turbine to suddenly stop operate by activate the emergency brakes. Frequent activation of the emergency brake on wind turbines can cause direct damage to the brake system. Additionally, such activations can cause the turbine to vibrate, potentially leading to structural damage to the turbine and foundation. Therefore, ensuring the structural integrity of the turbine tower, electricity-generating components, and foundation is crucial for safety. The Wind Energy Development Company conducts annual structural inspections, with a particular emphasis on the reinforced concrete foundations of the turbines, which bear the weight of the turbines and transfer it to the ground, as shown in Figure 7. Frequent emergency stops can cause significant damage to the wind power plant, particularly the wind turbine equipment, which can deteriorate faster due to transient loads when the emergency brake activates. Transient load is one factor that can shorten the lifespan of wind turbines. The components most affected are the gearbox, mechanical brake, main bearing, and blade. Moreover, this could potentially result in structural damage to the turbine and the foundation. The impact on the quality of electricity in the distribution system can often result in sudden stoppages of wind turbines. The impact of such events may damage the structure of the wind turbine and have long-term adverse effects on wind turbine structures. This could potentially cause damage to life and property from the aforementioned impacts. Moreover, the sudden stoppage of wind turbines can affect the reliability of wind turbine insurance.

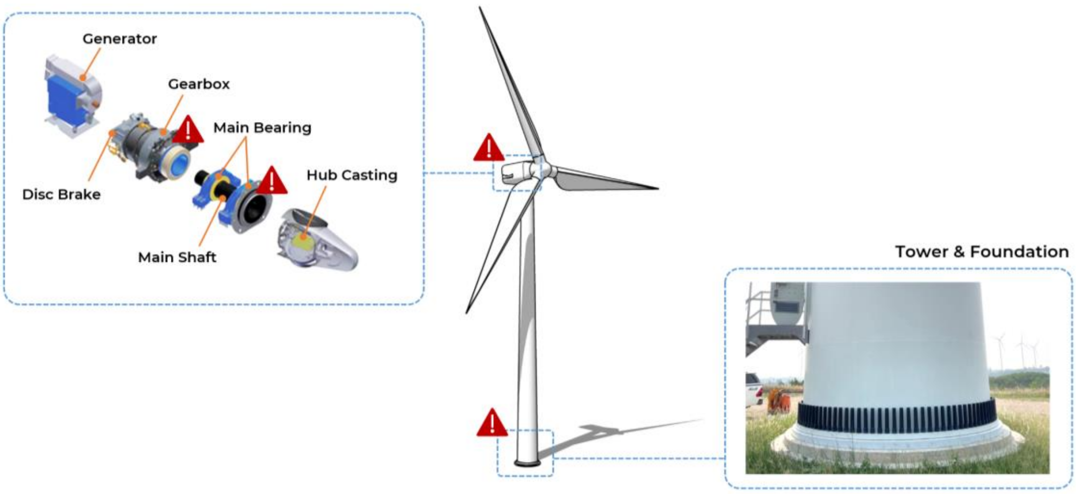



Figure 7 The Impact of a Wind Turbine Plant Trip

Due to the aforementioned problem, the researcher is interested in conducting research on "***The Power Quality and Stability Improvement of Wind Power Plant Connected with Medium Voltage Distribution Network***" in order to solve the fluctuation problem of electricity production from wind power plants, improve the quality of electricity in the distribution network, and increase the stability of the distribution system of wind power plants connected to the distribution network. the conceptual design we will install energy storage system combine with wind power plant, as shown in Figure 8.

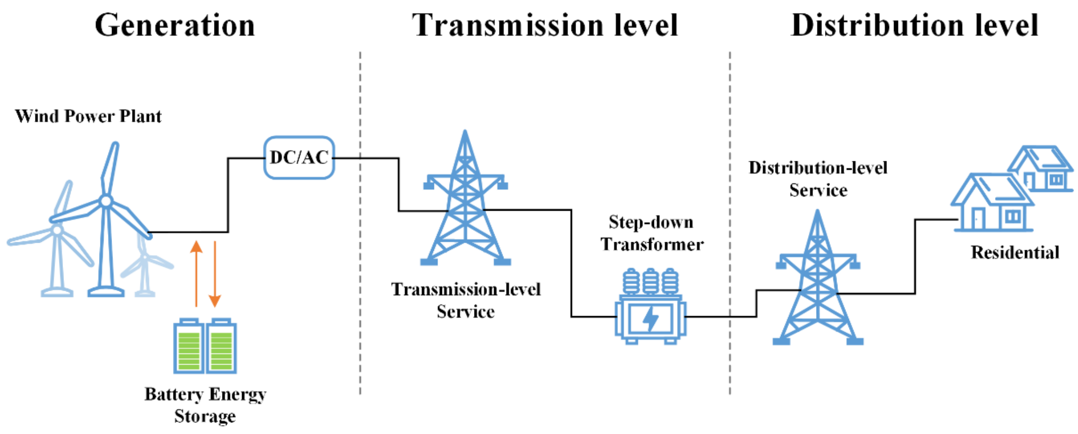
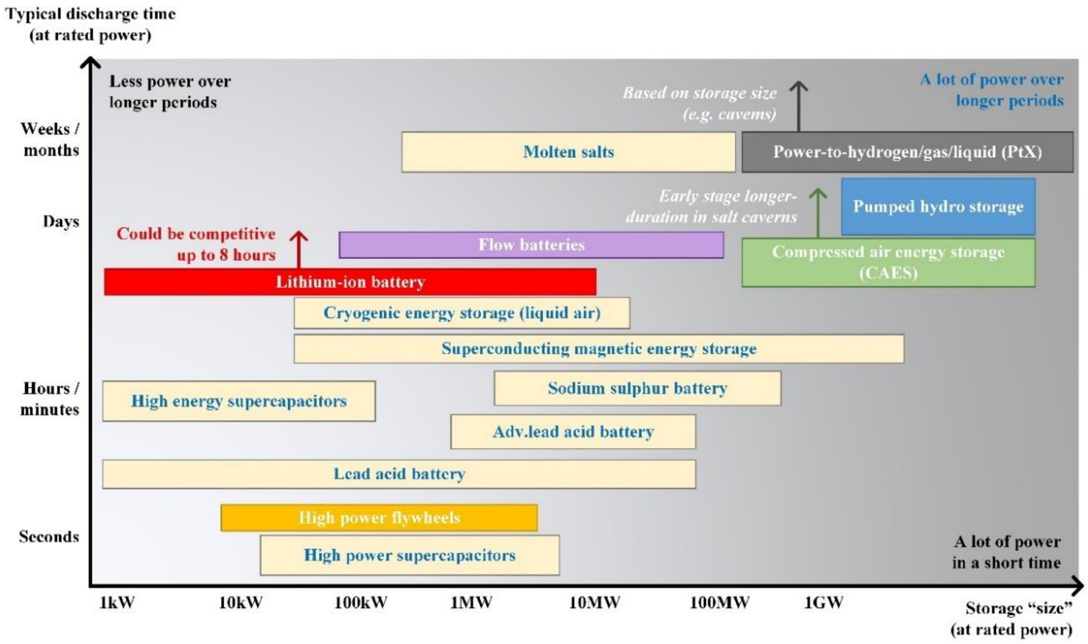



Figure 8 Conceptual diagram of BESS with wind power plant

However, research studies conducted in other countries have found that the integration of energy storage systems (ESS) with high variability wind power plants can significantly improve system stability, maintain power quality, and enable the management and scheduling of power output. because ESS can perform several functions, such as power quality and UPS, bridging power, and energy management, as shown in Figure 9.




**Source:** Energy Transitions Commission

Figure 9 Energy storage solutions vary depending on storage size and discharge time performance.

Each of the different energy storage technologies has applications for which it is best suited [4], which need to be considered in the implementation. Key issues that must be assessed are the charge and discharge profiles, the storage capacity capability, and potential scalability. Moreover, the expected lifetime in terms of cycling frequency before degradation sets in also needs to be factored into a cost-benefit analysis. The figure shows that for the sub-minute level of response, supercapacitors are the main option. The rapid cost declines that lithium-ion has seen and are expected to continue in the future make battery energy storage the main option currently for requirements up to a few hours and for small-scale residential and electric vehicle applications. Therefore, designing an energy storage system that is suitable for wind power plants is crucial for the system's operation. Improving power quality and increasing reliability is a solution to electrical quality problems for electricity users, enhancing the performance and stability of wind power plants and the electricity distribution system, reducing public discomfort caused by electricity usage, minimising sudden stoppages of wind turbines, and minimising the impact on the wind turbine structure due to the fluctuation problem of the electric grid. This will be a way out and a guide to promoting the use of alternative energy sources to achieve the goals of the PDP 2024 energy plan that have the least impact on the electricity system, as well as laying the groundwork for the development of a smart grid network in the future, in accordance with the master plan for the development of Thailand's smart grid network system from 2015–2036, which clearly prioritises the importance of energy storage systems for the smart grid network.

## 1.2 Purposes of the Study

1. Improve the quality of electricity and increase the stability of the distribution system of a wind power plant connected to the medium-voltage distribution system.
2. The study aims to analyze the impact on wind turbine foundations for the target wind power plant that is connected to the medium-voltage distribution system.
3. Analyze the technical and economic aspects of the power plant system resulting from improving the quality of electricity and increasing the stability of the distribution system of a wind power plant.

## 1.3 Scope of the Study

This research analyses the technical and financial aspects of wind power plants connected to the medium-voltage distribution system that cause fluctuations in electricity production from wind power to the regional electricity distribution system. The study focuses on an 8 MW wind power plant in Nakhon Ratchasima province and simulates the energy storage system using DigSilent Power Factory software.

1. Improve the quality of electricity and increase the stability of the distribution system of wind power plants connected to the medium-voltage distribution system to reduce the impact of plant shutdowns or trips of wind power plants.
2. Analyse the technical aspects of wind power plants by using data on electricity production from wind power, wind speed, and wind forecasting to design and develop a model of the system to improve the quality of electricity and increase the stability of the distribution system of wind power plants.
3. Analyzing the effects of frequent trips or plant shutdowns on the foundation of wind turbines, particularly those connected to the medium-voltage distribution system.
4. Analyse the financial aspect of the system design and development, including the financial internal rate of return of the investment.

**1.4 Key Words**

Wind Power Plant/ Power Quality/ Medium Voltage Distribution Network

**1.5 Benefits of the study**

1. Reduce the effects of a wind power plant shutting down or tripping, which causes electricity production to fluctuate a lot and isn't up to the standards of the grid connection code and regulations of distribution lines. The wind power plant can work efficiently.
2. Improve the quality of electricity and increase the stability of the distribution system of wind power plants with problems to create a reliable electricity distribution system for the regional electricity distribution system and surrounding electricity users.
3. Understand the impact on the foundation of wind turbines when a wind power plant connected to the medium-voltage distribution system experiences frequent trips or plant shutdowns, which can result in emergency stops for the turbines. This is to prevent potential damage and future risks.
4. Finding the financial return on investment from improving the quality of electricity from wind power plants and the suitability of the investment, including the financial internal rate of return (FIRR) of the system design and development.

# CHAPTER II

# LITERATURE REVIEW

Wind energy is a renewable and clean source of energy that is generated from the natural power of the wind. Now, wind energy is used to produce electricity by wind turbines. Wind turbines are used to convert the kinetic energy of the wind into mechanical power, which is then transformed into electricity through a generator. The use of wind energy has been increasing rapidly in recent years, with countries around the world adopting this sustainable energy source to reduce their dependence on fossil fuels and mitigate climate change. Wind energy has become an important part of the global transition towards a low-carbon and sustainable future.

## 2.1 Wind energy

Thailand has wind energy because it is on the equator. This means that the wind speeds are fairly strong. So, if Thailand wants to use wind energy, it needs to choose or create wind turbine technology that works well with the way the wind blows there. Areas with strong winds are often narrow regions that occur in specific topographic features such as hills, mountain passes, or summits, which help to increase wind speeds. According to a study by the Department of Alternative Energy Development and Efficiency, the potential wind energy map for Thailand was updated in 2010, indicating that at a height of 90 meters, the average wind speed in most parts of the country ranges from 4 to 5 meters per second, [1] as shown in Figure 10.

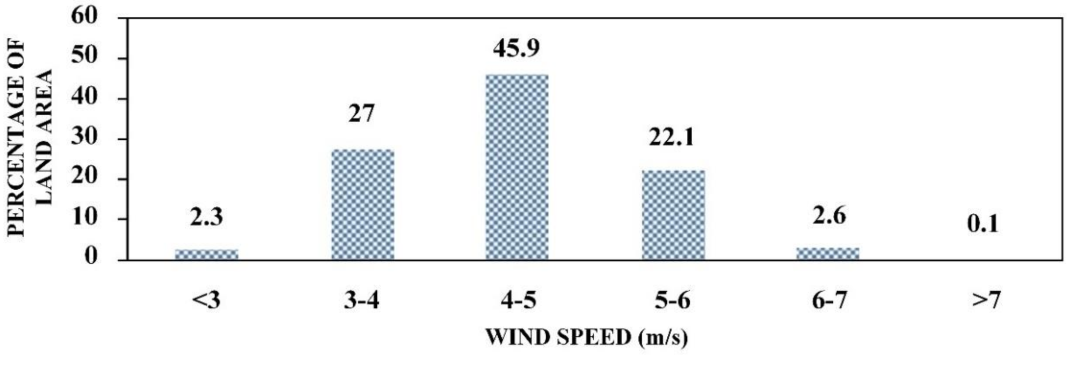



Figure 10 The distribution of areas according to wind speed at a height of 90 meters.

The southern region of Thailand has relatively higher wind speeds, especially in the lower parts of the southern mountain range and the upper western part of the southern region, due to the influence of the southwest monsoon wind from the Andaman Sea and the northeast monsoon wind from the Gulf of Thailand. The average annual wind speed in these areas ranges from 6-7 meters per second. In the northeastern part of the country, the upper and eastern parts of the region, which are characterized by hills and mountain ranges, have an average wind speed of 6-7 meters per second, while the central and lower parts, which are high plains, have calmer wind conditions. In the central region, the western part is influenced by the southwest monsoon wind, and narrow areas with wind speeds of 5-7 meters per second can be found along the mountain ranges. However, wind energy development in Thailand faces several limitations, such as the need for permission to use the land, the mismatch between the demand for electricity and the potential wind energy sites, which are often far from communities, resulting in high transmission costs, and the uncertainty of investment returns. With its abundant wind resources and climate, has a significant potential for wind energy generation, with coastal areas in the south and mountainous regions in the north and northeast offering high wind speeds suitable for wind energy projects. Therefore, Thailand is well-positioned to tap into its wind energy potential and become a leader in the region's renewable energy transition.

## 2.2 Wind Turbines

A wind turbine is a device that converts kinetic energy from the wind into electrical energy. It consists of a rotor with several blades mounted on a tall tower. As the wind blows, the blades of the rotor rotate, which turns a generator that produces electricity. The amount of electricity generated by a wind turbine depends on the speed and direction of the wind, the size and shape of the blades, and the efficiency of the generator. There are two main types of wind turbines: horizontal-axis turbines and vertical-axis turbines. Horizontal-axis turbines have blades that rotate around a horizontal axis, while vertical-axis turbines have blades that rotate around a vertical axis. Horizontal-axis turbines are more commonly used for large-scale wind power generation because they are more efficient and produce more electricity per unit of area swept by the blades. However, vertical-axis turbines are suitable for small-scale wind power generation and can be installed in urban areas where space is limited.

### 2.2.1 Vertical axis wind turbine (VAWT)

A vertical axis wind turbine (VAWT) is a type of wind turbine in which the rotor blades rotate around a vertical axis. This is in contrast to the more common horizontal-axis wind turbines (HAWT), which have blades that rotate around a horizontal axis. VAWTs have several advantages over HAWTs, such as their ability to operate in turbulent or gusty winds and their lower noise level. There are several types of VAWTs, including the Darrieus, Savonius, and Giromill designs. The Darrieus VAWT has two or more curved blades that resemble an eggbeater and is suitable for areas with low wind speeds. The Savonius VAWT has two or three curved blades that resemble a cylinder and is suitable for urban or rural areas with low wind speeds. The Giromill VAWT has a rotor that consists of straight, vertical blades arranged around a vertical axis and is suitable for medium- to high-wind speed areas. VAWTs are often used for small-scale applications, such as powering homes, farms, or telecommunications towers. However, they have lower efficiency compared to HAWTs, and their use for large-scale wind power generation is limited.

Figure 11 Darrieus-type wind turbine

(source: https://upload.wikimedia.org/wikipedia/commons/9/92/Darrieus_rotor002.jpg)

**2.2.2 Horizontal axis wind turbine (HAWT)**

A horizontal axis wind turbine (HAWT) is a type of wind turbine in which the rotor blades rotate around a horizontal axis. This is in contrast to the vertical axis wind turbine (VAWT), which has blades that rotate around a vertical axis. HAWTs are the most common type of wind turbine used for large-scale wind power generation. The blades of a HAWT are made to look like airfoils, like the wings of an airplane, so that they can catch the wind's energy as efficiently as possible.The blades are usually made of composite materials, such as fiberglass or carbon fiber, and are mounted on a hub that is connected to a gearbox and generator. As the wind blows, the blades rotate, turning the generator to produce electricity. HAWTs are typically used for large-scale wind power projects, such as wind farms, that are connected to the electrical grid. They can also be used for small-scale applications, such as powering homes, farms, or businesses.

Figure 12 Horizontal axis wind turbine

### 2.2.3 Component of horizontal axis wind turbine

The main components of a horizontal axis wind turbine (HAWT), as shown in Figure 13, include:

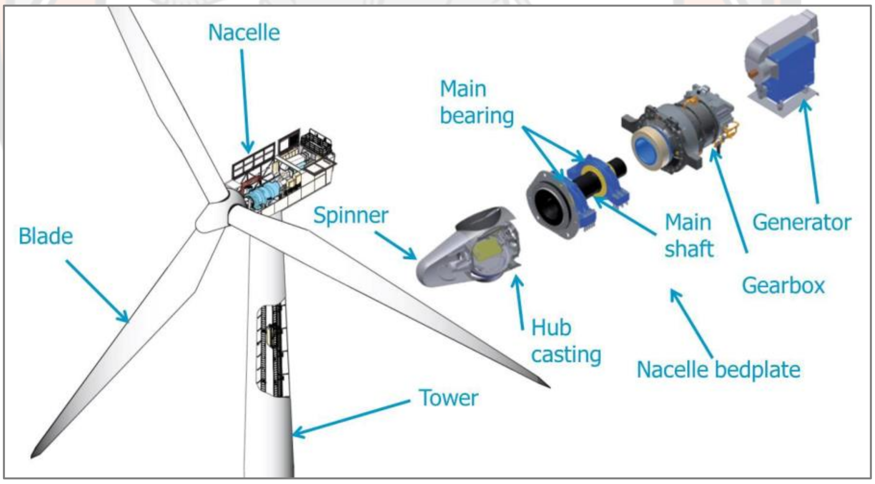



Figure 13 The main components of a horizontal axis wind turbine

(source: https://www.facebook.com/engiideas/photos/pcb.1918934885079230/1918933648412687/)

**Rotor Blades:** The rotor blades are the most visible part of a wind turbine. They are designed to capture the energy of the wind and convert it into rotational energy. Most rotor blades are made of composite materials, such as fiberglass or carbon fiber.

**Rotor Hub:** The rotor hub connects the rotor blades to the main shaft. It is designed to transfer the rotational energy of the blades to the shaft.

**Nacelle:** The nacelle is the housing that contains the gearbox, generator, and other control components. It is mounted on top of the tower and rotates to face into the wind. as shown in Figure 14. The internal components of the nacelle include:

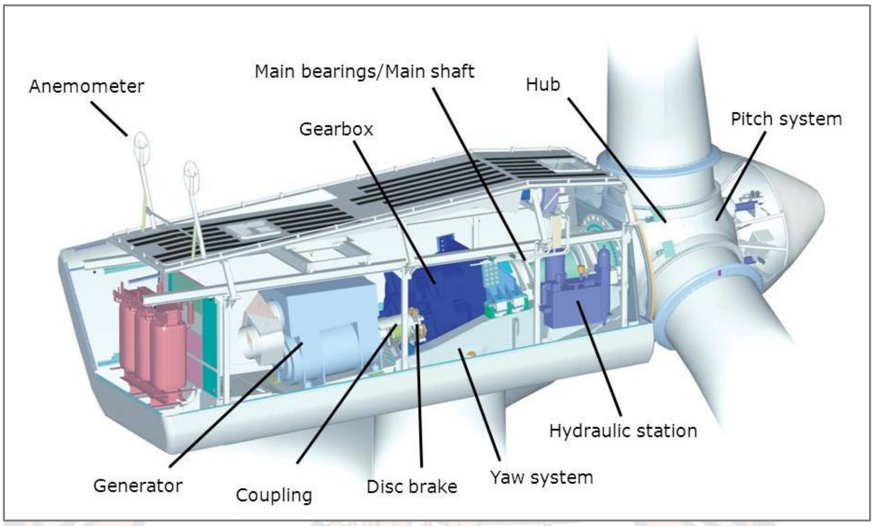



Figure 14 Internal components of the nacelle.
(source: https://slideplayer.com/slide/5778016/)

- **Generator:** The generator is the main component of the nacelle, and it is responsible for converting the kinetic energy from the rotating blades into electrical energy.
- **Gearbox:** The gearbox is responsible for increasing the rotational speed of the generator to achieve the necessary power output.
- **Rotor hub:** The rotor hub connects the rotor blades to the main shaft of the wind turbine and transfers the rotational force generated by the blades to the gearbox.
- **Main shaft:** The main shaft is a large, high-strength steel shaft that connects the rotor hub to the gearbox and the generator.
- **Brakes:** The brakes are used to stop the rotor blades in the event of an emergency or maintenance.
- **Cooling system:** The nacelle contains a cooling system to prevent overheating of the internal components.
- **Control system:** The control system manages the operation of the wind turbine and regulates the speed and output of the generator.
- **Sensors:** Sensors are used to monitor the performance of the wind turbine and detect any issues that may arise.

**Gearbox:** The gearbox is a complex mechanical system that increases the rotational speed of the rotor to the speed required by the generator. It is typically housed in the nacelle.

**Generator:** The generator converts the rotational energy of the rotor into electrical energy. It is typically a three-phase, synchronous generator.

**Tower:** The tower supports the rotor and nacelle at a height where the wind speed is high and consistent. Towers are usually made of steel or concrete and can range in height from 30 to over 100 meters.

**Controller:** The controller is the brain of the wind turbine. It manages the operation of the turbine by monitoring wind speed and direction, controlling the pitch angle of the rotor blades, and regulating the speed of the generator.

**Electrical System:** The electrical system includes power cables, transformers, and switchgear that connect the wind turbine to the electrical grid or to a local load. The electrical system also includes control panels and monitoring systems that allow operators to monitor and control the turbine's operation

**Foundation:** The foundation of a wind turbine is an essential component that supports the structure of the turbine and transfers the loads generated by the turbine to the ground. The foundation must be designed to withstand the forces generated by the rotor blades and tower during normal operation and extreme weather conditions, such as high winds and earthquakes. The foundation of a wind turbine must be designed to meet specific requirements, such as soil conditions, wind speeds, and the weight and dimensions of the turbine. The design process typically involves geotechnical investigations, structural analysis, and site-specific considerations to ensure that the foundation can withstand the loads and maintain stability over the lifetime of the wind turbine.

## 2.3 Wind Power Profile

The power output of wind turbines depends upon the wind speed as the speed fluctuates continuously, the power output varies. The power output of turbines is a function of wind velocity ($V^3$), as the wind speed reaches its double, the power output of the turbine increases 8 times. The available Power in wind can be calculated by using equation 1 [5].

**Available Power in Wind**

$$P=\frac{1}{2}\rho AV^3 \tag{1}$$

Where;

P = power available in the wind

$\rho$ = density of air, $Kg/m^3$

A = Area of the rotor

V = wind speed, m/s

**Mechanical Power of Wind Turbine**

The mechanical output power $P_{\mathrm{mech}}$ of the turbines can be calculated by using equation (2);

$$P_{mech}=\frac{1}{2}C_p\rho AV^3 \tag{2}$$

Where;

$C_p$ = power co-efficient represents the wind turbine efficiency (the maximum value pointed out by Betz is 0.593)

$P_{mech}$ = the maximum power that can be extracted from wind through wind turbine (maximum mechanical power)

**Electrical power of wind turbine generator**

The power output of the generator is given by $P_{gen}$;

$$P_{gen}=\frac{1}{2}C_p\rho AV^3\eta \tag{3}$$

Whereas, η is efficiency of generator if there is no gear box. If the gearbox is existing, the combine efficiency may be taken in consideration in equation (3)

## 2.4 Wind turbine working

Wind turbines are devices that convert the kinetic energy of wind into electrical energy. They are an important source of renewable energy, and they play a critical role in reducing our reliance on fossil fuels. Here is a detailed explanation of how wind turbines work. as shown in Figure 15.

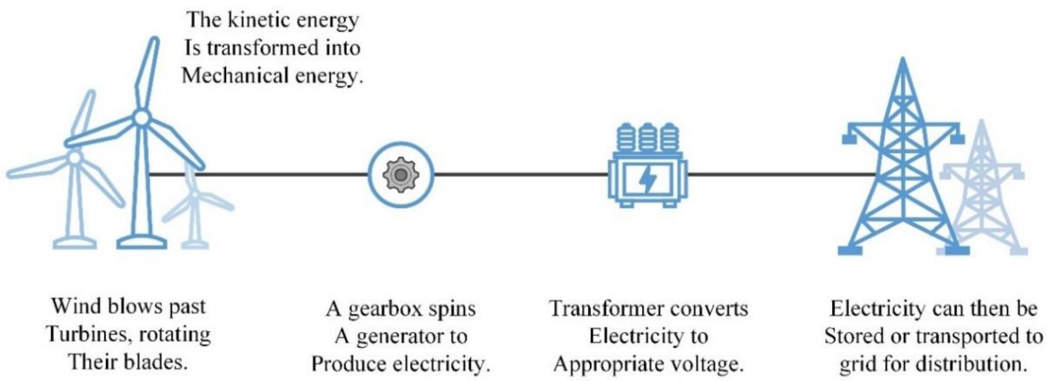



Figure 15 Working of the Wind Turbine

**The blades:** Wind turbines have two or three blades attached to a rotor. The blades are shaped like airfoils and are designed to capture the energy in the wind. When the wind blows, it causes the blades to rotate. The rotation of the blades sets the rotor in motion.

**The shaft:** The rotor is connected to a shaft that runs through the center of the turbine. As the blades turn, they rotate the shaft. The shaft is connected to a gearbox that increases the speed of rotation. The gearbox converts the slow rotational speed of the blades into a faster speed that is required by the generator.

**The generator:** At the end of the shaft, there is a generator. The generator is the component of the turbine that converts the mechanical energy of the rotor into electrical energy. The generator consists of a rotor and a stator. The rotor is a rotating electromagnet, while the stator is a stationary electromagnet. When the rotor spins, it induces a current in the stator, which produces electricity.

**The control system:** The wind turbine has a control system that monitors wind speed and direction. If the wind is too strong or too weak, the control system adjusts the pitch angle of the blades to optimize energy production. The pitch angle is the angle at which the blades are set relative to the wind. If the wind is too strong, the control system will reduce the pitch angle to prevent the blades from spinning too fast. If the wind is too weak, the control system will increase the pitch angle to allow the blades to capture more energy.

**The transmission system:** The electricity generated by the turbine is transmitted through a cable to a substation, where it is converted to a higher voltage and sent to the power grid. The power grid distributes the electricity to homes, businesses, and other consumers.

## 2.5 Types of Wind Power Plants

There are several types of wind power plants, each with its own unique design and operating characteristics. The main types of wind power plants include:

### 2.5.1 Stand-alone wind power plant system.

A stand-alone wind power plant, also known as an off-grid wind power plant, is a type of wind power plant that operates independently of the electrical grid. These plants are typically used in remote or isolated areas where it is not feasible or cost-effective to connect to the grid. A stand-alone wind power plant typically consists of a wind turbine, a generator, and a battery storage system. The wind turbine generates electricity, which is then stored in the battery system for use when the wind is not blowing. The generator is used to provide backup power when the battery system is depleted or when there is not enough wind to generate electricity.

Stand-alone wind power plants can be used to power a variety of applications, such as homes, businesses, telecommunications equipment, and water pumping stations. These plants offer several advantages, including reduced dependence on fossil fuels, lower energy costs over the long term, and increased energy security. However, stand-alone wind power plants also have some limitations. They are typically more expensive to install and maintain than grid-connected wind power plants, and they may require a larger battery storage system to ensure reliable operation. In addition, the amount of power that can be generated by a stand-alone wind power plant is limited by the size of the wind turbine and the capacity of the battery system, as shown in Figure 16.

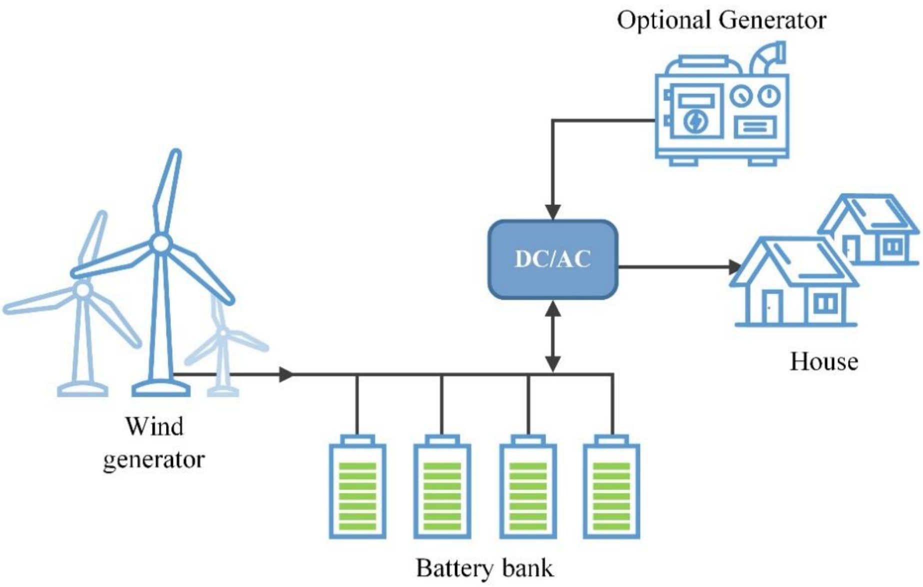



Figure 16 Stand-alone wind power plant.

**2.5.2 Grid connected wind power plant system.**

A grid-connected wind power plant, also known as an on-grid wind power plant, is a type of wind power plant that is connected to the electrical grid. These plants generate electricity from the wind, which is then fed into the grid to supply power to homes, businesses, and other facilities. Grid Connected wind power plants typically consist of multiple wind turbines that are connected to a substation that steps up the voltage of the electricity generated by the turbines. The electricity is then transmitted to a central grid, where it can be distributed to consumers. Grid-connected wind power plants offer several advantages over stand-alone wind power plants. It can generate a larger amount of electricity, and excess electricity can be sold back to the grid for a profit. They also offer greater energy reliability and stability, as they can draw on the grid for backup power if necessary.

However, grid-connected wind power plants also have some limitations. They require a reliable grid connection and may experience downtime if the grid experiences a power outage or other disruption. They may also require extensive infrastructure to connect to the grid, which can add to the cost of installation and maintenance. Overall, grid-connected wind power plants are a popular choice for renewable energy generation, as they offer reliable and efficient electricity production with the ability to sell excess power back to the grid, as shown in Figure 17.

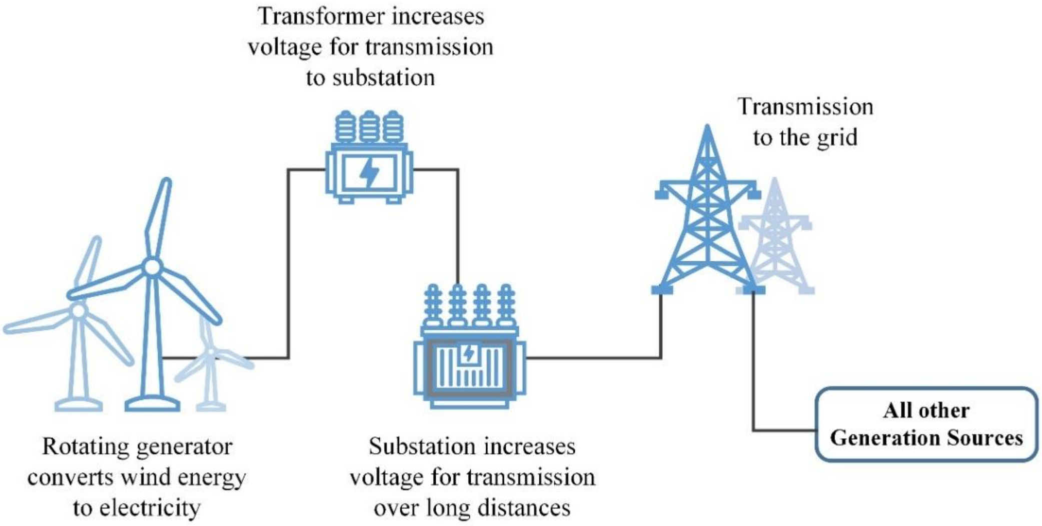



Figure 17 Grid connected wind power plant system.

**2.5.3 Hybrid wind power plant system.**

A hybrid wind power plant is a type of wind power plant that combines wind power with one or more other sources of energy, such as solar power, battery storage, or a backup generator. The combination of different sources of energy can provide a more stable and reliable source of power, especially in areas where wind or solar power alone may be unreliable. Hybrid wind power plants typically consist of a wind turbine, a solar array, and a battery storage system. The wind turbine and solar array generate electricity, which is then stored in the battery system for use when the wind is not blowing or the sun is not shining. A backup generator may also be included to provide power during extended periods of low wind or solar output.

The integration of different energy sources in a hybrid wind power plant offers several advantages. It can provide a more stable and reliable source of power, reducing the risk of power outages or fluctuations in energy supply. It can also improve the overall efficiency of the power plant by using multiple sources of energy to generate electricity. However, hybrid wind power plants also have some limitations. They require additional infrastructure and equipment to integrate the different energy sources, which can add to the cost of installation and maintenance. They may also require more complex control and monitoring systems to ensure that the different sources of energy are used efficiently and effectively. Overall, hybrid wind power plants are a promising technology for renewable energy generation, as they offer a more reliable and efficient source of power by combining the strengths of different energy sources, as shown in Figure 18.

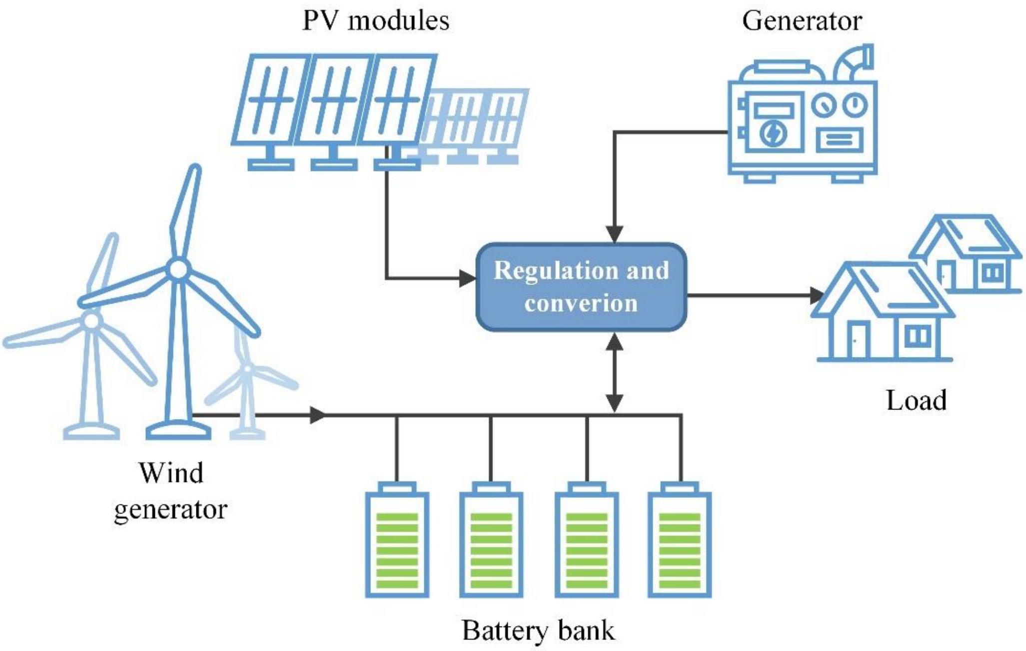



Figure 18 Hybrid wind power plant system.

**2.6 Energy storage system**

An energy storage system is a device that holds energy in reserve for use at a later time. Usually, batteries are used for storage, or other technologies are used to store extra energy produced during periods of low demand for use during periods of high demand. You can use BESS for a variety of purposes, including:

- **Integration of renewable energy:** BESS can be used to store excess energy generated by wind turbines and solar panels for use when the wind is not blowing or the sun is not shining.
- **Grid stabilization:** BESS plays a crucial role in stabilizing the electrical grid by providing backup power during power outages or periods of high demand.
- **Peak shaving:** BESS can be used to reduce peak demand on the electrical grid by storing excess energy during times of low demand and using it during periods of high demand.
- **Uninterruptible power supply (UPS):** Vital applications like data centers or hospitals can use BESS as a backup power source to ensure access to electricity in the event of a power loss.

### 2.6.1 Battery technologies overview

With the development of smart grids and microgrids, there is a growing need for energy storage in power systems. In the paper, we deal with batteries, which are an electrochemical storage technology [6]. There are different battery technologies; the following are presented:

#### 1. Lead-acid

Lead-acid battery is a type of rechargeable battery that uses a chemical reaction between lead and lead dioxide with sulfuric acid to produce electrical energy. The battery is made up of lead plates covered in lead oxide ($PbO_2$) and lead (Pb), as well as a plastic container that is filled with a solution of sulfuric acid and water. An electrical current passes through the battery during charging, triggering a chemical reaction. The lead dioxide on the positive plate reacts with the sulfuric acid to form lead sulfate ($PbSO_4$) and water ($H_2O$), while the lead on the negative plate reacts with the sulfuric acid to form lead sulfate and hydrogen gas ($H_2$). During discharge, the chemical reaction is reversed, and the lead sulfate on both plates is converted back into lead dioxide and lead, respectively. This process releases electrons, which flow through an external circuit to power a device, as shown in Figure 19.

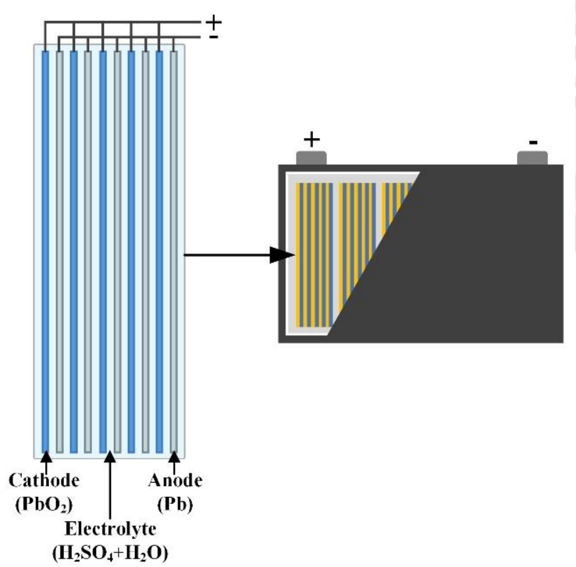



Figure 19 Lead-acid battery.

Lead-acid batteries have many benefits, including low cost and excellent dependability. They are also relatively easy to maintain and can be recharged quickly. However, they have some drawbacks, including their weight, which can make them difficult to move, and their tendency to release hydrogen gas during charging, which can be a safety hazard if not properly ventilated. Additionally, lead-acid batteries are not as efficient as some other types of rechargeable batteries and have a limited lifespan.

**2. Lithium-ion**

A lithium-ion battery is a rechargeable battery that utilizes lithium ions as the primary component of its electrolyte. Lithium-ion batteries possess a notable energy density, allowing them to store a substantial amount of energy inside a compact and lightweight enclosure. They are often used in portable electronics like smartphones, laptops, and tablets. They are also used in electric cars and systems that store energy. The main components of a lithium-ion battery are the anode, cathode, electrolyte, and separator. Graphite often serves as the anode, while lithium compounds like lithium cobalt oxide or lithium iron phosphate form the cathode. The electrolyte is a fluid or gel material that facilitates the movement of lithium ions between the anode and cathode during the charging and discharging processes. A separator is a slender material layer that serves to isolate the anode and cathode, thereby preventing any possibility of short circuits, as shown in Figure 20.

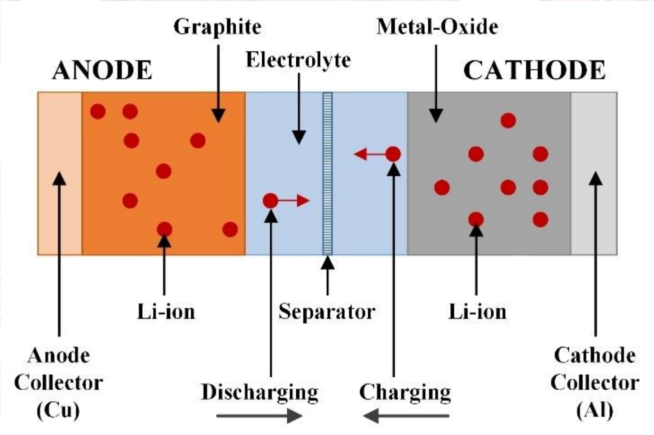



Figure 20 Lithium-ion battery.

Lithium-ion batteries have several advantages over other types of batteries, including their high energy density, low self-discharge rate, and long cycle life. Additionally, their low weight makes them ideal for portable devices, and they can recharge quickly. Nevertheless, lithium-ion batteries may be costlier than other battery types and are susceptible to high temperatures or overcharging, which can lead to instability and associated hazards. Furthermore, the components used in lithium-ion batteries are often scarce and challenging to extract. Despite their limitations, lithium-ion batteries remain an important technology for many applications. Ongoing research is focused on improving their safety, efficiency, and environmental impact and developing new materials and manufacturing techniques to make them even more powerful and cost-effective.

**3. Nickel-cadmium**

A nickel-cadmium (NiCd) battery is rechargeable and uses nickel oxide hydroxide and metallic cadmium as electrodes. Often, a NiCd battery uses potassium hydroxide as its electrolyte. It facilitates the movement of ions between the electrodes during the charging and discharging processes. During charging, the cadmium in the negative electrode is oxidized, producing cadmium hydroxide and releasing electrons. At the same time, the nickel oxide hydroxide in the positive electrode is reduced, accepting electrons and forming nickel hydroxide. During discharging, the opposite reaction occurs, and the nickel hydroxide in the positive electrode is oxidized, releasing electrons and forming nickel oxide hydroxide, while the cadmium hydroxide in the negative electrode is reduced, accepting electrons and forming metallic cadmium, as shown in Figure 21.

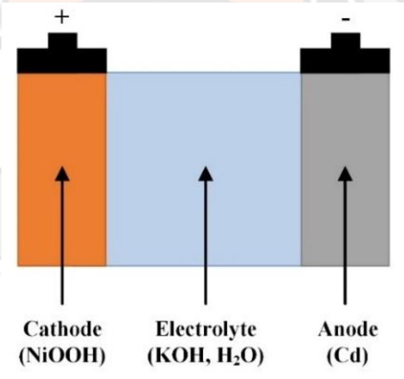



Figure 21 Nickel-cadmium battery.

One of the primary benefits of NiCd batteries is their comparatively affordable price and exceptional longevity. Applications that require a substantial power output, like power tools, flashlights, and emergency backup systems, often utilize NiCd batteries. In addition, they possess a prolonged lifespan and can undergo several recharges without seeing any decrease in their capacity. However, NiCd batteries have a lower energy density than other types of batteries, meaning they cannot store as much energy in the same amount of space. They are also known to suffer from a phenomenon called "memory effect," which can reduce their capacity if they are not fully discharged before recharging.

**4. Nickel-metal hydride**

A nickel-metal hydride (NiMH) battery is a rechargeable battery that uses a hydrogen-absorbing metal alloy rather than cadmium as the negative electrode. The positive electrode is typically made of nickel hydroxide, similar to the nickel-cadmium battery. The electrolyte is typically an alkaline solution, such as potassium hydroxide. During charging, the nickel hydroxide in the positive electrode is oxidized, while the hydrogen-absorbing alloy in the negative electrode absorbs hydrogen ions and electrons, producing metal hydride. During discharging, the opposite reaction occurs, and the nickel hydroxide in the positive electrode is reduced, while the metal hydride in the negative electrode releases hydrogen ions and electrons, producing water and returning to its original state, as shown in Figure 22.

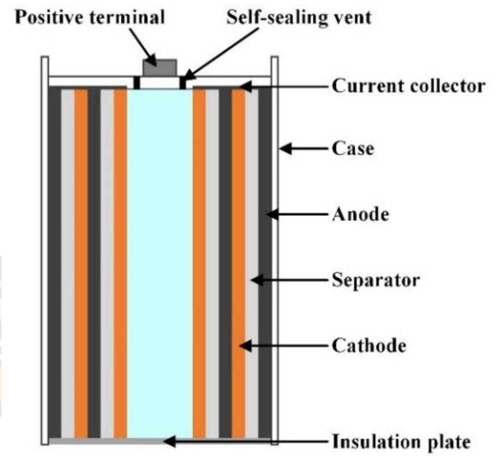



Figure 22 Nickel-metal hydride battery.

One advantage of NiMH batteries over NiCd batteries is their higher energy density, meaning they can store more energy in the same amount of space. They also have a longer cycle life and do not suffer from the "memory effect" that can reduce the capacity of NiCd batteries. Additionally, NiMH batteries are more environmentally friendly than NiCd batteries since they do not contain toxic cadmium. However, NiMH batteries are more expensive than NiCd batteries, and their performance can be affected by high temperatures or overcharging. They also have a tendency to self-discharge over time, which can reduce their capacity if they are not used regularly.

**5. Sodium-sulfur**

Sodium-sulfur (NaS) battery is a type of rechargeable battery that uses a liquid sodium anode and a solid-state sulfur cathode. Typically, a ceramic material such as beta-alumina serves as the electrolyte in a NaS battery. This ceramic material facilitates the transfer of sodium ions between the electrodes during battery charging or discharge. During charging, the sodium ions are absorbed by the sulfur cathode, causing it to expand. When the battery is discharged, the sodium ions move back to the anode, generating an electrical current that powers the device, as shown in Figure 23.

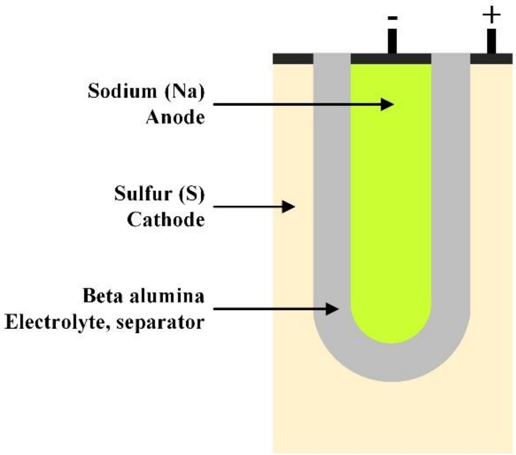



Figure 23 Sodium-sulfur battery.

An important benefit of NaS batteries is their exceptional energy density, enabling them to store a substantial amount of energy in a compact form. In addition, they exhibit exceptional efficiency, achieving a round-trip efficiency of up to 90 percent. This implies they store and distribute about the same energy. Extensive energy storage systems, particularly in power grids, often use sodium-sulfur (NaS) batteries. Known for their high energy density and efficiency, these batteries are perfect for storing renewable energy from sources like solar and wind power. Additionally, some electric cars use them due to their exceptional energy density, which allows them to provide substantial power over an extended period without requiring recharging. NaS batteries function at high temperatures, often ranging from 300 to 350 degrees Celsius. This necessitates the use of specialist components and may pose safety risks if not well regulated. In addition, the materials used in NaS batteries are very costly and might pose challenges in terms of procurement.

**6. Vanadium-redox flow**

Vanadium-redox flow battery is a type of rechargeable battery that uses vanadium ions in different oxidation states to store and release electrical energy. The battery consists of two tanks, each containing a solution of vanadium ions in different oxidation states, separated by a membrane. The two solutions flow through the membrane and react during charging and discharging to produce an electrical current, as shown in Figure 24.

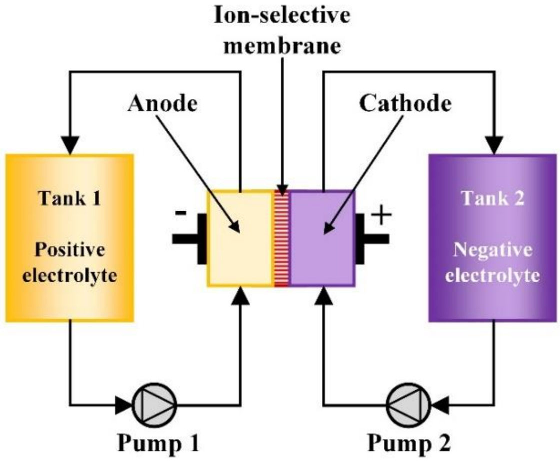



Figure 24 Vanadium-redox flow battery.

An inherent benefit of vanadium-redox flow batteries is their exceptional energy density, allowing for the storage of a substantial amount of energy in a compact form. In addition, these batteries possess a substantial lifespan, can be rapidly recharged, and may be readily adjusted in size to accommodate various applications. Extensive energy storage applications, such as power grids, often use vanadium-redox flow batteries due to their notable energy density and scalability. These batteries are particularly suitable for storing renewable energy generated from sources such as solar and wind power. However, vanadium-redox flow batteries are relatively expensive to manufacture, and the materials used in the battery, particularly vanadium, can be expensive and difficult to source. Additionally, the battery requires a large amount of space and infrastructure to operate, which can make it challenging to implement in some applications.

An overview of battery technologies used in grid applications. Lead-acid batteries are affordable and efficient but have a low number of lifetime cycles. Lithium-ion batteries are the most advanced and efficient but have a higher price tag. Nickel-metal hydride batteries are suitable for extreme temperatures and have a lower price but lower efficiency. Sodium-sulfur batteries are suitable for high lifetime cycle applications but have a high working temperature. Vanadium-redox flow batteries have a high number of lifetime cycles and are suitable for long-term energy storage but have low energy and power density and require a large space for placement. Overall, lithium-ion batteries are the most suitable for different applications due to their high specific power and energy, highest power and energy density, highest cell voltage, and highest efficiency. However, ongoing research is focused on improving the efficiency and reducing the cost of other battery technologies and developing new applications that can take advantage of their unique properties.

| Characteristics | Pb-acid | Li-ion | NiCd | NIMH | NaS | VRFB |
|---|---|---|---|---|---|---|
| Specfic energy [Wh/kg] | 25-50 | 80-250 | 30-80 | 40-110 | 150-240 | 10-130 |
| Specfic power [kWh/m$^3$] | 150-400 | 200-2000 | 80-300 | 200-300 | 90-230 | 50-150 |
| Energy density[kW/m$^3$] | 25-90 | 95-500 | 15-150 | 40-300 | 150-350 | 10-33 |
| Power density [€/kWh] | 10-400 | 50-800 | 40-140 | 10-600 | 1.2-50 | 2.5-33 |
| Energy cost [€/kWh] | 40-170 | 500-2100 | 680-1300 | 170-640 | 250-420 | 130-850 |
| Power cost [€/kW] | 250-500 | 1000-3400 | 420-1300 | 200-470 | 850-2500 | 500-1300 |
| Lifetime [years] | 2-15 | 5-15 | 10-20 | 2-15 | 10-15 | 5-15 |
| Lifetime cycles [cycles] | 250-2000 | 100-1000 | 1000-5000 | 300-1800 | 2500-40000 | 10000-16000 |
| Cell voltage [V] | 2-21 | 2.5-5 | 1.2-1.3 | 1.2-1.35 | 1.8-2.71 | 1.2-1.4 |
| Efficiency [%] | 63-90 | 75-97 | 60-90 | 50-80 | 75-90 | 75-90 |

Figure 25 Comparison of battery technologies.

### 2.6.2 Function of the energy storage system

The function of the energy storage system (ESS) is to store energy for later use. Energy storage systems may mitigate the challenges posed by the intermittent, variable, and unpredictable nature of renewable energy sources while also enhancing energy dependability and security. Several essential functions of an energy storage system include the following:

- Load shifting: Energy storage systems can shift energy consumption from peak demand periods to off-peak periods, reducing stress on the electricity grid and lowering energy costs.
- Renewable energy integration: Energy storage systems can store excess energy generated by renewable energy sources such as solar and wind power for use when the energy generation sources are not producing energy.
- Backup power: Energy storage systems have the capability to supply alternative power in the event of power outages or when the electrical grid is not functioning, guaranteeing the continuous continuation of essential activities.
- Grid stabilization: Energy storage devices play a crucial role in maintaining the stability of the energy grid by providing backup power during times of increased demand or in case of a power failure.

- Power quality management: Energy storage systems can improve power quality by providing fast and accurate responses to voltage and frequency fluctuations, reducing the risk of power surges or dips.

The function of the energy storage system is to help manage the supply and demand of energy in a way that is efficient, reliable, and sustainable. The functionality of an energy storage system is contingent upon the particular application and the requirements of the energy system it is incorporated into, as seen in Figure 26.

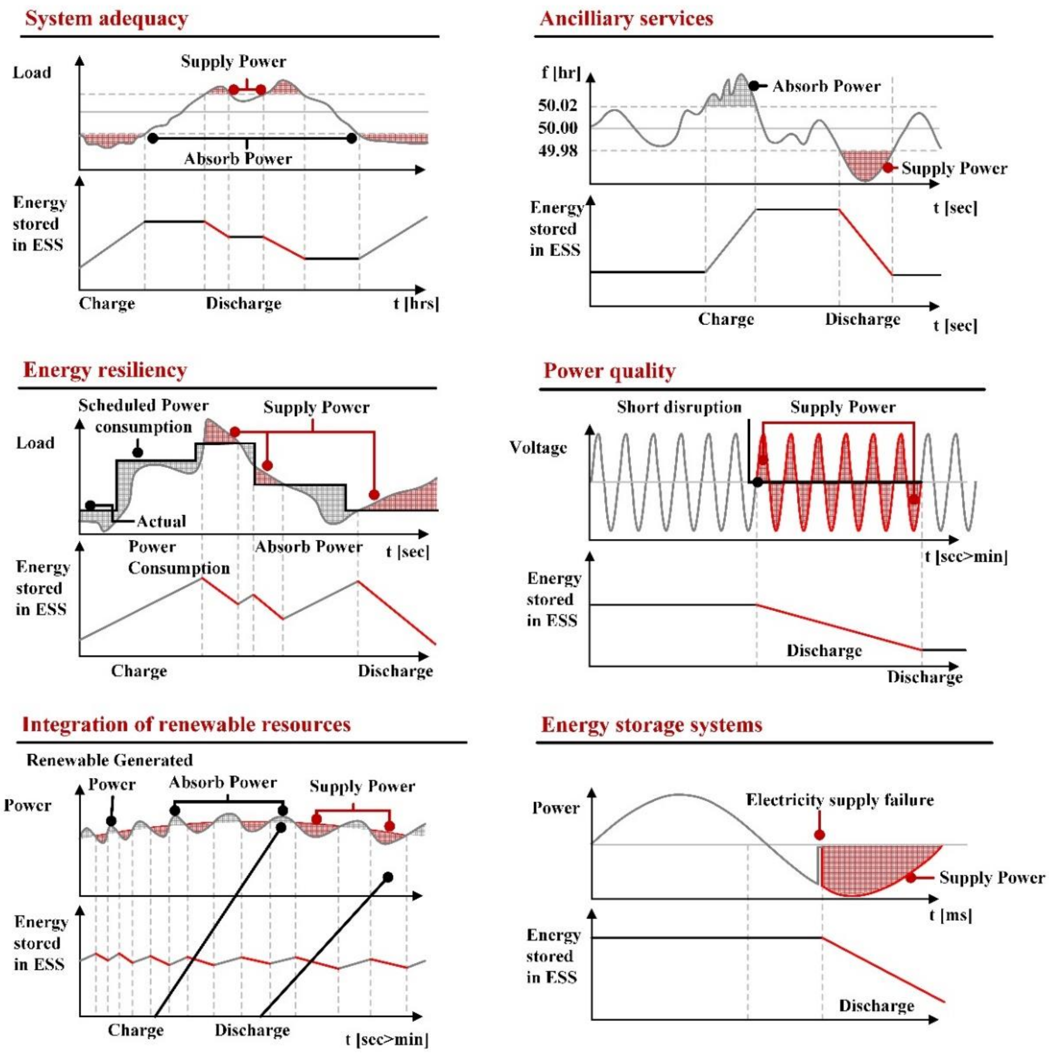



Figure 26 Function of the energy storage system.

### 2.6.3 Hybrid wind power plant system

The position of the energy storage system depends on the specific application and the needs of the electricity grid and users. The energy storage system can play a key role in improving energy efficiency and increasing energy reliability and security for all stakeholders in the electricity system.

The energy storage system is often positioned between the energy-producing sources, such as wind or solar power plants, and the electrical grid in the electricity production system. An energy storage system is used to store surplus energy produced during periods of low demand and then release it during periods of high demand or when the energy-generating sources are inactive.

In the transmission line system, energy storage systems can be located at key points along the grid, such as substations or interconnection points, to provide backup power and help regulate voltage and frequency fluctuations. Energy storage systems can also be used to support the integration of renewable energy sources into the grid by providing a buffer to absorb fluctuations in energy output.

For users, energy storage systems can be installed at the point of use, such as homes, businesses, or industrial sites, to provide backup power during outages or reduce peak demand on the grid. Energy storage systems have the capability to store surplus energy produced by rooftop solar panels or other decentralized energy sources for future use.

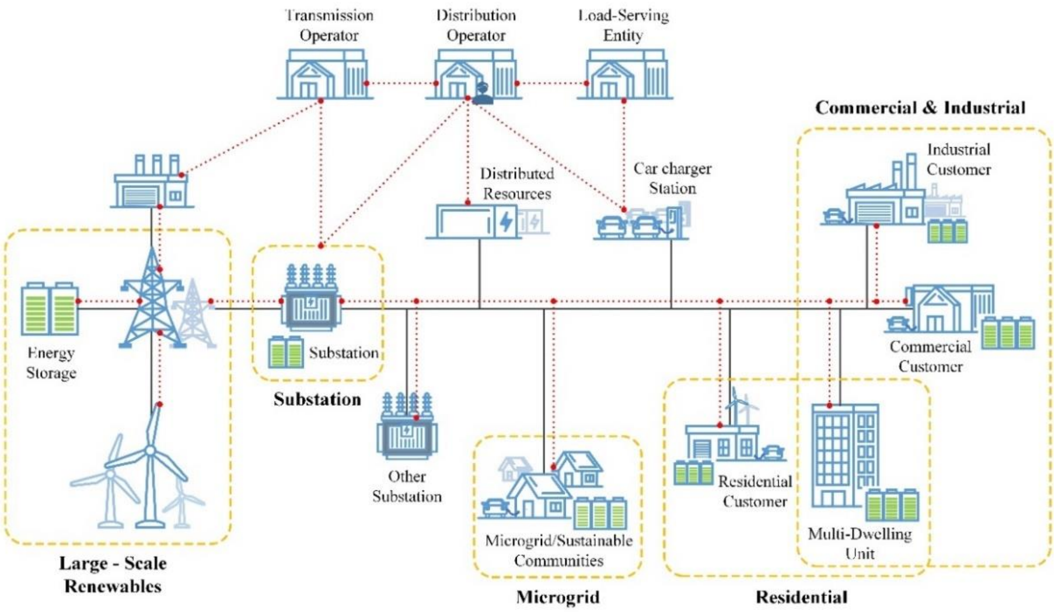
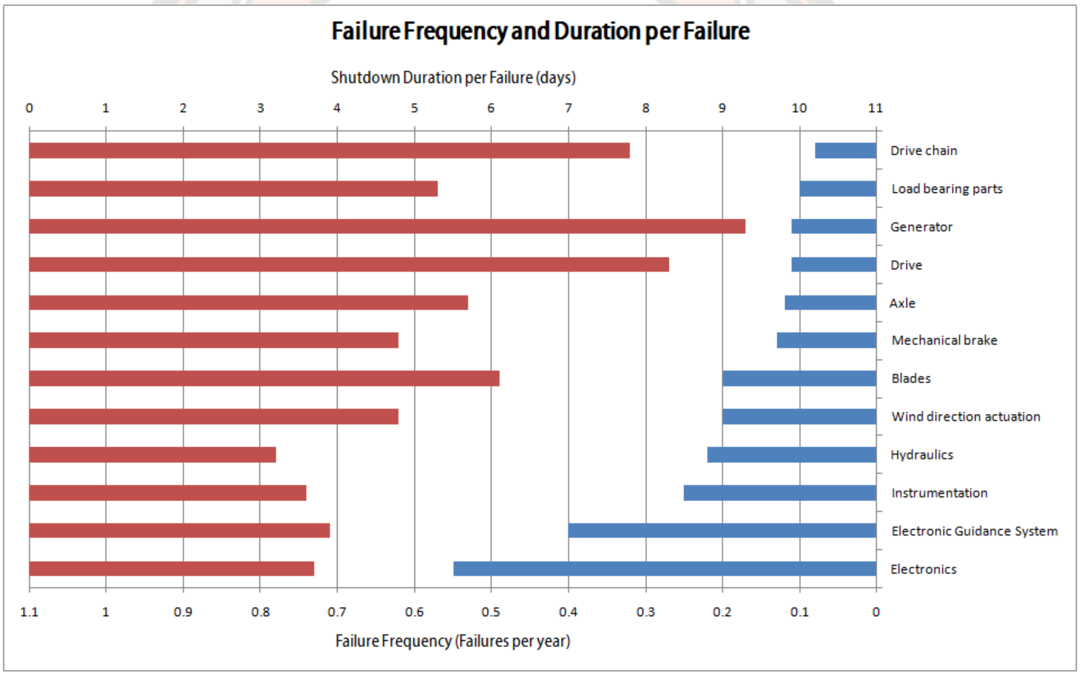



Figure 27 There are cases for using energy storage systems.

## 2.7 The wind turbine’s structure maintenance

Effects on the quality of electricity distribution systems can often lead to feeder trips and plant shutdowns at wind power plants, which can cause damage to the wind turbine structure and have long-term consequences on the system. In addition, it can cause damage to life and property due to the impact. Wind turbine component failures may result in unplanned stoppages, leading to unexpected and costly servicing and repairs for the operator. This might possibly breach the manufacturer's warranty, result in failure to meet peak energy demand, and cause a loss of income. Under exceptional circumstances, a wind turbine has the potential to ignite, resulting in catastrophic outcomes. Several studies have examined the dependability of wind turbine parts, mostly using data from older turbines. These studies have shown significant patterns that indicate the locations where issues often arise, as shown in Figure 28.




**Source:** Algorithmic Technologies

Figure 28 wind turbine component failure rates and downtime. [7]

Wind farm operators use both preventive and predictive maintenance strategies to reduce downtime and fulfill their warranty obligations. Preventative maintenance refers to scheduled maintenance activities that aim to extend the asset's lifespan. Maintenance check-ups typically take place a few times a year. Wind turbine maintenance activities are wide-ranging, as shown in Figure 29.

Figure 29 preventive maintenance of wind turbine.

Checking the strength of the wind turbine will involve inspecting the main structure of the wind turbine. The checking and testing of wind turbine structures is crucial to ensuring their long-term operation, reliability, and safety. A well-designed and well-maintained wind turbine can operate for several decades, providing clean energy with minimal environmental impact. However, any structural issues or defects can compromise the turbine's performance, shorten its lifespan, and increase the risk of catastrophic failure. In general, the work carried out will include:

**Visual Inspection:**

Visual inspections are the most basic form of checking the structure of wind turbines. Conduct a visual inspection of the wind turbine's blades, tower, foundation, and other components to ensure that they appear to be in good condition. This should be done regularly to identify any signs of wear and tear, corrosion, or other forms of damage. Regular inspections can help identify any signs of damage or wear and tear on the turbine's blades, tower, and other components. Inspections can be conducted either manually or through the use of drones, which can capture detailed images of the turbine's exterior.

**Non-Destructive Testing (NDT):**

Non-destructive testing (NDT) techniques, such as ultrasonic testing, magnetic particle testing, and radiography, are used to check for any internal defects in the turbine's structure. to check for any cracks, corrosion, or other defects in the structure of a wind turbine. This is especially important for the critical components of the turbine. NDT can detect even the smallest cracks or corrosion, which can compromise the turbine's structural integrity.

**Load Testing:**

Load testing involves subjecting the wind turbine to extreme loads to test its strength and durability. Perform load testing to check the strength and durability of the wind turbine's structure. This will help identify any weak points in the turbine's structure and ensure that it can withstand the loads it is expected to encounter during normal operation. Load testing can be performed either by applying loads directly to the turbine or through computer simulations.

**Finite Element Analysis (FEA):**

Finite element analysis (FEA) is a computer simulation technique used to analyze the structural behavior of wind turbines. Conduct FEA to simulate the stresses and strains experienced by the wind turbine under various loads and conditions. This will help identify any potential structural issues and allow for corrective measures to be taken before they become a major problem.

**Manufacturer Inspection:**

Manufacturer inspections are also important, as they can provide detailed information on the design and maintenance requirements of the turbine. The manufacturer may also have specific inspection procedures and schedules that need to be followed to ensure that the wind turbine is being inspected according to the manufacturer's specifications, which can help identify any potential warranty issues.

The standards that apply to wind power plants and the structures of wind turbines are established by organizations like the International Electrotechnical Commission (IEC) and the American Society of Mechanical Engineers (ASME). These standards cover a wide range of topics. Checking and testing the structure of wind turbines in wind power plants is essential to ensuring their safe and reliable operation. A comprehensive inspection and testing program, following the relevant standards and best practices, can help identify any potential issues and prevent catastrophic failures, prolonging the life of the turbine and ensuring that it operates at peak efficiency.

## 2.8 Review of Related Articles

This study comprehensively investigates various aspects related to energy storage in wind power plants, such as optimizing the placement of wind turbines, integrating renewable energy, assessing wind potential, optimizing the placement and sizing of wind turbines, implementing energy storage systems, predicting wind power, and understanding the impact of wind power on power systems.

Kheder-Haddouche and Saheb-Koussa analyzed the wind capacity in the Mecheria area of Algeria and calculated the expenses associated with generating electricity from a wind farm. The input consists of a decade's worth of wind data, which is then used to identify the places with the highest wind speeds based on various wind turbine types. Experiments are conducted to identify a highly effective system. Further, using HOMER software, 40 MW grid optimizations are performed to estimate the economic and environmental impacts [8].

Hashem et al. developed a multi-objective optimization method to reduce the significant presence of intermittent wind power by determining the optimal dimensions of wind turbines and energy storage devices. They use the Equilibrium Optimizer (EO) algorithm and a Loss Sensitivity Factor (LSF) in conjunction to mitigate energy loss and voltage swings, while simultaneously enhancing voltage stability. These serve as performance indicators for the distribution system [9].

There are several analytical and optimization methods accessible to raise the effectiveness and efficiency of energy-storage-equipped wind power systems. In order to determine appropriate wind farm sites, yearly wind speed, power-generating capacity, and system size within the Korean government's 17 GW installation timeframe, Moon et al. suggested a weighted assessment technique. In addition, probability density models and the discrete Fourier transform are used to improve energy storage systems (ESS) in order to preserve grid stability [10].

Yan et al. used a steady-state model to propose an ideal technique for BESS scaling. In this analysis, wind power is forecasted to establish the established system for commercial grade, and additional operation and maintenance are incorporated to determine the appropriate economic EES for local grid stability [11].

For optimizing the EES, several studies on power forecasting, error mitigation, long-term wind speed variability, and wind power resource evaluation have been carried out [12-14].

Yi et al. studied the optimization of EES capacity, EES lifespan, wind curtailment, and profitability using various operating techniques. The dynamic control method outperformed the other techniques by extending the EES's lifespan to 13.39 years and yielding a noticeably larger profit of 717,207.44 USD. Reliability, cost-effectiveness, efficiency, profit extension, and energy storage are all achieved by optimized EES, which maintains 0% overcharging or discharging [15].

To comply with Australian electricity bids, Felix et al. carried out an EES optimization at hourly intervals. 55 MW of battery storage systems are designed to discharge over 12 hours (110 MWh) based on the modeling results of a year's worth of GIS data used in this research to create power production via different renewable energy sources. It was discovered that the LCOE was much lower, from 13 to 23 percent, with EES's help. Portugal develops BESS integration in accordance with Flexi et al. to lessen power curtailment via the use of diverse renewable energy sources. For improved optimization, unit commitment and economic dispatch algorithms are used in this work. Notably, the installed capacity of the thermal power plant, wind, hydro-geothermal, and waste-to-energy systems is 47.6 MW, 12.6 MW, 1.4 MW, 3 MW, and 1.7 MW, respectively, while the overall load requirement for the chosen area is 35 MW [16].

Climate change makes it unlikely that renewable energy sources would provide electricity steadily; yet, by combining BESS with non-conventional energy, the annual oil consumption of 1500 tons was greatly reduced. The created system's sensitivity analysis shows that combining 1500 KW and 6300 kWh of BESS is a financially viable solution for the area being studied, which leads to a 59% drop in RE curtailment [17].

Due to the unpredictability of wind output in China's climate, Xin et al. designed a battery energy storage system (BESS). Model Predictive Control (MPC) is used to run a day-ahead simulation, and real-time data is used to evaluate the findings. In comparison to a myopic controller, wind power generation linked to BESS promotes grid stability and greater precision when employing the MPC approach. Second, BESS is economically advantageous at a reserve State of Charge (SOC) of 0.1; any higher SOC results in a lower profit [18].

To lessen wind energy curtailment for China's climate, Chen et al. devised an optimization method using a CPLEX solver. Due to significant variance and unexpected wind speed, wind energy curtailment reached 40.16 percent in the absence of a BESS. Since phase change materials (PCM) are efficient at removing thermal energy, they are used as a secondary storage device in this research to lower the peak charging/discharging battery operating temperature. The BESS in this investigation is a sodium-sulfur battery [19].

To lower their power consumption from the conventional grid during the low wind period, Watson et al. designed a 2 MWh BESS for Canada's 10 MW research and development wind energy center. The wind farm sends 40 GWh of electricity to the grid annually. Nevertheless, the wind farm needs to draw around 13.13 MWh from the grid during a low wind period in order to operate the wind energy institute. Low grid voltage and increased grid load are the results of energy use during the low wind period. A 339-hour low wind speed period, or around 63% of the energy usage, may be decreased with the use of BESS [20].

Ikni et al. investigated the usage of lithium-ion BESS with an offshore wind farm with a capacity of 300 MW to keep the grid frequency steady during power fluctuations brought on by unreported wind speed. Wind turbine power output oscillates considerably between 130 and 180 MW in a 600-second time span, resulting in a grid frequency coding mismatch. By adding a 30 MW lithium-ion battery, the BESS kept the grid's feeding voltage and frequency code much better, which reduced feeder trips and power cuts [21].

Dratsas et al. conducted research to determine whether it would be feasible for tiny islands to use the BESS in order to generate electricity using unconventional technologies and maintain grid stability. Wind energy is abundant on the islands; however, in comparison to other renewable energy sources, wind speed and power output stability are unappealing. When there is a decrease in wind, diesel engines often get compensation. An additional power producer, BESS, reduces 42.75 percent of wind curtailments, or 1442.8 MWh annually [22].

Because the power and energy density of a BESS are inversely related, Liu et al. devised intricate modeling and control methodologies to comprehend the nonlinear and stochastic character of BESS operations. The Model Predictive Control (MPC) mechanism controls how the BESS charges and discharges to the grid, and multi-objective optimization is essential for tracking the power and energy density of the device. It has been discovered that, in comparison to the current BESS, 30% more electricity is sent into the grid, and regulated thermal management lengthens the operating lifespan of the BESS [23].

According to a number of studies, DIgSILENT PowerFactory is a dependable and effective solution for employing a dynamic simulation to optimize distributed power production and BESS capacity. Mostly, it involves using load-shedding techniques and a simple analytical model to quickly respond to frequency control [24-26].

Monitoring frequency deviation, frequency nadir, and rate of change of frequency is made easier with Aggregated System Frequency Response (ASPR) modeling. This improves grid frequency stability when BESS is used. Afterwards, using real frequency data to assess the frequency nadir, ASPR and the second-order approximation approach determine that a BESS capacity of 0.5-2.5% of the rated capacity of wind turbines is needed. In contrast, this strategy maintains the system frequency response and suggests the lowest BESS capacity among other approaches [27].

Song et al. developed a multi-objective optimization method, and they also divided the process into initialization, evaluation, selection, and reproduction. This method evaluated the system's performance by using the temperature effect and the BESS deterioration rate. Fuzzy logic (FL) and genetic algorithms (GA) depend on population size, crossover rate, and mutation rate to minimize uncertainty. The devised algorithm yields reductions in energy consumption, greater use of renewable energy, and decreased peak load demand by 23.7%, 18.5%, and 15.3%, respectively [28].

Optimizing the capacity of BESS is a major task, especially when it comes to an economic aspect, as an increase in the capacity of BESS increases the return on investment. Several studies state that BESS internal losses such as performance degradation, thermal-oriented operational stress, and improper power management widely affect system efficiency [29-31].

The BESS for the Tehran, Iran, site was improved by Niaz et al. to reduce power curtailment and preserve grid frequency. The Iranian Renewable Energy

Organization provides historical wind farm data, load profiles, and other environmental characteristics that are used to train the model. Using a 50 MW/600 MWh BESS, various power curtailments of 25%, 50%, 75%, and 100% are carried out in order to evaluate the economic effect on the system. It was discovered that reducing the power curtailment was not possible when the renewable energy system was operated in 100% BESS mode [32].

To optimize the BESS under different operating situations, an island renewable energy-generating system including PV, wind, and biomass is deployed. Real-time resources are employed for biomass, and input parameters are received from the National Aeronautics and Space Administration (NASA) to create the actual power output from PV and wind. Here, the extra energy from the several renewable energy sources listed above is stored in lead-acid and lithium-ion (Li-ion) batteries. Lead-acid batteries are comparatively less expensive to purchase than Li-ion batteries, but their running costs are higher. The integration of PV/wind/biomass with lead acid batteries results in a high net present cost (NPC); however, the NPC of PV/wind, PV/biomass, and PV alone with Li-ion batteries is greater [33].

The hybrid energy storage system is implemented for a stand-alone system located in a rural region of Egypt, given that the renewable energy generator under examination experiences power curtailments ranging from 8% to 12%. BESS has the advantageous effect of reducing power curtailment by 5%, which increases revenue by 7%. For the Ras Ghareb site, PV and wind turbines alone produce 9874.71 kWh; in contrast, BESS with water electrolyzer electricity output reached 16,984.51 kWh. There has been an annual energy generation boost of 26.62% and 27.28% for Mersa Matrouh and the Aswan area, respectively. Because of seasonal variations in the output of renewable energy, Mersa Matrouh and the Aswan area had more economic benefits than Ras Ghareb [34].

The locations and local grid power purchase agreement determine whether a BESS integration is economically viable. In the Spanish market, Lobato et al. assessed the BESS's economic feasibility for a 30 MW wind farm. Since the BESS initial investment cost and efficiency are different but the end-of-life (EoL), EoL efficiency, and daily cycle count are the same, Li-ion and Vanadium-Redox (Va-Red) are used in this instance to assess the economic viability. Even though the wind farm benefits from the seamless power production that comes with BESS integration, there hasn't been much of an economic shift. The worldwide coordination of automatic frequency restoration and stable system operations is still in the planning stages, which explains the lack of a significant improvement [35].

### 2.8.1 Summary of Literature Review

Table 1 Recent literature study of wind farms associated with BESS.

| Technical | | | | | |
|---|---|---|---|---|---|
| **No.** | **Author** | **Location** | **RE & ESS capacity** | **Study platform** | **Findings** |
| 1 | Pokhriyal et. al [36] | Spain | Wind 481.5 MW ESS 50 MWh | MATLAB Simulink | Wind turbine frequency matching is performed using BESS to stabilize the grid voltage. |
| 2 | Gu et. al [37] | Taiwan | Wind 3.6 MW ESS 0.72 MW | Simulation | Wind gusts, wind crescendos, and random wind strategies are used to smooth wind power production. |
| 3 | Koganti et. al [38] | India/Korea | Wind 3 MW ESS 500 Ah | Simulation | Neuro-fuzzy inference hybrid controller used to monitor the wind turbine and BESS for power filter. |
| 4 | Pechlivanoglou et. al [39] | Greece | Wind multi-MW ESS 94 Ah | Simulation | Wind speed and other related data are collected from the EUNICE ENERGY GROUP (EEG) to optimize the BESS using the discrete wavelet transform method. |
| 5 | Gholami et. al [40] | Iran | Wind 160 MW ESS 21-80 MWh | Analytical model (Simulation) | Optimal BESS is calculated based on the one-year wind farm data and by applying different scenarios such as optimum method, full compensation, and no compensation are taken into consideration in optimizing the BESS. |

Table 1 Recent literature study of wind farms associated with BESS. (Cont.)

| Technical | | | | | |
|---|---|---|---|---|---|
| **No.** | **Author** | **Location** | **RE & ESS capacity** | **Study platform** | **Findings** |
| 6 | Yuan et. al [41] | Cape Verde | Wind 5.95 MW<br>ESS 9 MWh | Autoregressive Integrated Moving Average (ARIMA) | A combination of ARIMA forecasting with BESS improved the grid reliability. |
| 7 | Wu et. al [42] | Mongolia and Sinkiang | Wind 60 MW, 45 MW<br>ESS 2.01 MW, 1.34 MW | Simulation | The wind power prediction model is proposed to reduce the error in power production using a modified statistical distribution model. |
| 8 | Michiorri et. al [43] | France | Wind 9 MW<br>ESS 36 MWh | Simulation | Simulation is performed for four different cases to optimize the BESS capacity to minimize the wind power curtailment and to improve the BESS lifetime. |
| 9 | Nayak et. al [44] | India | Wind 100 kW<br>ESS 24 kWh | Simulation | The Inherited Competitive Swarm Optimization (ICSO) algorithm is used to improve the BESS performance with wind turbine and load regulation. |

Table 1 Recent literature study of wind farms associated with BESS. (Cont.)

| Technical | | | | | |
|---|---|---|---|---|---|
| **No.** | **Author** | **Location** | **RE & ESS capacity** | **Study platform** | **Findings** |
| 10 | Rayit et. al [45] | United Kingdom | RE - ESS 1.25 GWh | novel approach to optimizing battery capacity for wind farm participation in energy markets, considering real-world operational complexities and maximizing economic efficiency. | Analytical method for estimating short-term wind power fluctuations, determining optimal battery capacity, and estimating battery lifetime under non-uniform conditions. The method's effectiveness is demonstrated through a case study using wind speed data. |
| 11 | Yao et. al [46] | China | Wind 200 MW, PV 50 MW ESS 125 MWh | The study is exploring the economic advantages of incorporating energy storage systems into new, independently operated energy power stations. | The study involves modeling the expenditure of new energy power stations, calculating energy storage costs, formulating optimal charging and discharging strategies, comparing storage technologies, and identifying economic efficiency drivers. |
| 12 | Wang et. al [47] | Germany | RE - ESS 20 MWh | Evaluates the economic feasibility of energy storage power plants, using a life-cycle cost model, analyzing their benefits, and demonstrating their economic viability through example analysis. | The study presents a life-cycle cost model for energy storage power plants, highlighting their economic benefits, including reduced peak demand, improved grid stability, integration of renewable energy sources, and deferred infrastructure upgrades. |

Table 1 Recent literature study of wind farms associated with BESS. (Cont.)

| Technical | | | | | |
|---|---|---|---|---|---|
| **No.** | **Author** | **Location** | **RE & ESS capacity** | **Study platform** | **Findings** |
| 13 | Lobato et. al [35] | Span | Wind 30 MW<br>ESS 2.5 MWh | An economic assessment tool for evaluating the integration of battery energy storage systems (BESS) into renewable power plants. | A novel tool calculates the investment price for balancing energy storage systems (BESS) in Spanish electricity markets, showing promising returns but no significant improvement in combining multiple applications. |
| 14 | Yin et. al [48] | China | Wind 20.7 MW, PV 17.34 MW<br>Li-ion 14 GWh, VRB 15.6 GWh | Comparing energy storage technologies (ESS) for accommodating renewable energy sources, reducing curtailment, and analyzing their economic and technical effectiveness. | The paper discusses the mechanism for renewable energy accommodation using BESS technologies, compares four types, and develops a simulation-based method for economic comparison. |
| 15 | Ayodele et. al [49] | South Africa | PV/Wind microgrid<br>ESS 30 kW | Explores the economic feasibility of a hybrid PV and wind microgrid system in a South African rural healthcare clinic, examining the impact of storage technologies. | The study identifies three feasible energy storage technologies for microgrid applications, highlighting their impact on microgrid architecture and economic feasibility. |
| 16 | Wali et. al [50] | United Nations | PV 8.67 kW<br>ESS 7 kWh | Evaluates the technical feasibility and economic viability of a standalone hybrid renewable energy system in Bangladesh, focusing on specific factors relevant to developing countries. | The paper proposes a promising method for providing clean, reliable energy to rural communities in developing countries through hybrid renewable energy systems, emphasizing the need for collaboration. |

Table 1 Recent literature study of wind farms associated with BESS. (Cont.)

| Technical | | | | | |
|---|---|---|---|---|---|
| **No.** | **Author** | **Location** | **RE & ESS capacity** | **Study platform** | **Findings** |
| 17 | Fambri et. al [51] | Italy | PV 40 kW<br>ESS 145 kWh | Explores the use of heat pumps as building-based virtual energy storage (VES) in renewable energy communities (RECs), aiming to enhance grid flexibility and self-consumption. | The paper introduces a cost-effective, flexible "building-based VES" concept for optimizing renewable energy self-consumption in high RES areas, requiring further research for wider applicability. |
| 18 | Medghalchi et. al [52] | Cyprus | PV 2.89 MW,<br>Wind 1.15 MW<br>ESS 2.31 MWh | The innovative approach combines renewable energy sources like solar and wind with energy storage systems like batteries and hydrogen fuel cells in a hybrid system, aiming to reduce energy costs. | This paper presents a novel approach to renewable energy optimization, demonstrating its effectiveness in achieving cost-efficient and sustainable energy systems. |
| 19 | Jamroen et. al [53] | Thailand | PV 3.9 kW<br>ESS 32 kWh | Novel BES power control strategy and state of charge management to enhance the reliability of off-grid residential PV systems, thereby reducing power outages. | The study proposes a novel BES power control strategy and effective SoC management for improved reliability, reduced outage risk, optimized BES sizing, and enhanced system performance. |
| 20 | Nirbheram et. al [30] | - | PV 1.52 MW,<br>Wind 1.78 MW<br>ESS 360.2 kWh | Optimizing a standalone hybrid renewable energy system (HRES) by considering the degradation of components and the potential use of additional batteries. | The paper emphasizes the significance of considering component degradation in sizing, the potential benefits of additional batteries, and the trade-offs between different configurations and COE impact. |

Table 1 Recent literature study of wind farms associated with BESS. (Cont.)

| Technical | | | | | |
|---|---|---|---|---|---|
| **No.** | **Author** | **Location** | **RE & ESS capacity** | **Study platform** | **Findings** |
| 21 | Emad et. al [54] | Egypt | PV 126 kW, Wind 100 kW ESS - | Develop a mathematical model to optimize hybrid PV/wind/battery systems for remote areas, minimizing COE and considering power outage risk. | This paper presents a cost-effective and reliable hybrid renewable energy system design approach for remote areas, demonstrating its potential for wider application in diverse contexts. |

### 2.8.2 Conclusion of Literature Review

According to the literature review, wind speed and availability have an impact on wind farms' overall energy output. Energy yield varies with wind speed and can be determined from wind farm logbooks. Performance analyses evaluate energy yield, turbine availability, grid availability, capacity factor, and system availability. BESS is often used in conjunction with wind turbines to control grid frequency and prevent power curtailment. As was previously indicated, wind power production is erratic and often falls short of the anticipated power output, which causes voltage fluctuations and mismatches in the grid load [55]. Depending on the availability of the BESS capacity, the wind farm mostly maintained its power factor at unity. Compared to direct electricity feeding from a wind farm without a BESS, the wind farm's overall performance increased by 3.97%. [56]. According to the research mentioned above, incorporating BESS promotes lowering power curtailment, increasing grid stability, and smoothing out power delivery. Because the local grid load profile and energy output affect the BESS's performance with wind farms, maximizing the system's capacity is essential to achieving improved system efficiency. Second, each location's economic feasibility for BESS integrations varies, and they really rely on the local grid power purchase arrangement. To the best of the author's knowledge, no research has been done on the economic implications of BESS optimization for Thailand's wind farm. In light of this research gap, we adjusted the BESS in this study based on our earlier research, and we statistically examined the power production to determine the system's dependability. Moreover, economic viability is assessed in the context of actual operational circumstances.

# CHAPTER III
# RESEARCH METHODOLOGY

This study aims, using real wind power plant data, to maintain the power quality of wind power plants by using energy storage systems for management. Real wind farm data was obtained from commercial-scale grids connected to a wind farm located in Thailand. Based upon the available data, the wind power plant's technical and economic performance was evaluated to increase reliability, reduce fluctuation, and reduce uncertainty, which almost impacts the distribution system of an electricity utility. There are five main steps in the thesis methodology, which are given below:

**1. Literature review:** Study research related to improving the quality and stability of electricity distribution systems for wind power plants connected to the grid and analyze the technical impact of wind fluctuations on the electricity production system's structure of wind turbines and electrical systems. This research encompasses installation and operation experience from actual energy storage systems in various countries.

**2. Data collection:** Collected the data from the wind farm, which encompassed wind speed measurements, energy output, periods of inactivity, fault details and duration, projected energy production, grid outage durations, customer interruption durations, grid regulator information, etc.

**3. Design and develop functional:** Design and develop functional prototypes for hybrid electricity generation from wind power plant and energy storage. To solve the problem of electricity fluctuations caused by wind power plants, it is possible to control the quality of electricity to comply with the grid connection code for electricity, including the appropriate system that can work efficiently with wind power plants. This can be installed together with existing wind power plants to prevent plant trips or plant shutdowns.

**4. Evaluate the structure of wind turbines:** Analysing the impact on the root base of wind turbines generating electricity from feeder trip and plant shutdown incidents of wind energy power plants, which caused the wind turbines to stop abruptly, for examining the impact on the root base of the wind turbines and solutions to prevent future damages and hazards.

**5. Performance evaluation of wind power plant:** Simulation of the operation of a wind power plant system designed to examine the operation and quality of electricity connected to the medium-voltage distribution network.

**6. Economic evaluation of wind power plant:** Financial analysis of investing in a wind power generation system, including cost analysis of system installation and maintenance, as well as financial returns and investment return rates.

**7. Conclusion:** Summarizing the technical and economic issues of the prototype system: major factors affecting the performance and structure of wind power plants connected to the medium-voltage distribution network.

### 3.1 Wind Farm Description

For the present study, an 8 MW commercial-scale onshore wind farm, Wind Farm SubPlu 1, is located in Nakhon Ratchasima province, Thailand. There are 4 sets of G114-2.0 MW of Gamesa wind turbines (Double-Fed Induction Generation (DFIG)). The main specifications of the turbines are given in Table 2.

Table 2 Main Specification of Wind Turbine Generator

| Parameter | Notes |
| --- | --- |
| Rated power | 2.0 MW |
| Rotor diameter | 114 m |
| Tower Design | Steel Tube/ Concrete |
| Rated wind speed | 10 m/s |
| WEC type | Horizontal Axis |
| Rotor Speed range | 7.8 rpm to 14.8 rpm |
| Hub height (above ground) | 125 m |

Figure 30 Commercial scale 8 MW wind farm Thailand.

### 3.2 Research Plan

For the research to be carried out smoothly and completed in accordance with the objectives, the researcher has planned the implementation of the work in a step-by-step manner. The details of the research implementation process are shown in Figure

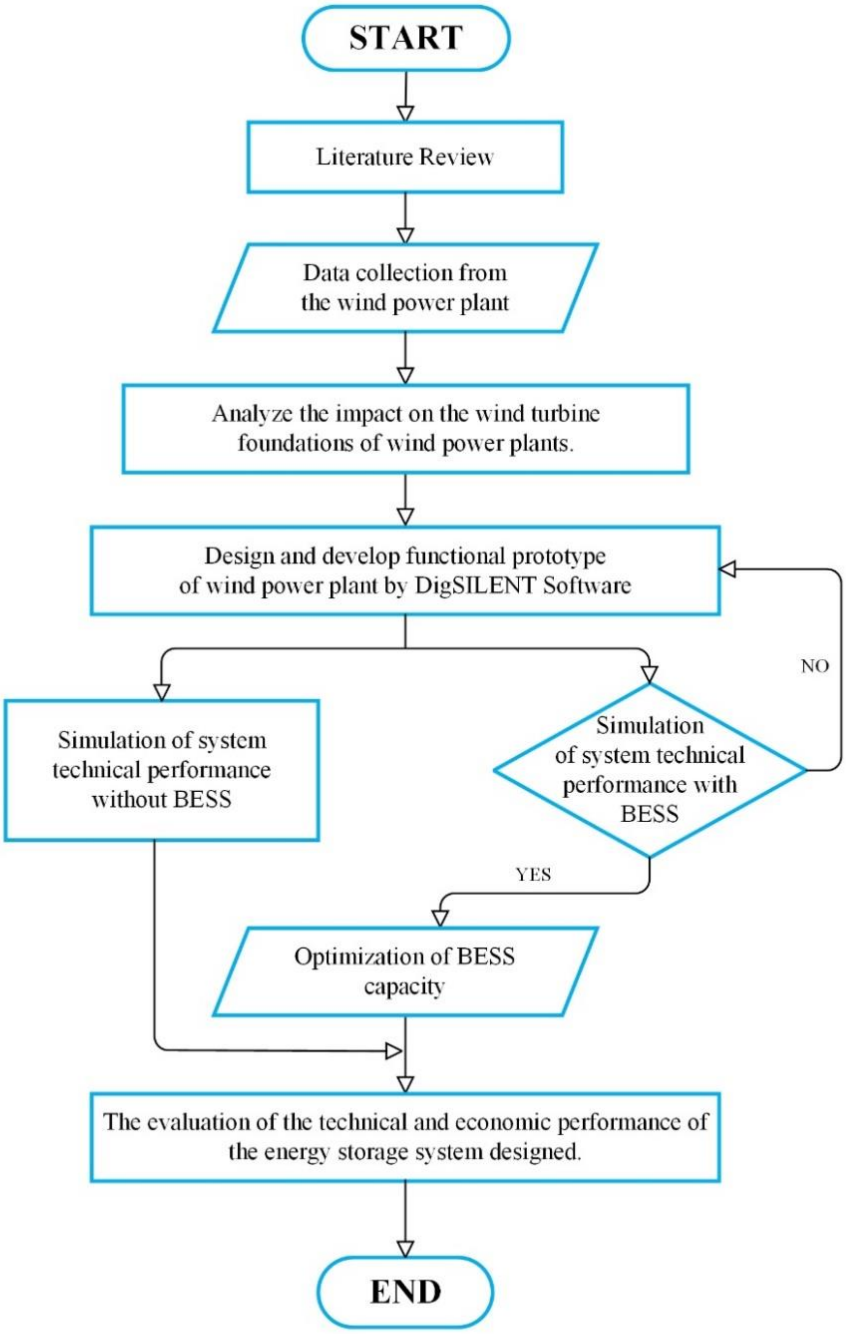



Figure 31 Research Methodology

The wind farm's energy management system meticulously monitors both power generation and grid voltage to ensure smooth operation. Overvoltage, a potential issue stemming from excess wind energy or reduced demand, is effectively countered by the Battery Energy Storage System (BESS). By absorbing or releasing stored energy as needed, the BESS keeps the grid voltage within the strict limits set by the Provincial Electricity Authority (PEA). This not only maintains the system's general stability but also reduces the occurrence of feeder trips, in accordance with the criteria provided by the wind turbine manufacturer. In conclusion, the incorporation of battery energy storage systems (BESS) into wind power plants greatly improves the stability of the electrical grid and the quality of electricity in the distribution network. To visualize this process, please refer to Figure 32 for Analysis of Energy Storage System Design for an 8 MW Wind Farm to Improve Stability and Power Quality of a Medium Voltage Distribution Network.

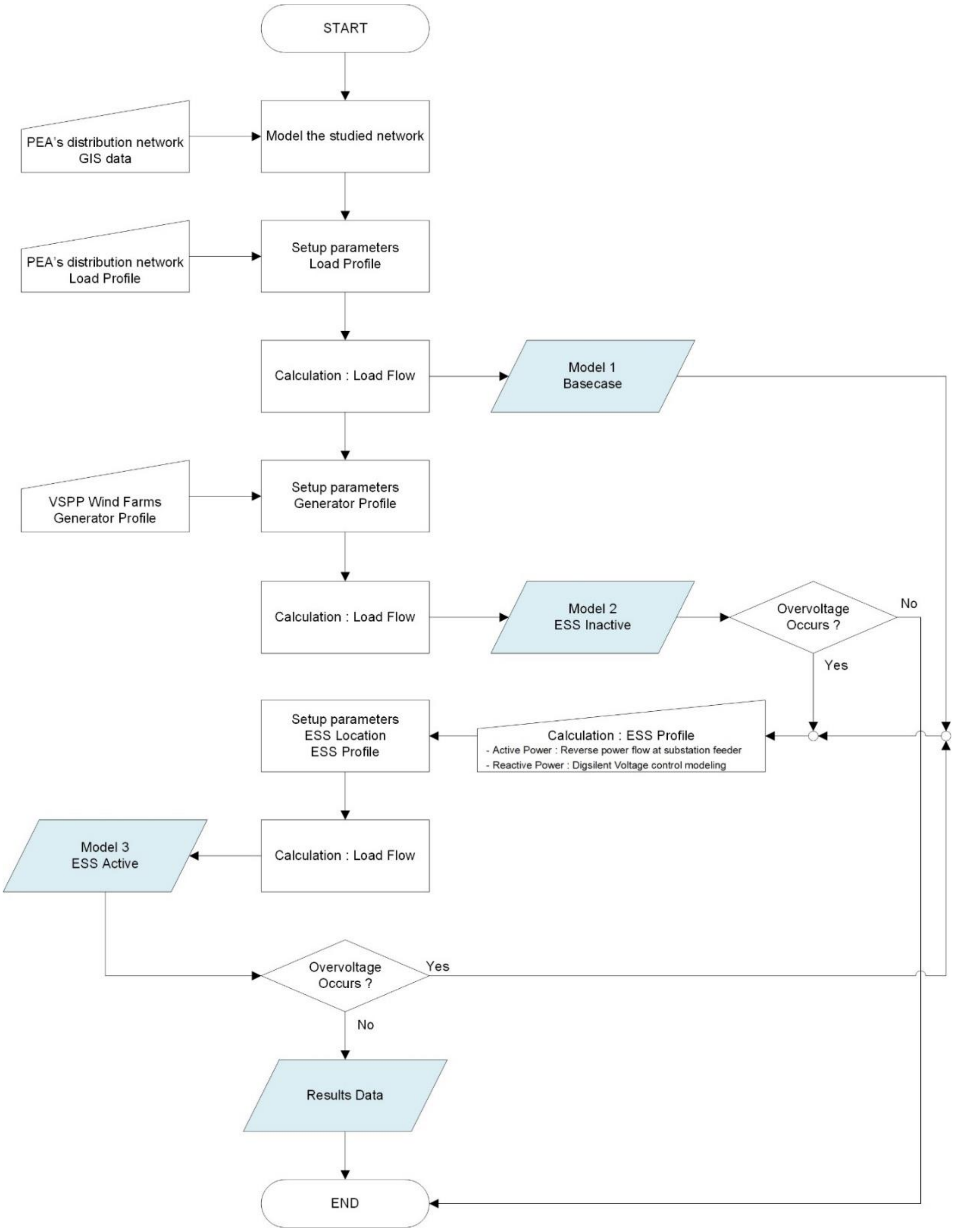



Figure 32 Research Methodology of BESS optimization for 8 MW wind farm.

## 3.3 Data Collection

Collected the real data from the 8 MW wind power plant, which contains wind speed, energy yield, down time, fault descriptions and duration, forecasted energy production, grid outage time, customer stop time, grid regulator, and other data. This data is collected from the wind power plant, wind turbine manufacturer, and Provincial Electricity Authority (PEA).

### 3.3.1 Technical Data

Data collection at a wind power plant connected to the distribution system of PEA revealed system fluctuations. Supervisory control and data acquisition (SCADA) systems data is essential for the technical assessment of the wind power plant and was obtained from the wind power plant site office in order to evaluate various performance parameters. The necessary data for analysis, including general information on wind power plants, electrical data of the wind power plant, regulatory information related to the grid regulator, and installation costs The details of the data and variables used for analysis are shown in Table 3.

Table 3 The parameters, details, and sources of information

| Data | Sources |
|---|---|
| **1. Wind Power Plant** | |
| 1.1 Data information of wind power plant | Wind power plant |
| 1.2 Detail of wind turbine | Wind power plant |
| 1.3 Electrical diagram of wind power plant | Wind power plant |
| 1.4 Capital cost structure of wind power plant | Grid regulator |
| **2. Electrical Information of Wind Power Plant** | |
| 2.1 Power generation of wind power plant | Monitoring system of wind power plant |
| 2.2 Wind power potential | Monitoring system of wind power plant |
| 2.3 Effect of wind turbine | Monitoring system of wind power plant |
| 2.4 Other electrical data (V, I, PF, VAR etc.) | Monitoring system of wind power plant |
| **3. information related to Grid Regulator** | |
| 3.1 Detail grid connection code | PEA regulation |
| 3.2 Detail Regulation | PEA regulation |
| **4. Other data** | |
| 4.1 Energy storage technology information | Energy storage manufacturer |

### 3.3.2 Economic Data

In order to evaluate the economic performance of the wind farm, essential data was collected from the wind farm e.g. total initial cost, O&M cost, tariff etc. The description of the required economic data e.g. total initial cost, interest rate, tariff rate, O&M cost etc. is given in Table 4

Table 4 Economic data of the wind farm

| Parameter | Unit |
|---|---|
| 1. Total Initial Cost | US $ |
| 2. O&M Cost | US $ |
| 3. Miscellaneous Cost | US $ |
| 4. Tariff | US cents/ kWh |
| 5. Interest Rate | % |
| 6. Cost of energy storage | US $ |

### 3.3.3 Design and develop functional

Design and develop functional prototypes for hybrid electricity generation from wind power plant with energy storage. The DigSILENT Power Factory Software is used and the technical performance of the system. To solve the problem of electricity fluctuations caused by wind power plants, it is possible to control the quality of electricity to comply with the grid connection code for electricity, including the appropriate system that can work efficiently with wind power plants. The functions of the BESS are given in Table 5.

Table 5 The functions and details of BESS for wind power plant

| Function | Details |
|---|---|
| Installed in conjunction with existing wind power plant. | Can be connected to the electrical circuit of the existing wind power plant to stabilize the grid. |
| Complies with the Regulation for Very Small Power Producers (VSPP). | Managed under the Regulation for VSPP.<br>If there is any non-compliance, it favours designing a plan with the least possible impact to propose an exemption from the Regulation for VSPP. |
| Complies with the grid connection code. | Overall control complies with the grid connection code. |
| Prevents tripping. | The use of BESS prevents tripping the wind power plant under various conditions, within an acceptable range. |

### 3.4 The wind power plant is connected to a distribution network.

In this study, over-voltage faults are widely discussed compared to low and residual voltage faults because the 8 MW wind farm faces over-voltage protection faults for most of the operational period. Further, to understand the nature of the wind farm, a particular day three-phase voltage profile is shown in Figure 33. Slight oscillations are noted for all three phases throughout the working day. Secondly, A-B Vrms and B-C Vrms faced overvoltage production with a peak of 24088 V and 23978 V, respectively. Comparatively, C-A Vrms maintained the voltage profile under the overvoltage mode throughout the day; however, when the other phases reached over-voltage, the feeder trips automatically. To control the overvoltage faults, a different BESS capacity is performed with the real-time wind power plant for three cases of higher feeder trip, low wind speed, and high wind speed months.

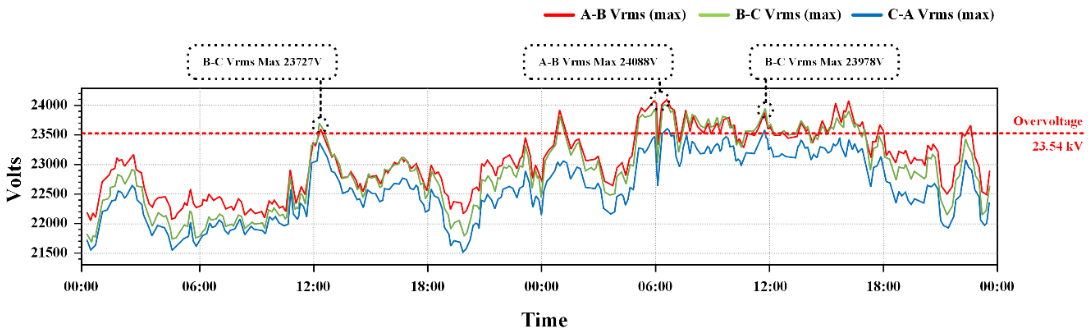



Figure 33 Voltage profile of 8 MW wind farm on 22 kV distribution line.

The Provincial Electricity Authority (PEA) of Thailand has a grid connection code and regulations for controlling the power quality of distribution lines to meet the requirements. The acceptable range of voltage in the Thailand grid code is required to maintain a stable frequency in the transmission and distribution systems, and the voltage feed of the wind turbine is strictly monitored. When the voltage production of the wind turbine falls below 0.95 PU or exceeds 1.05 PU, as shown in Figure 34, it is considered a detrimental risk to the load. In response, the protection control system automatically trips the feeder, causing the wind farm to shut down until the voltage production returns to an acceptable range. In terms of economics, wind farms faced significant challenges from the grid authority and PEA, primarily because of the extensive disruption in feeder trips.

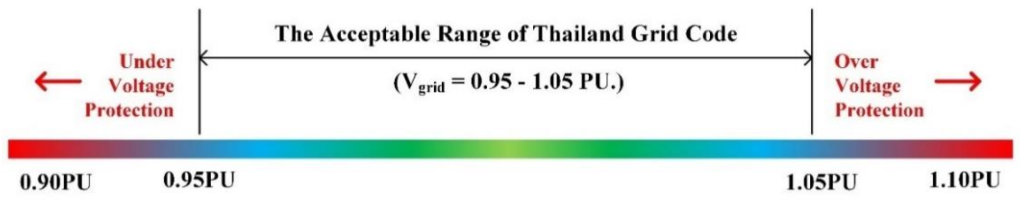



Figure 34 Thailand’s grid code for under, over, and acceptable voltage range.

A protective system equips the wind power plant, regulating the electricity quality in accordance with the grid connection code. Table 6 categorizes the system into three primary components: under-voltage protection, over-voltage protection, and residual over-voltage protection. The protection control system oversees the line voltage in wind farms that do not include battery energy storage systems (BESS). When the voltage exceeds the allowable range, the grid removes the wind turbines. Using BESS, excess energy from the wind turbines is stored in the battery resulting in feeder trips being controlled and wind power curtailments being minimized.

Table 6 The desired range of voltage for wind power plant.

| Protection Relay | Parameter | Time |
|---|---|---|
| Under Voltage Protection (27) | Line Voltage < 0.95 PU | 1 Sec |
| Over Voltage Protection (59) | Line Voltage > 1.05 PU | 0.25 Sec |
| Residual Over Voltage Protection (59N) | Residual Voltage > 0.2 PU | 0.25 Sec |

When a plant shutdown occurs at a wind power plant, the emergency brake of the wind turbine will activate. The plant will stop operating and stop generating electricity until the status at the grid connection point is ready for the wind power plant to connect to the grid (wait to sync). Only then will the wind turbine be restarted and begin generating and selling electricity as normal (normal operation) again. The details are shown in Figure 35. Frequent Plant Shutdowns at wind power plants can cause significant damage to the plant, especially the wind turbine equipment, which can deteriorate faster due to transient loads when the emergency brake activates. It is also a waste of opportunity to generate and sell electricity while the wind power plant is not connected to the distribution system.

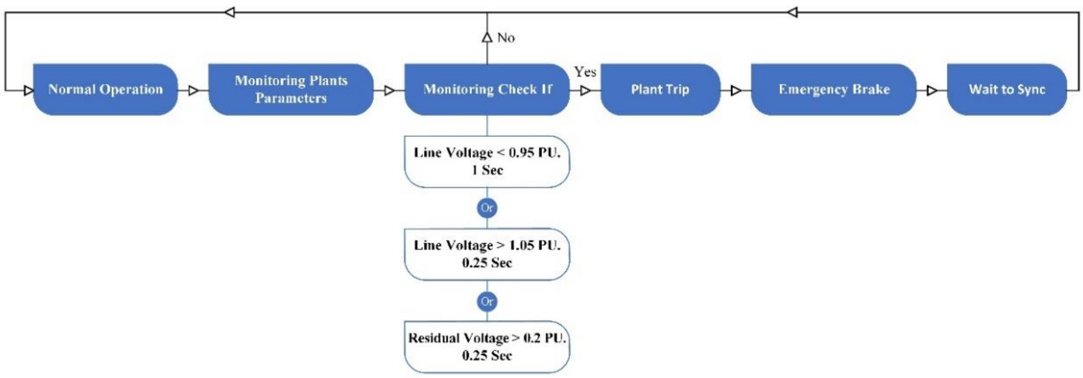



Figure 35 Plant shutdown of wind power plant.

The Subplu project was completed and began selling electricity to the Provincial Electricity Authority (PEA) on March 17, 2016. The electricity is transmitted through a 22 kV transmission line. The project has been selling electricity for over 8 years. Wind Energy Development Co., Ltd. (WED) has entered into a 10-year maintenance and management contract with the wind turbine manufacturer ("Siemens Gamesa Thailand Co., Ltd.") as a condition of the loan agreement that WED has with a commercial bank in Thailand. Under the maintenance and management contract, the turbine manufacturer is responsible for maintaining and managing the wind farm to ensure that it can generate electricity at a minimum of 97.5% availability. The availability guarantee will expire if the number of trips exceeds the manufacturer's specified limit. The actual number of trips that the project's monitoring system has recorded is 146, according to the data gathered. Those affected can be divided into three main groups.

- **The Provincial Electricity Authority (PEA)**

Volatility in electricity generation from wind power plants This directly affects power quality at the grid connection point on the 22 kV distribution line, which directly affects the Provincial Electricity Authority. After a feeder trip or voltage fluctuation, causing damage to the protection systems of the system operator In the case of a feeder trip, the data collection takes one hour. Besides, it affected the credibility of users in the feeder.

- **Wind Power Plant Company**

The impact of the wind power plant shutdown resulted in up to 10% of business losses. from a reduced power factor (PF) of 0.90-0.95 to maintain power quality. Power production must sometimes be reduced in order to reduce the impact of the distribution system.

- **User in Feeder**

Currently, users in the feeder of an 8 MW wind power plant are connected. System fault conditions from the tripping of wind power plants can be a major concern to the user, such as overvoltage, voltage dips, and voltage fluctuation. which have a direct impact on factories, shops, and households, especially the business lost by the factory in feeder.

Applying analytical and optimization techniques to optimize the size and placement of energy storage systems can lead to benefits such as energy loss reduction, congestion and voltage deviation management, and improved wind power system stability and controllability. It is found that a hybrid electricity generation system of wind energy and energy storage benefits both the wind farm and distribution system (end-user). Further, this research focuses on the development of the Battery Energy Storage System (BESS) to minimize the variability in power production from an operating 8 MW onshore wind farm located in Nakhon Ratchasima province, Thailand. This information is shown in Figure 36. The main goal of designing the Battery Energy Storage System (BESS) is to reduce the number of feeder trips by effectively managing overvoltage and enhancing power quality through ramp control. The main objective of this study is given below:

- An operating 8 MW commercial-scale onshore wind farm in the Nakhon Ratchasima region of Thailand provides data in real-time. The purpose of this data collection is to analyze the characteristics of wind speed, wind directions, frequencies, and the yearly feeder trip.
- To optimise the capacity of BESS, a high feeder trip period (September) is chosen to reduce the complexity in operations, and the least grid load of 10% is used to perform the DigSILENT simulation with a varying BESS capacity.
- A comparison analysis is conducted to evaluate the voltage and power generation of wind turbines utilizing various battery energy storage systems (BESS) in order to determine the most suitable BESS for the wind farm's operations.
- Additionally, the optimized Battery Energy Storage System (BESS) manages the feeder trip and power output reliably at both low and high wind speeds.

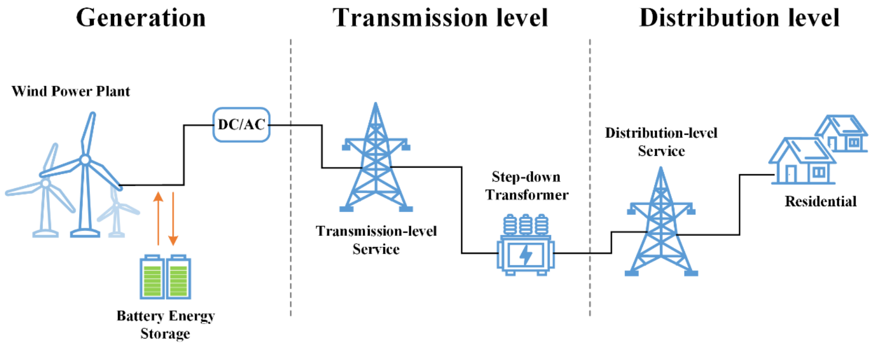



Figure 36 Conceptual diagram of BESS with wind power plant

Currently, there are several solutions to the problems that occur at wind power plants. One solution is to reduce the power factor to maintain the quality of electricity in the distribution system. However, this solution is not always effective. According to research conducted in foreign countries and by the research team, the problems at wind power plants can be solved by using energy storage systems. Energy storage systems (ESS) can perform a variety of functions, including power quality & UPS, bridging power, and energy management. This allows them to maintain the quality of electricity and manage the electricity produced by wind power plants. BESS can also help to reduce the volatility of electricity production, making it more stable and controllable. In addition, BESS can be used to schedule the delivery of electricity into the distribution system.

## 3.5 Data Analysis

Analysis and comparison of the system's technical performance to determine the technical performance of the BESS with a wind power plant The performance of wind turbines depends upon their technical availability, which can be analyzed by using the following factors to evaluate technical availability:

### 3.5.1 Technical Analysis

**Annual Usage Time:**

The ratio of the annual energy production (MWh) by the turbine to the turbine's rated power is called Annual Usage Time (AUT) which is calculated by;

$$AUT = \frac{Energy\ output\ (MWh) in\ a\ month\ or\ year}{Rated\ power\ (MWh) \times Total\ hours\ in\ month\ or\ year} \tag{4}$$

**Machine Availability (MA):**

The meaning of the machine availability (MA) is availability of the wind turbine. It is defined as the number of hours in which the turbine was available for power production to the total number of periods in a day or month or year. The MA daily, monthly or yearly can be calculated by;

$$MA = \frac{number\ of\ hours\ wind\ turbine\ in\ operation\ (h)}{total\ number\ of\ hours\ in\ time\ period\ \ h} \tag{5}$$

**Grid Availability:**

Grid availability (GA) means the readiness of grid to absorb the power from wind farm. It is the ratio of grid available in hours to absorb power from the wind park in (day, month and year) to the total hours (day, month and year). Grid availability is calculated by following equation 6;

$$GA = \frac{number\ of\ hours\ grid\ is\ capable\ \ to\ absorb\ \ the\ power}{total\ number\ of\ hours\ in\ time\ period\ \ h} \tag{6}$$

**Capacity Factor (CF):**

Capacity factor (CF) is the ratio of the average power generated to the rated peak power of the turbine. CF is given as;

$$CF = \frac{P_{avg}}{P_{rated}} \tag{7}$$

**System Availability:**

System Availability (SA) is the product of the turbine availability to the grid availability. System availability is given as;

$$SA = GA \times MA \tag{8}$$

**Wind Resource Availability (WRA):**

Machine technical availability does not consider the machine stoppage time due to calm winds. The real availability considers machine stoppage time along with machine technical availability [57]. The wind turbine cannot produce electricity during low wind time when wind speed is below the cut-in speed. WRA is calculated by using equation 9.

$$WRA = \frac{number\ of\ hours\ in\ timne\ period\ (h) - weathr\ ouitage\ hours(h)}{total\ number\ of\ hours\ in\ time\ period\ (h)} \tag{9}$$

**Forecast Error (%):**

It is the ratio of difference between actual energy produced and the expected energy for the period to the actual energy. The expected energy calculation based on the average annual reference power curve as configured in with SCADA for average wind speed for fault duration. Production efficiency ratio is determined by using equation 10.

$$Forecast\ error\ (\%) = \frac{actual\ energy\ produced\ (MWh)\text{-}expected\ energy\ (MWh)}{Expected\ Energy\ (MWh)} \tag{10}$$

**Production Efficiency Ratio:**

The production efficiency ratio (PER) is the ratio of actual energy produced to the expected energy for the period. Expected energy calculation is based on the average annual reference power curve which is configured in wind SCADA for the average wind speed during the fault period. Production efficiency ratio is determined by using equation 11.

$$PER = \frac{actual\ energy\ produced\ (MWh)}{expected\ energy\ (MWh)} \tag{11}$$

### 3.5.2 Economic Analysis

**Levelized Cost of Energy (LCOE):**

LCOE estimates the operation cost of wind turbine or represents the unit (kilo watt hour) cost of the electricity generation. If uniform amount of electricity production and uniform cash flows are assumed over life span of wind turbine generators, then LCOE may be calculated from the equation 12 [58].

$$LCOE = \frac{annual\ cost\ of\ operations\ brought\ to\ present\ value}{annual\ electricity\ generation} \tag{12}$$

**Clean Development Mechanism & Certified Emission Reduction (CER) Credits:**

The clean Development Mechanism (CDM) is one of the provisions of Kyoto Protocol which allows Annex-B countries to earn CER credits and sell it to Annex-A countries (host countries) to generate the additional revenues. One CER credit is equivalent to 1 ton of $CO_2$ [59]. Annual emission reduction (tons of carbon dioxide per year) $CO_2$/ year or certified emission reductions (CERs) earned per year is calculated by using equation 13 [60]. Revenue generated against emission reduction is calculated by using equation 14 [61].

$$CER_s\ Earned = E_{out} \times E_{fuel} \qquad (13)$$

Whereas, $E_{out}$ is annual energy produced by wind farm and $E_{fuel,}$ is the emission factor.

$$CRI_t = CER_{S_t} \times P_c \qquad (14)$$

Whereas, $CRI_t$ is income from emission reduction for year t, $CERs_t$ is CERs earned for year t and $P_c$ is carbon trading price.

**Payback Period (PBP):**

Payback period indicates the time span wherein, the investment would be earned back [62]. DPP can be determined by using equation 15.

$$PBP = \sum_{n=1}^{N} (B_n - C_n) = 0 \qquad (15)$$

Whereas;

$B_n$ = expected benefit at the end of year, n.

$C_n$ = expected cost at the end of year, n.

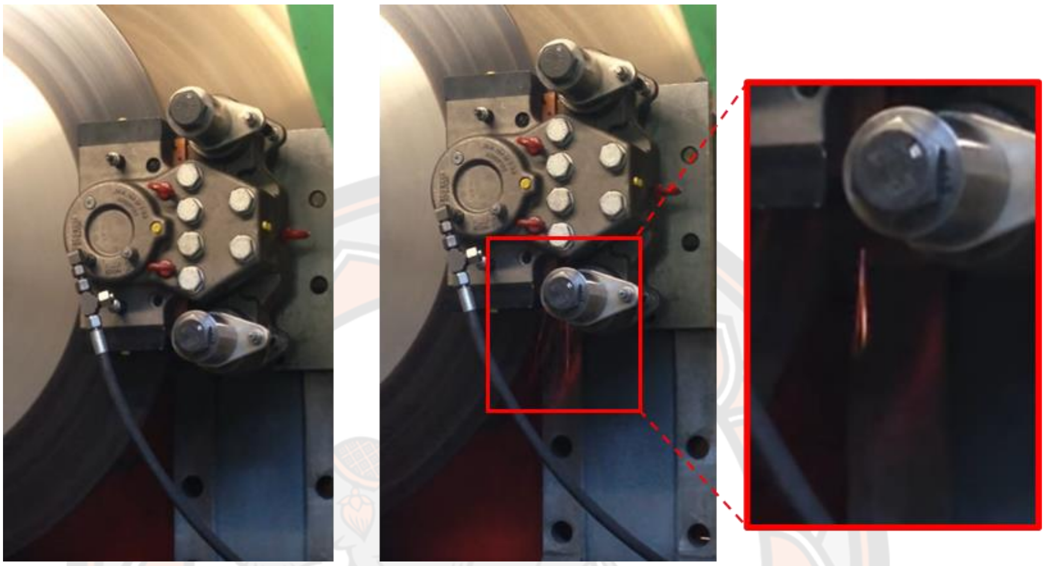
**Benefit to Cost Ratio (BCR):**

Benefit to cost ratio is defined as the ratio of present value benefit to present value cost. BCR value greater than one reflects higher benefits, while BCR below one intimates that project is in loss. BCR can be calculated by using equation 16 [63].

$$BCR = \frac{present\ value\ benefit}{present\ value\ cost} \qquad (16)$$

## 3.6 Evaluate the structure of wind turbines

Evaluate the structural strength of wind turbines by gathering data from structural examinations of wind turbine foundations. This is because a plant shutdown of the wind power plant can make wind turbines stop by emergency brakes, as shown in Figure 37.



Solf Break Emergency Break

Figure 37 Effect of emergency brake

Frequent activation of the emergency brake on wind turbines can cause direct damage to the brake system. Additionally, such activations can cause the turbine to vibrate, potentially leading to structural damage to the turbine and foundation. Therefore, ensuring the structural integrity of the turbine tower, electricity-generating components, and foundation is crucial for safety. The Wind Energy Development Company conducts annual structural inspections, with a particular emphasis on the reinforced concrete foundations of the turbines, which bear the weight of the turbines and transfer it to the ground. The details and topics used in testing the turbine's foundation structure are as follows:

### 3.6.1 Crack mapping testing of the foundation of a wind turbine.

Measuring the width of cracks using a crack width gauge to measure cracks that occur at the concrete foundation of wind turbines. This gauge, depicted in Figure 38 - 39, is a clear plastic tool with markings indicating widths. Place the gauge over the crack location and select the appropriate width marking to match the widest part of the crack for measurement. According to ACI 224R-90 standards (control of cracking in concrete structures), allowable crack widths in reinforced concrete structures are 0.30 mm.

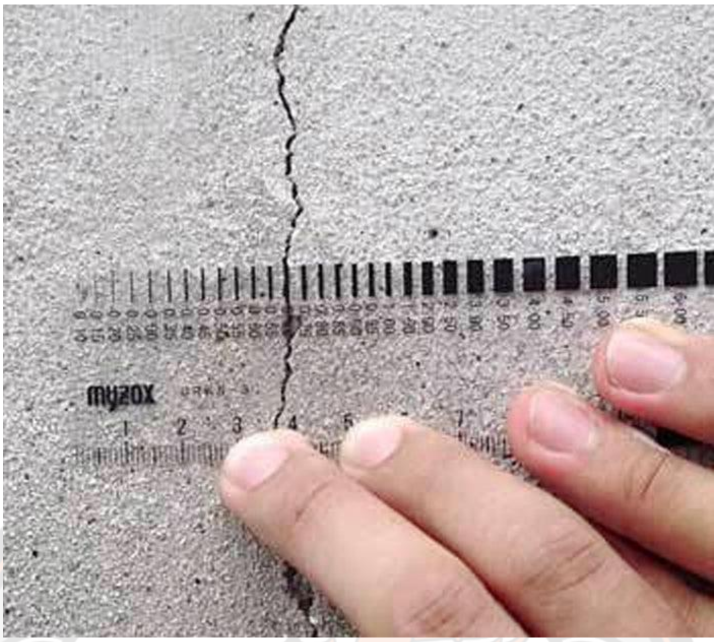



Figure 38 Crack mapping testing

(Source: https://lasersurveyingequipment.com.au/product/avongard-crack-width-gauge)


Figure 39 Crack Width Indicator.

(Source: https://www.globalgilson.com/crack-width-gauge)

### 3.6.2 Non-destructive testing of concrete's compressive strength was conducted by the Rebound Hammer-Schmidt method.

We conducted non-destructive testing of the concrete's compressive strength using the Rebound Hammer-Schmidt method to assess the maximum compressive strength, or fc', of the concrete. This method relies on measuring the rebound number index, generated by pressing the plunger and housing against the concrete surface with the Schmidt hammer held perpendicular. The rebound force from the internal spring causes the test rod to bounce, resulting in a rebound index ranging from 10 to 100, depending on the concrete surface's energy absorption capacity. Surfaces with greater compressive strength exhibit higher rebound indices. Figures 40–41 show the Hammer-Schmidt testing device.

Figure 40 Non-destructive testing by the Rebound Hammer-Schmidt method

(Source: https://www.screeningeagle.com/en/products/original-schmidt)


Figure 41 Schmidt Hammer

(Source: https://www.globalgilson.com/original-schmidt-type-l-concrete-test-hammer)

# CHAPTER IV
# RESULT AND DISCUSSION

## 4.1 Design and develop functional

This research study investigated a wind power plant with an installed capacity of 8 MW located in Dan Khun Thot District, Nakhon Ratchasima Province. The plant uses a GAMESA wind turbine (WT), model G114-2.0, with a tower height of 125 meters. The generator used is a doubly fed induction generator (DFIG). The plant began feeding electricity into the 22 kV distribution system of the Provincial Electricity Authority on March 17, 2016, as shown in Figure 42.

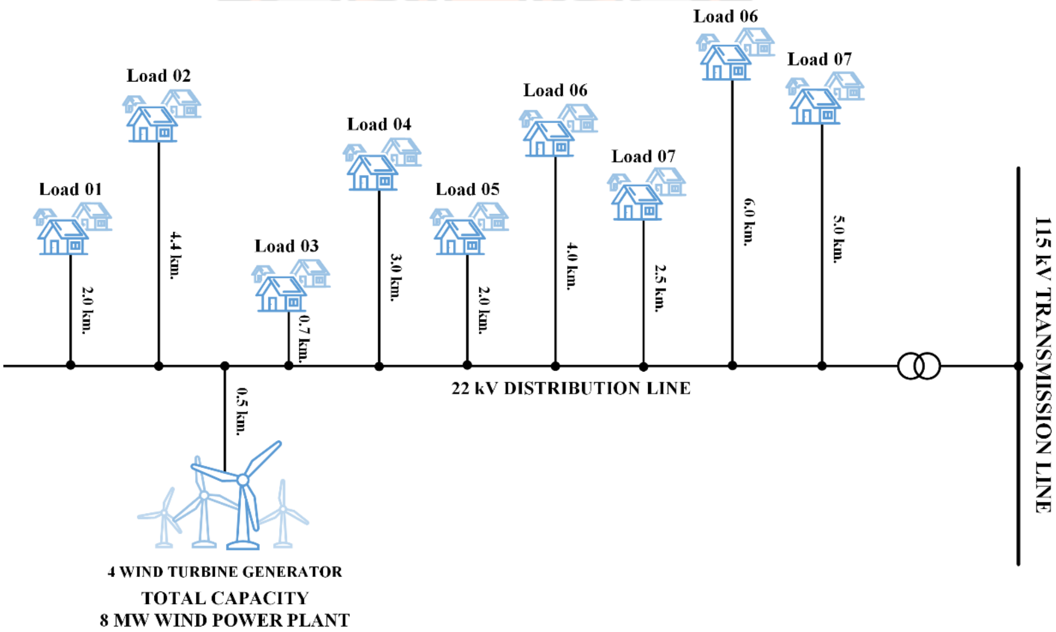



Figure 42 Schematic view of 8 MW Windfarm distribution and transmission line

### 4.1.1 Concept design

The working principle of a wind power plant consists of three main parts. It consists of a power system, a protection system, and a control and surveillance system. The concept design of the energy storage system with wind power plants will use energy storage systems connected to wind power plants, as shown in Figure 43.

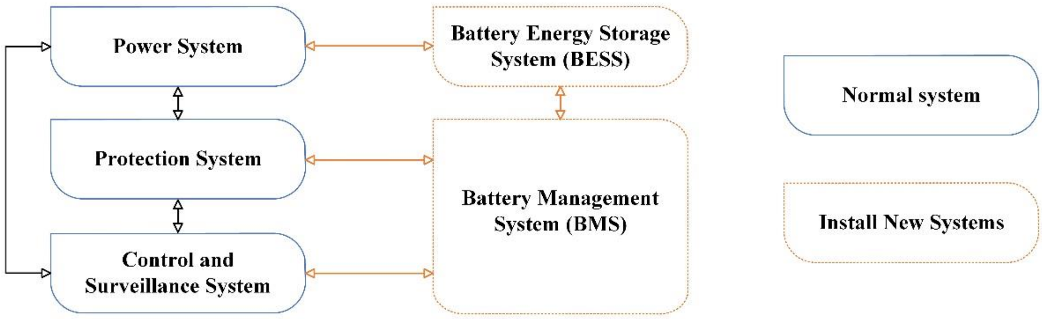



Figure 43 Concept design of the energy storage system with wind power plant

### 4.1.2 Energy Storage System

The development of a power flow algorithm aims to minimize the occurrence of feeder trips through the use of battery energy storage systems (BESS). We closely observe wind farm activities, including continuous monitoring of line voltage, during the normal functioning of the wind turbine. The monitoring system determines the state of the Battery Energy Storage System (BESS) and synchronizes it with a wind turbine if the line voltage is below 0.95 times the nominal voltage (Un) for a duration of 0.5 seconds, or above 1.05 times Un for 0.1 seconds, or above 0.2 times Un for 0.1 seconds. In this investigation, the line voltage remains above 0.95 Un and does not experience any decrease or residual voltage. Therefore, the Battery Energy Storage System (BESS) does not need to discharge power to the grid to boost the line voltage. We conduct the simulation to evaluate the likelihood of line overvoltage. We will use a gentle braking mechanism to align the wind turbine's operation with the Battery Energy Storage System (BESS) if its capacity remains available for charging. This power flow algorithm controls wind turbine operations and minimizes feeder trips. The BESS system regulates the power supply based on the plant's specified characteristics of the plant in order to comply with the grid connection code. While the wind farm is operating, if there are any abnormalities in the wind power plant's power quality, the Battery Management System (BMS) will coordinate the Battery Energy Storage System (BESS) with the wind turbines. This coordination aids in managing the power supply to the grid through the use of a soft brake or emergency brake mechanism. Following that, the wind turbine will remain idle until it can synchronize with the grid connection point again. Without the Battery Energy Storage System (BESS), the wind farm operation results in a feeder trip and the application of an emergency brake to safeguard the wind turbine, shown in Figure 44.

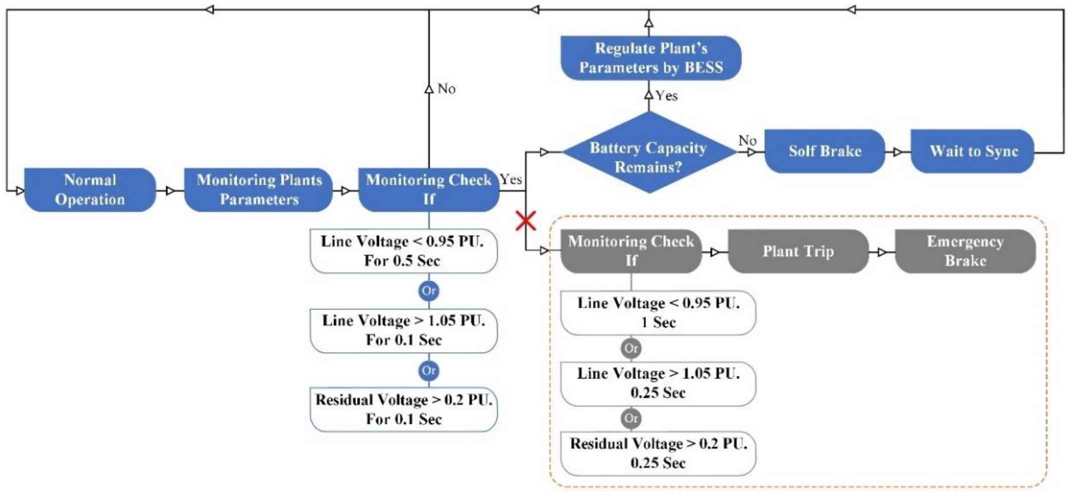



Figure 44 Power flow algorithm to protect the feeder trip.

### 4.1.3 Energy Management for Storage system

This research implemented the Battery Energy Storage System (BESS) for an operating 8 MW commercial-scale onshore wind farm called Wind Farm SubPlu 1 (as shown in Table 7), located in Nakhon Ratchasima province, Thailand. The wind farm's electricity generation is overseen by the energy management system, which also checks the electrical grid's voltage. Overvoltage mostly arises in two situations: when the wind turbine produces more power than expected and when the load demand lowers. The Provincial Electricity Authority (PEA) specifies that battery energy storage systems (BESS) keep the grid voltage within an acceptable range in both scenarios. Ensuring that the voltage input to the grid falls within an acceptable range helps to keep the power distribution system stable while also keeping the feeder trip within the limits specified by the wind turbine manufacturers. Hence, the integration of battery energy storage systems (BESS) with wind power plants enhances the stability and power quality of the distribution network. Figure 45 displays the schematic representation of the wind farm, together with the Battery Energy Storage System (BESS) and the study technique.

Table 7 Specification of wind turbine and BESS

| Description | Range |
|---|---|
| Wind turbine type | Doubly Fed Induction Generator |
| Rated power | 2 MW |
| Cut-in wind speed | 2.5 m/s |
| Rated wind speed | 10 m/s |
| Cut-out wind speed | 25 m/s |
| Survival wind speed | 60 m/s |
| Battery type | Lithium Ion |
| BESS capacity | 5 MWh / 2 MW |
| BESS depth of discharge | 90% |

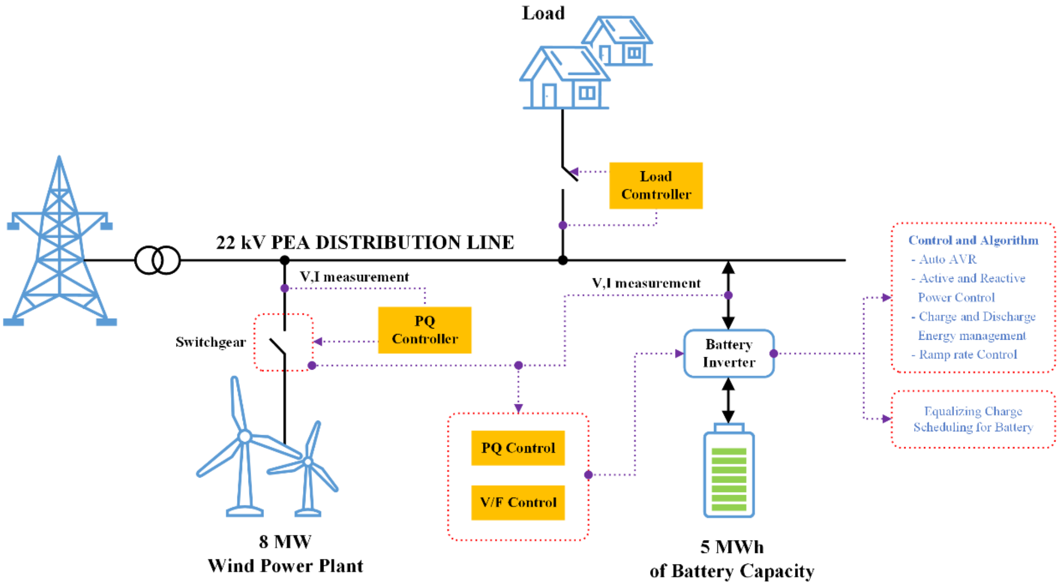



Figure 45 Conceptual diagram of BESS with wind power plant

The energy storage system must be performing the specified functions in grid support mode. by using wind forecasting data and load forecast data from wind power plants to determine the algorithm. The details of controlling the energy storage system are as follows.

1. **Automatic Voltage Regulation (AVR)** maintain the voltage level in the distribution system at the grid connection code, which can be active and reactive control or charge-discharge from the energy storage system.
2. **Ramp rate control** Ramp rate control is the process of maintaining power production from wind farms and energy storage systems to work

together when changing power production at distribution systems (22 kV) is too high. The energy storage system will keep making power so that the distribution system isn't affected as much.

When designing the control algorithm, it can control the energy storage system to maintain the quality of electricity in the distribution system, but it also involves designing procedures to maintain the energy storage system, such as performing an equalizing charge regularly to extend the service life of the energy storage system.

## 4.2 Technical Analysis

### 4.2.1 Wind speed and weather outage

The analysis of wind farm data in the design of an energy storage system together with a wind power generation system used the DigSILENT program to simulate in order to find the appropriate size of the energy storage system. The analysis used data from the target wind farm. The results of the analysis showed that the average wind energy value was highest in December with an average wind speed of 7.20 m/s, and the lowest average wind speed was 3.33 m/s in May. The average wind speed throughout the year was 4.89 m/s. The analysis of the amount of wind power that could be generated was in the months of July to August, with a maximum power generation of 7.50 MW. However, the analysis of the average annual power generation of the wind farm was 1.99 MW, which is low compared to the total installed capacity of 8.0 MW. One of the main problems is that the wind farm trips frequently due to the electrical quality impact of the wind farm connected to the Provincial Electricity Authority's medium-voltage distribution system. The details of the wind energy and power generation values are shown in Figure 46.

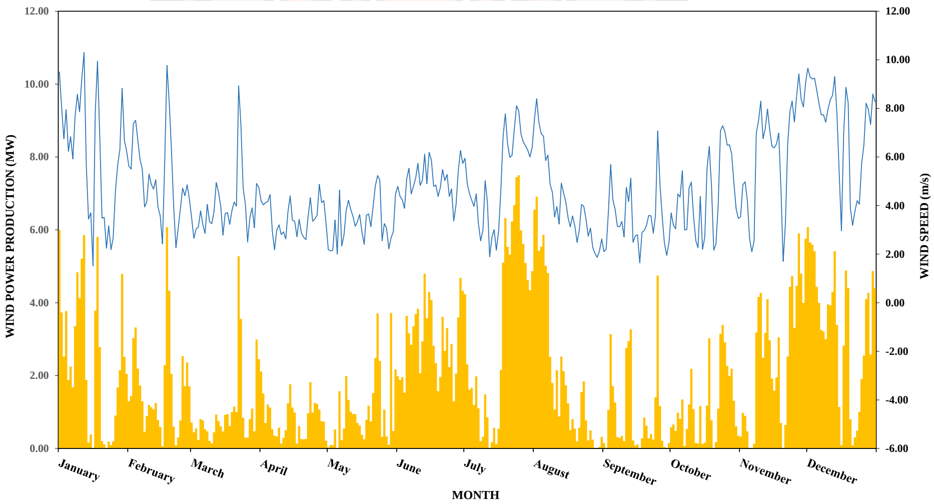



Figure 46 Data on wind speed and wind energy production.

Additionally, as shown in Figure 46, The wind energy and power generation values are evaluates the yearly wind speed to gain insight into the characteristics and patterns of wind movement. The wind rise graphic in Figure 47, on the left-hand side, illustrates the yearly wind speed direction. The wind in the southern direction towards the west has a longer duration and continues towards the north in the eastward direction. Generally, the majority of reported wind directions over this time indicate a southwestward trend in comparison to other directions. Figure 47, on the right-hand side, shows the distribution of wind speeds. The wind speed range of 3.60–5.70 m/s has the highest frequency of 30.5. Clams have the lowest frequency of 0.2, while wind speeds exceeding 11.10 m/s have a frequency of 0.8. Furthermore, we obtain frequencies of 9.6 and 6.5 for speeds ranging from 0.5 to 2.10 m/s and 8.80 to 11.10 m/s, respectively. Furthermore, we achieve frequencies of 26.8 and 25.6 for speeds ranging from 2.10 to 3.60 m/s and 5.70 to 8.80 m/s, respectively. Based on the data collected, it has been determined that the average yearly wind speed at the chosen site is 4.89 m/s. This indicates that the eastern part of Thailand has a higher capacity for harnessing wind energy.

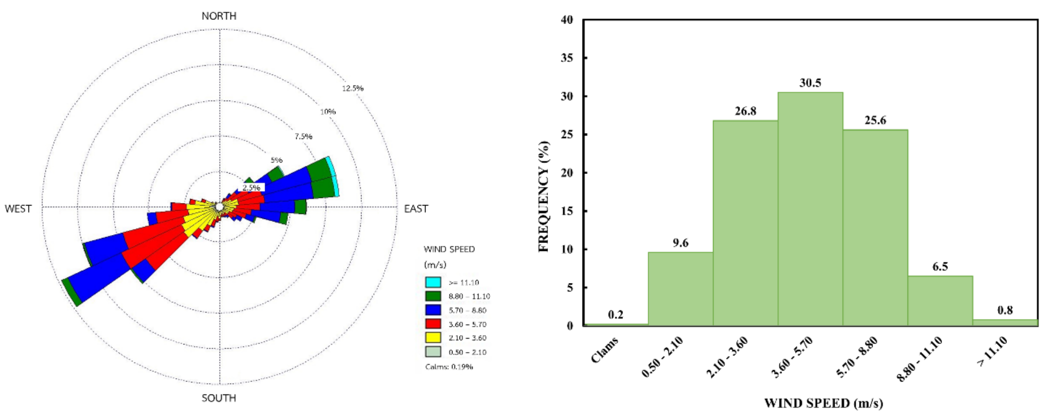



Figure 47 Wind rose diagram and frequency of wind speed.

### 4.2.2 Total trip time

The primary issue identified in this 8 MW wind farm is a feeder trip caused by unforeseen fluctuations in load demand and wind power generation. This causes a voltage increase and a subsequent voltage dip, resulting in the wind farm's shutdown. The system's inefficiency is exacerbated by unexpected and more frequent feeder trips. This is particularly problematic considering the manufacturer's assurance that the number of feeder trips should not exceed 52 per year for wind turbines. Based on the wind farm operation in 2021, the number of instances when the feeder trips exceeded the acceptable range increased. In order to have a thorough understanding of the feeder journey, precise data is gathered and graphed to depict monthly variations, as seen in Figure 48. The minimum number of trips made by the feeder is recorded in both January and February, while the maximum number is recorded in May and September, with a difference of 19 and 21 times, respectively. There are 146 recorded yearly feeder trips, surpassing the acceptable threshold by nearly twice. The resultant protective control system automatically initiated the feeder trip and shut down the wind power facility. In terms of economics, the wind farm faced several challenges from the grid authority and PEA, mainly due to significant disruptions in feeder trips.

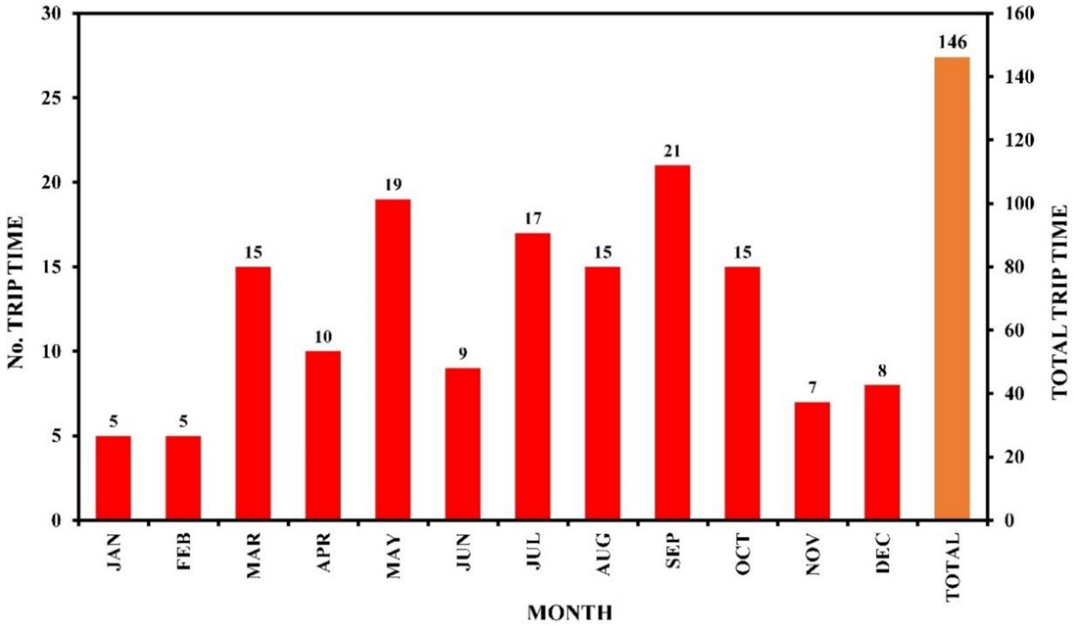



Figure 48 Monthly feeder trip of 8 MW wind farm in 2021

From the analysis of the occurrence of the trip of the wind farm throughout the year, it was found that the trip of the wind farm will occur in the range of wind speed at approximately 4.00–6.00 m/s, followed by the range of wind speed at approximately 6.00–8.00 m/s. This range of wind speed is the average wind speed that occurs in the area and is the wind speed at which the wind turbines operate. This causes significant damage to the power generation of the power plant. The details are shown in Figure 49.

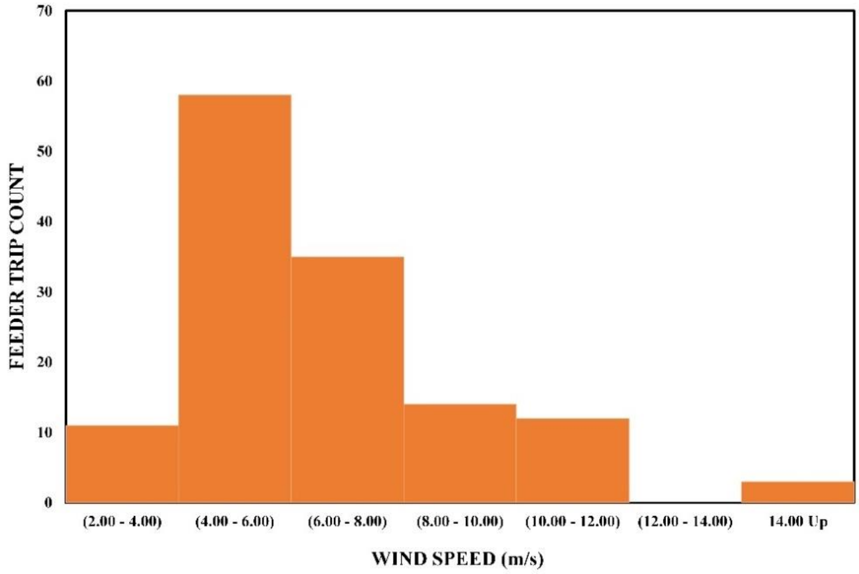



Figure 49 Feeder trip vs wind speed

When analyzing the time of trip occurrence, it was found that the time of trip occurrence most frequently occurred between 06:00 and 09:00 AM and between 15:00 and 18:00 PM. The details are shown in Figure 50.

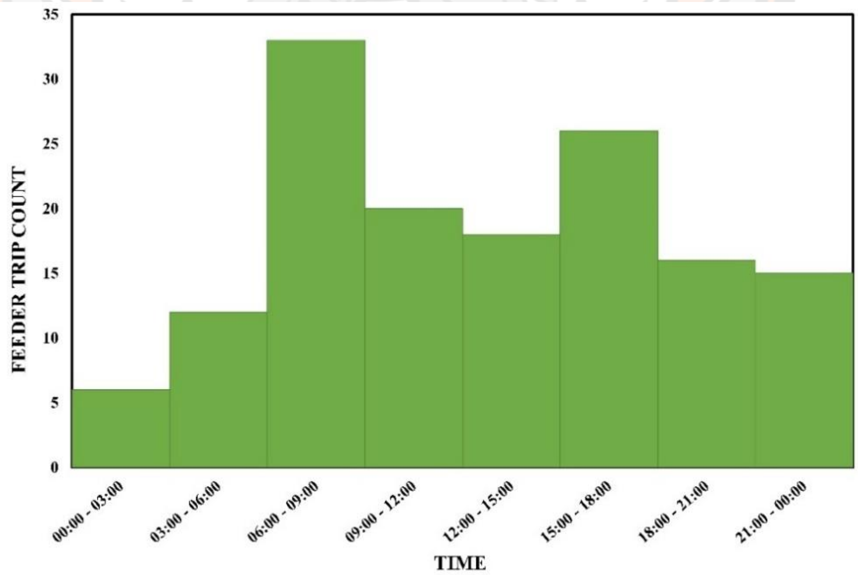



Figure 50 periods time vs feeder trip

Based on the data on the occurrence of trips at wind farms, it was found that in 2021, wind farms experienced trips that caused the farms to stop operating for more than 2,000 minutes. This had a significant negative impact on the production and sale of electricity from the wind farms, resulting in a loss of revenue from both the sale of electricity and increased maintenance costs. The most frequent duration of trips was

10 minutes, which occurred over 100 times. The second was 20 minutes, and trips that lasted longer than 100 minutes occurred in the smallest number. These trips were the most disruptive, as they resulted in the wind turbines being shut down for extended periods of time to inspect the systems. The details are shown in Figure 51.

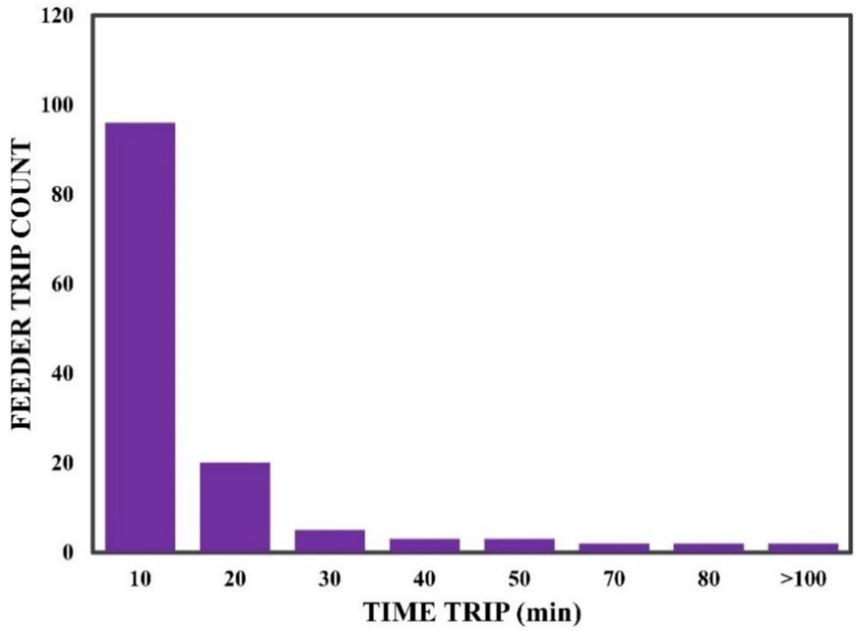



Figure 51 time trip vs feeder trip

When analyzing the loss of electricity production due to wind farm trips, it was found that the loss of electricity production value was approximately 146.44 MWh/year, which is a very high value and is the revenue that the wind farm loses each year. The details of the lost electricity value are shown in Figure 52.

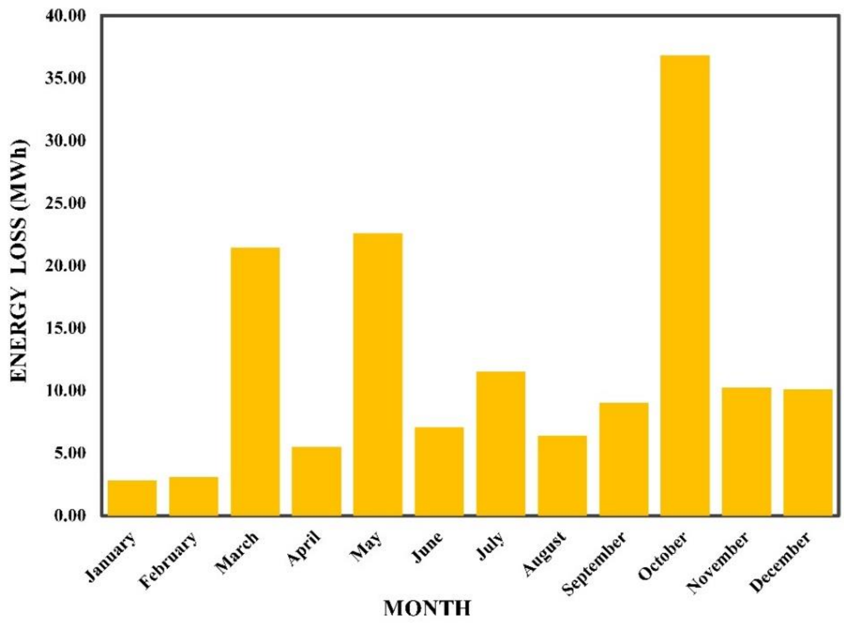



Figure 52 Energy loss during the feeder trip.

### 4.2.3 Wind power production

Based on data collection from an 8 MW wind farm installed in the area, it was found that the average wind speed in the wind farm area is about 4.89 m/s, with a maximum wind speed of about 15.68 m/s. This wind energy potential is sufficient for the installation of wind turbines in Thailand. The average wind power produced by the power plant was approximately 3.30 MW, with a minimum power output of 1.05 MW. The average power output was 2.00 MW/month. The details are shown in Figure 53.

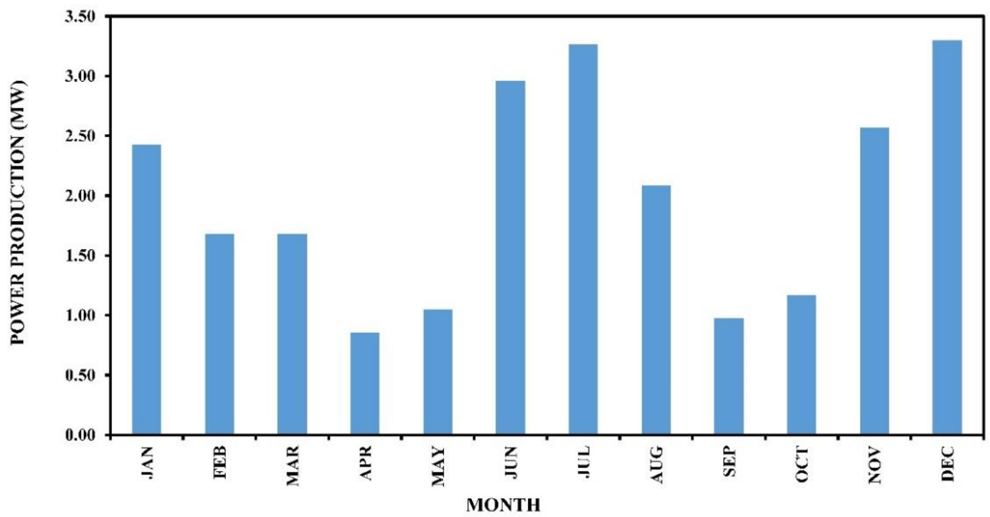



Figure 53 Wind power production.

Technical analysis of an 8 MW wind power plant to find the appropriate energy storage system. Load profile data is used to setup parameters in the DigSILENT program to simulate the system's operation, the impact on the electrical distribution system, and the analysis to find the appropriate size of the energy storage system. The details of the distribution network around the wind power plant are shown in Figure 54.

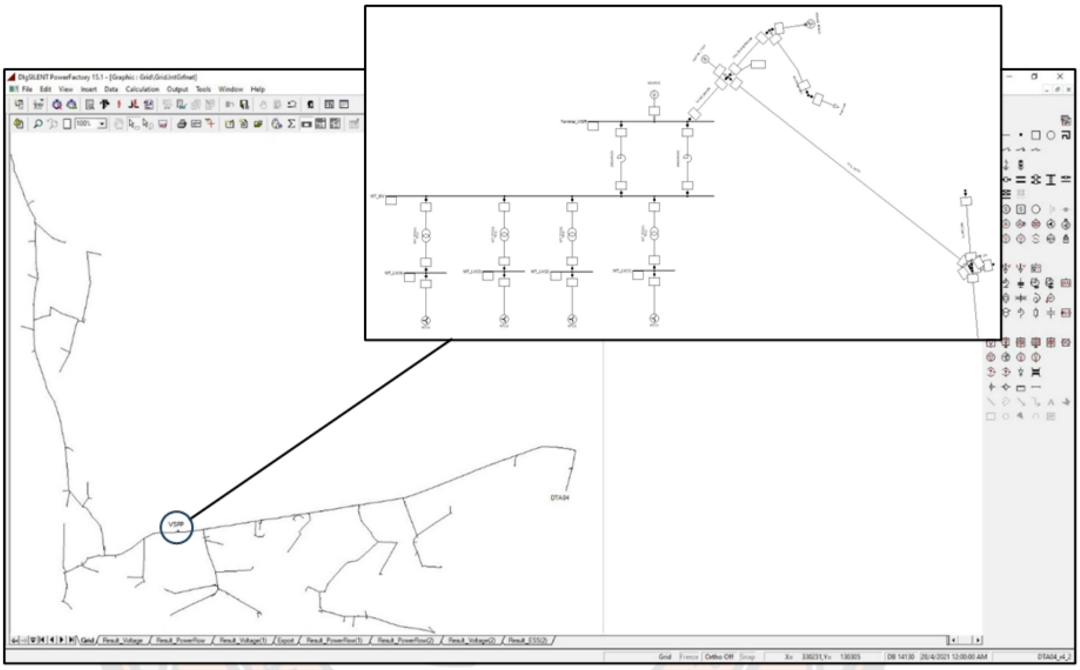


Figure 54 GIS PEA’s distribution network around wind power plant.

Analysis of wind power plants to find the appropriate size of the energy storage system to solve the problem of plant trips. The analysis will be divided into two cases: Case 1 is high power production, and Case 2 is low power production. This will ensure that the analysis covers the entire operating range of the plant throughout the year and covers any potential impacts. This will make the designed system the most suitable for the target wind power plant. The details of the analysis are as follows:

**Case 1: Hight Power Production**

The analysis will use the load profiles of the area around the wind power plant during the high power production period to simulate the operation of the system. This will ensure the accuracy of the analysis and system design. The load profile data was obtained from the Provincial Electricity Authority's (PEA's) distribution network and was used in the DigSILENT program to simulate the system before the installation of the wind power plant to check the electrical quality of the distribution system as a base. The details of the data are shown in Figure 55, which is the load profile data during the peak power production period that occurred in the area on July 25, 2021.

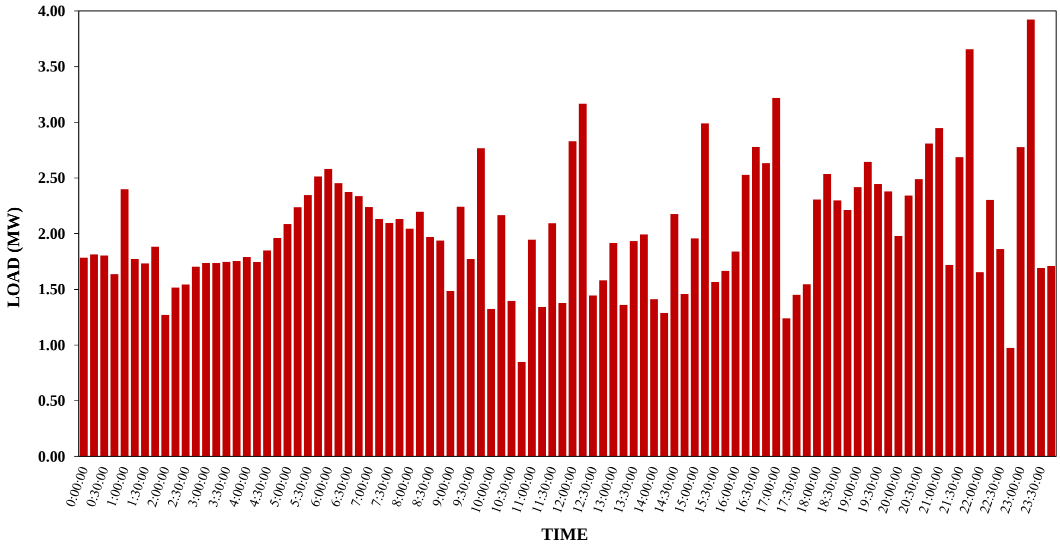



Figure 55 Load Profiles Wind Power Plant (July 25, 2021)

The analysis using the DigSilent program by running a load flow to see the conditions that occur in the distribution system before the production of electricity from the wind power plant. The details of the analysis are shown in Figure 56. The results of the analysis found that the electrical load that occurs in the area around the power plant is from a small village, and there are three cassava factories located in the area around the power plant, which are the main load in the area. The average load that occurs throughout the day is approximately 2.0 MW, and there will be a higher electrical load on a regular basis. The maximum electrical load is in the middle of the night, at approximately 21:00 PM–23:00 PM. The maximum electrical load value is equal to 3.92 MW at approximately 23:00 PM. When analyzing the voltage in the distribution system, it was found that the voltage in the distribution system of the electricity authority will change according to the use of the electrical load that occurs. The more load is used, the lower the voltage in the distribution system will be. The average voltage that occurs throughout the day is approximately 1.00 PU. The details are shown in Figure 57.

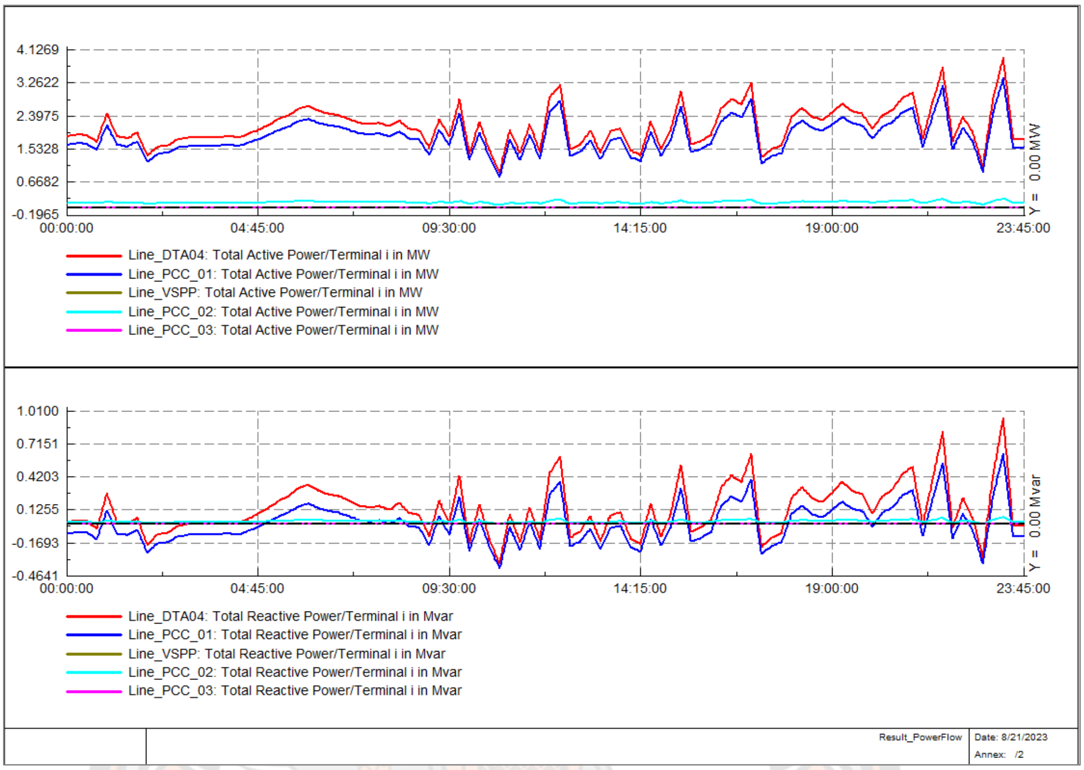



Figure 56 Output Base case Result Power Flow

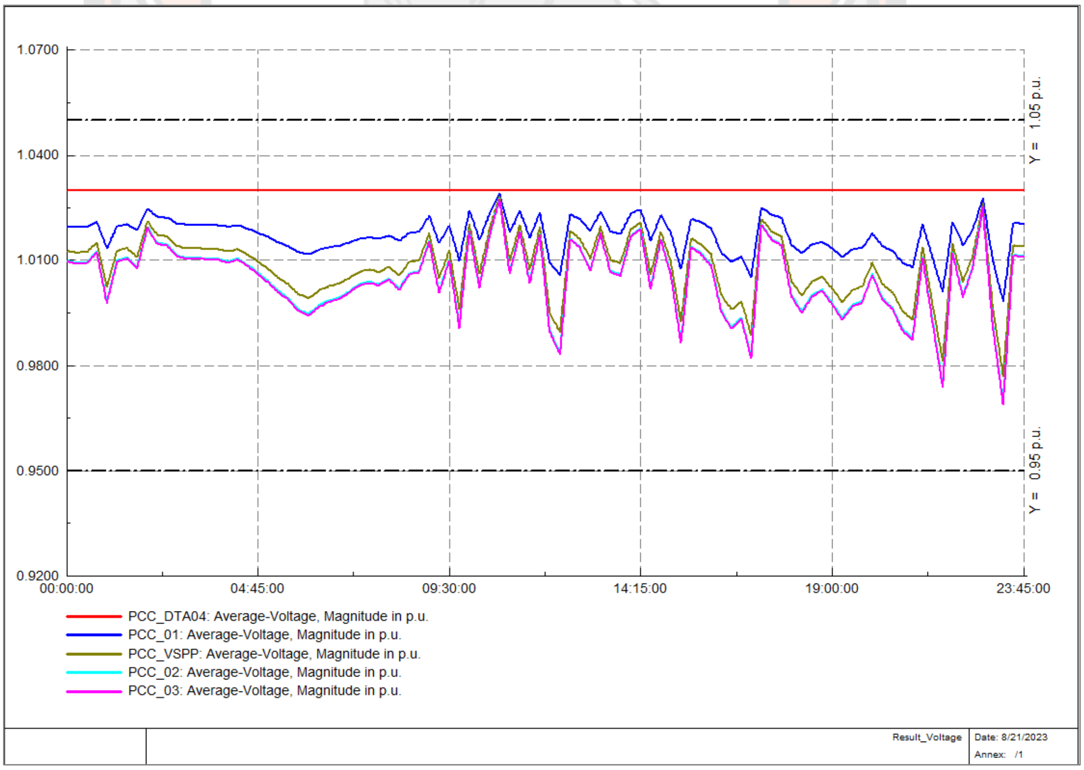



Figure 57 Output Base case Result Voltage

The data on the amount of electricity produced by the wind power plant during the peak production period (July 25, 2021) was used for analysis to design the system. The data was input into the DigSILENT program to simulate the operation of the system. The data on the maximum amount of electricity produced is shown in Figure 58.

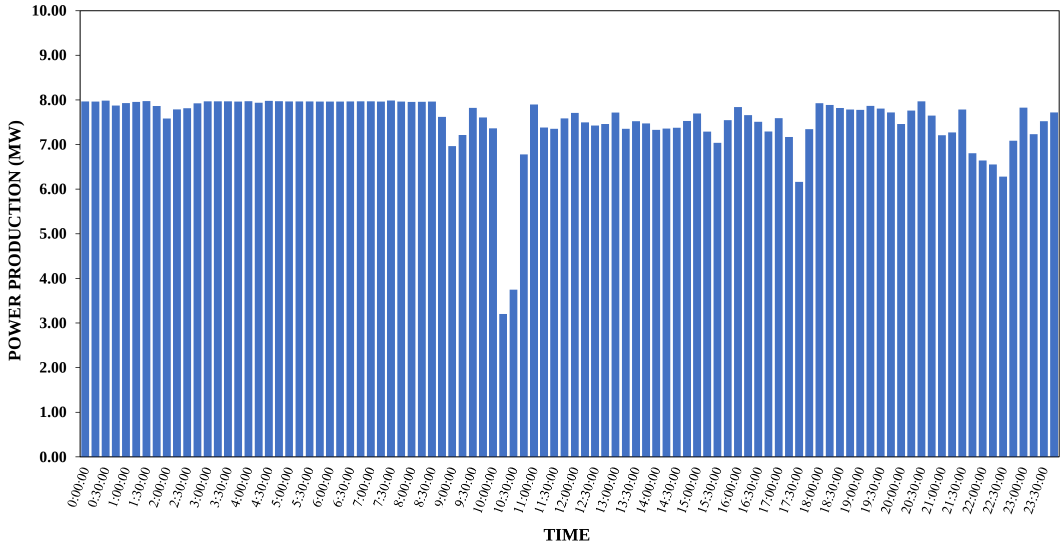



Figure 58 Wind Power Production Profiles (Power Max)

Load flow analysis (no storage) was performed using the DigSilent program to analyze the voltage and power flow values that occur in the distribution system when electricity is generated from the wind power plant into the Provincial Electricity Authority distribution system. From the results of the simulation, it was found that when analyzing the voltage values that occur in the distribution system of the electricity authority when electricity is generated from the wind power plant in the distribution area, the voltage values that occur in the distribution system exceed 1.05 PU. almost all day and power flows back to the grid all the time. The details of the simulation results are shown in Figures 59 and 56.

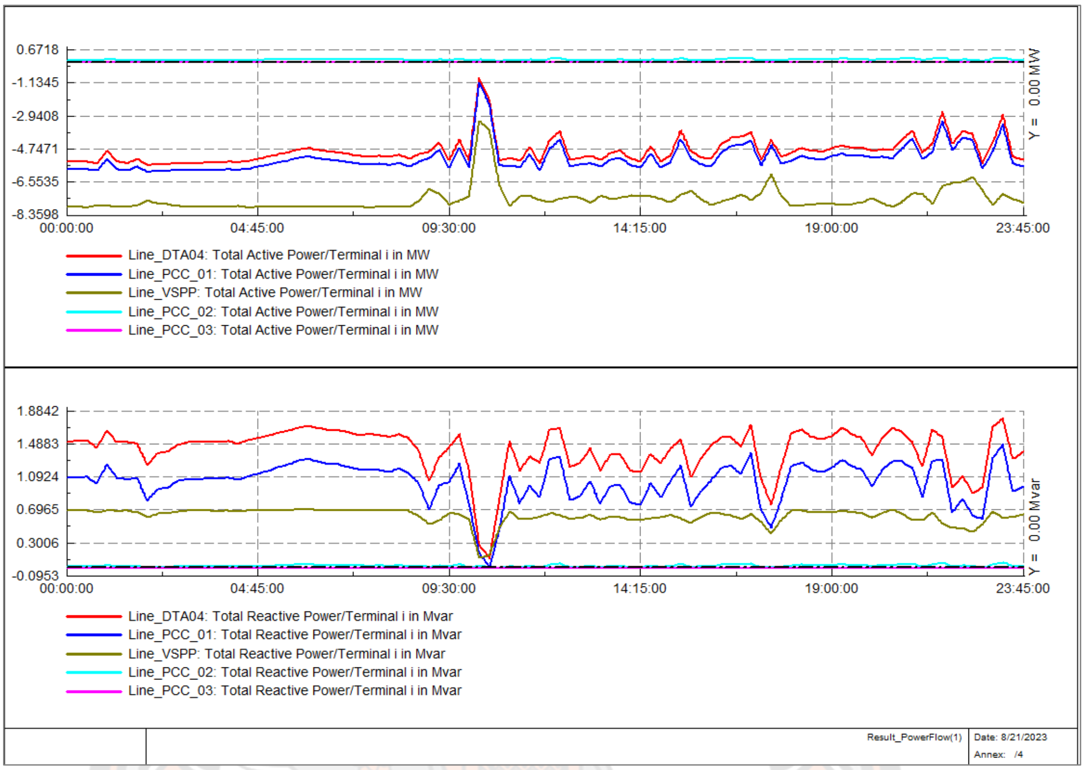



Figure 59 Output ADD VSPP Result Power Flow

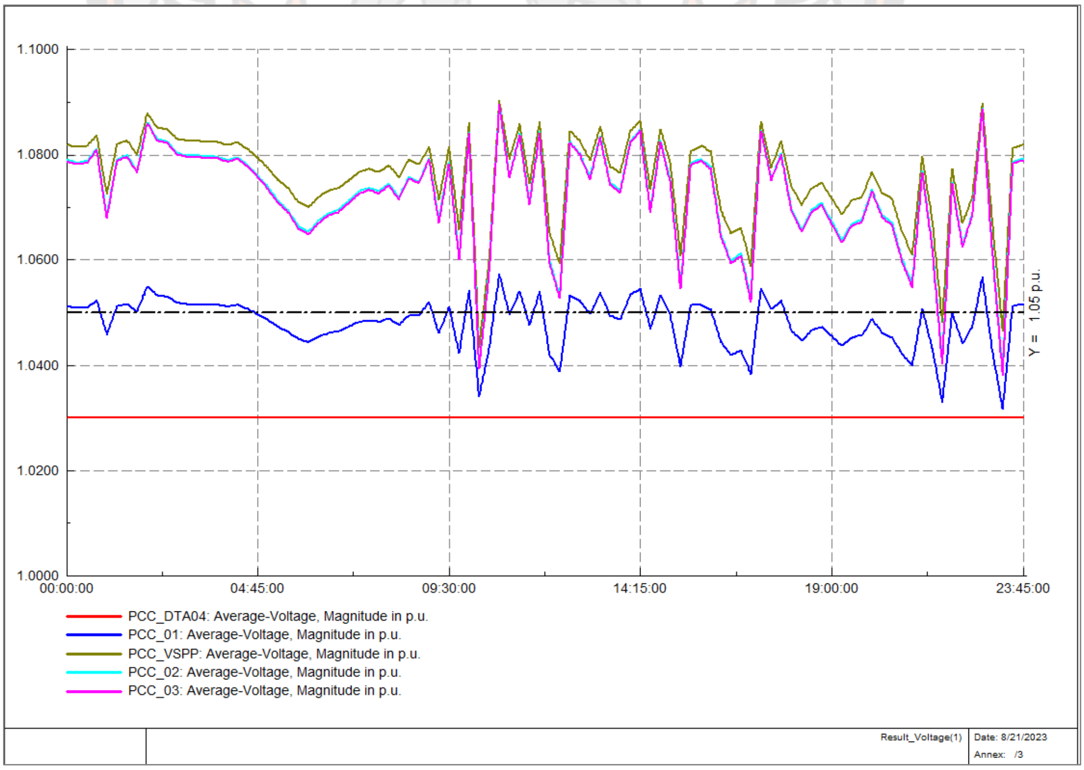



Figure 60 Output ADD VSPP Result Voltage

The parameters were input into the DigSilent program, including the BESS location and BESS profile, to perform the simulation. The storage profile was considered as follows:

- **Active Power:** Since the load flow data found that active power was flowing back into the Provincial Electricity Authority distribution system all the time, it was considered that the storage would charge and discharge according to the average active power.

- **Reactive Power:** Digsilent was configured to be calculated using mode voltage control at 1.045 PU.

A load flow analysis was performed to find the appropriate size of the energy storage system for the wind power plant. The operation was simulated to find the active power and reactive power values of the energy storage system that were appropriate and sufficient to reduce the overvoltage that occurred in the Provincial Electricity Authority distribution system and control the quality of electricity to comply with the Provincial Electricity Authority's grid connection code. The details of the results are shown in Figure 61.

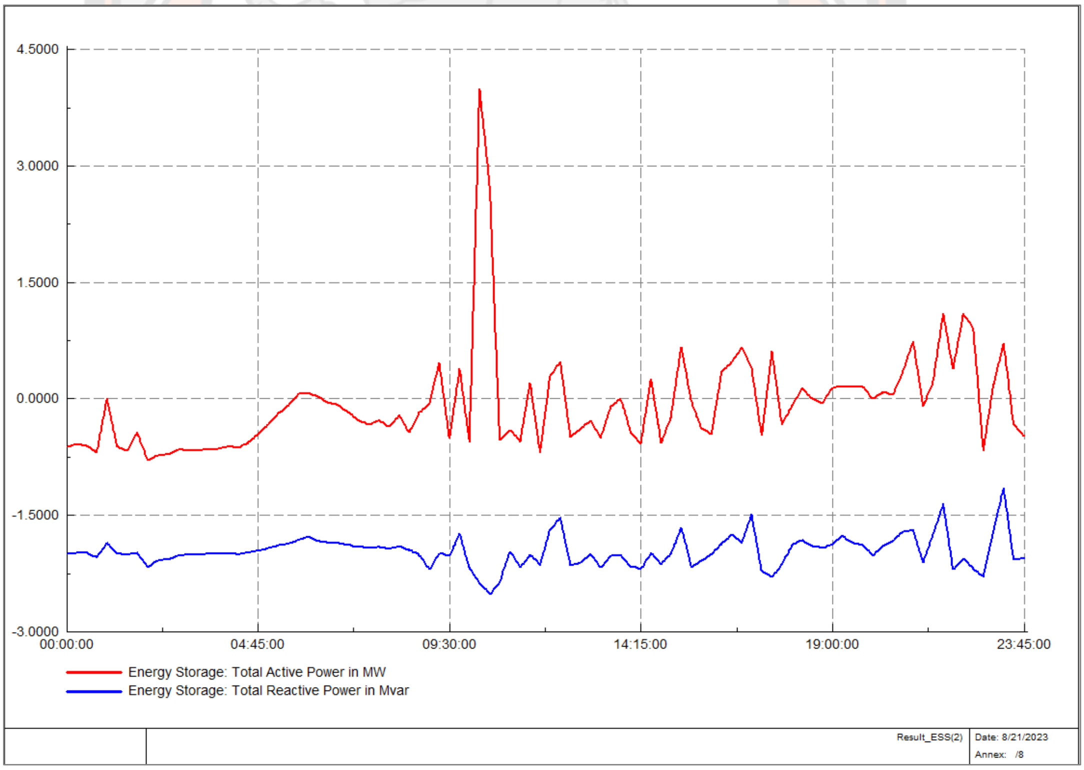



Figure 61 Storage Profile

From Figure 61, it was found that the maximum active power value is approximately 4 MW. Therefore, it was decided to design the system using an energy storage system with a capacity of 5 MWh. The Digsilent program was used to simulate the operation of an 8 MW wind power system. The storage profile value was put into the simulation program to look at the load flow in the simulation of the operation of the wind power system that has an energy storage system installed. The results of the simulation of the system found that the power was flowing back to the Provincial Electricity Authority distribution system all the time, and the stability of the system increased, no longer oscillating as before. The details are shown in Figure 62.

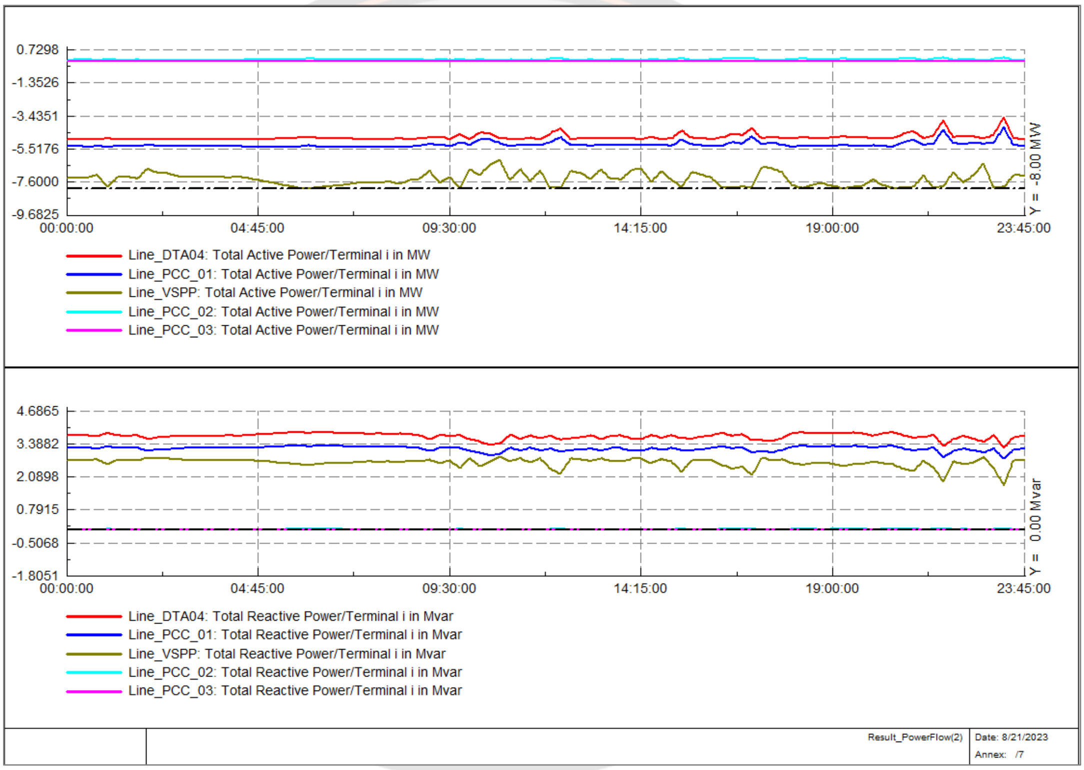



Figure 62 Output ADD BESS Result Power Flow

Then, the Digsilent program was used to run load flow simulations of how the wind power generation system would work with the energy storage system installed in order to look at the voltage value in the system. The results of the simulation found that the voltage value was in the range of 1.045 PU. throughout the day, resulting in no overvoltage in the Provincial Electricity Authority distribution system, making the system more stable. The details are shown in Figure 63.

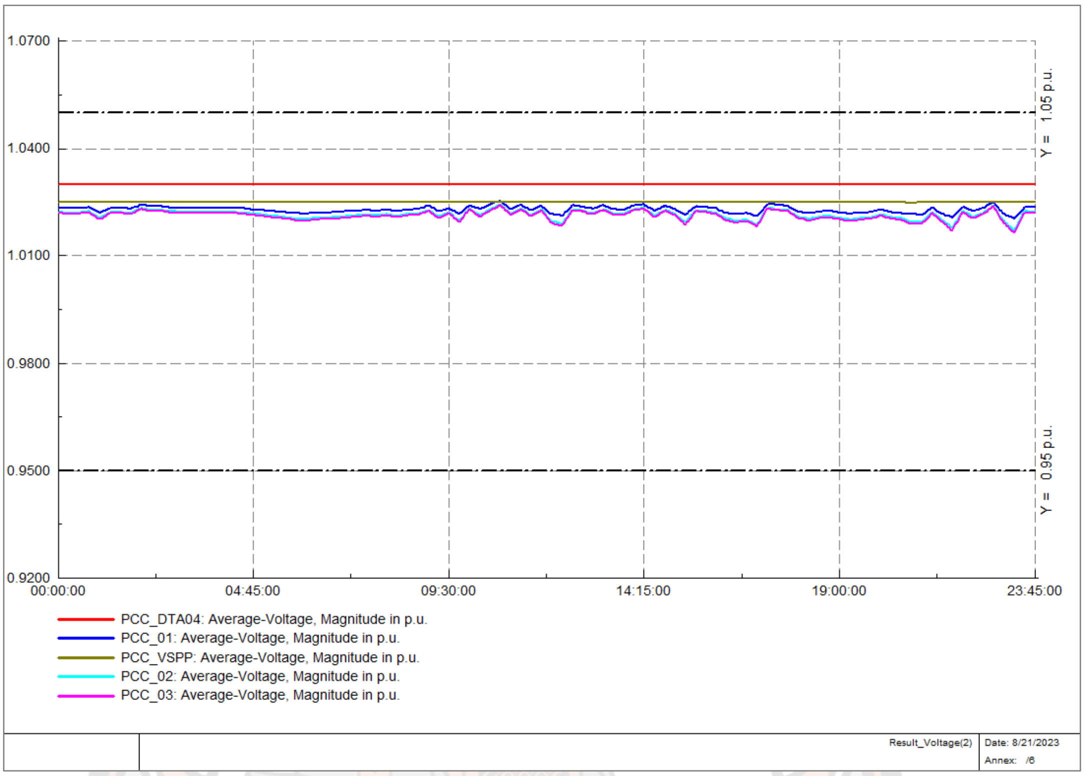



Figure 63 Output ADD BESS Result Voltage

Analyze the operation of an 8 MW wind power generation system with a 5 MWh energy storage system that was obtained from the system design. The State of Charge (SOC) value was set to be between 20% and 100%. The system was simulated for the entire day. The results of the simulation found that the energy storage system could charge and discharge to adjust the voltage in the Provincial Electricity Authority distribution system throughout the day. The details are shown in Figure 64.

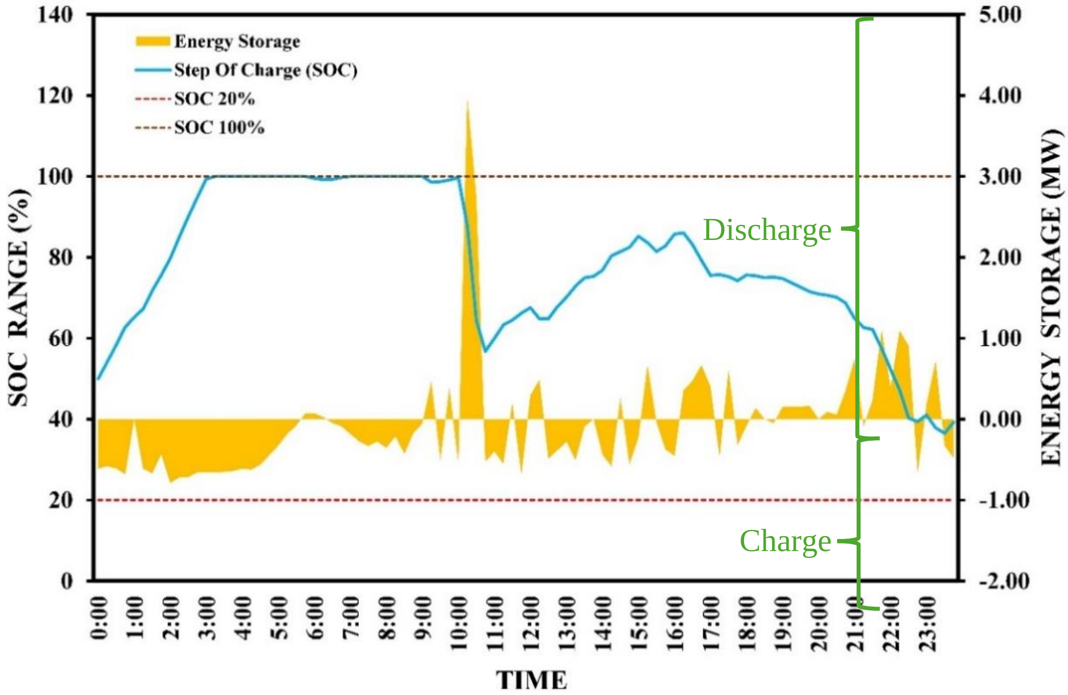



Figure 64 Energy Storage System Profiles

**Case 2: Low Power Production**

Then, an analysis was performed to design the energy storage system in conjunction with the wind power plant using the date on which the wind power plant produces the least electricity. The operation of the energy storage system in conjunction with the wind power plant was analyzed using the date on which the wind power plant produces the least electricity. This is to ensure that the analysis covers the operation of the energy storage system designed in conjunction with the wind power plant throughout the year. The analysis will use the energy usage data (load profiles) of the area around the wind power plant. This will ensure that the simulation is accurate in the analysis and design of the system. The energy usage data was taken from the Provincial Electricity Authority's (PEA's) distribution network and entered into the DigSILENT program to simulate the system before the installation of the wind power plant to check the quality of electricity in the Provincial Electricity Authority's distribution system as a base case. The details of the energy usage data in the area are shown in Figure 65, which is the lowest energy usage data that occurred in the area on April 28, 2021.

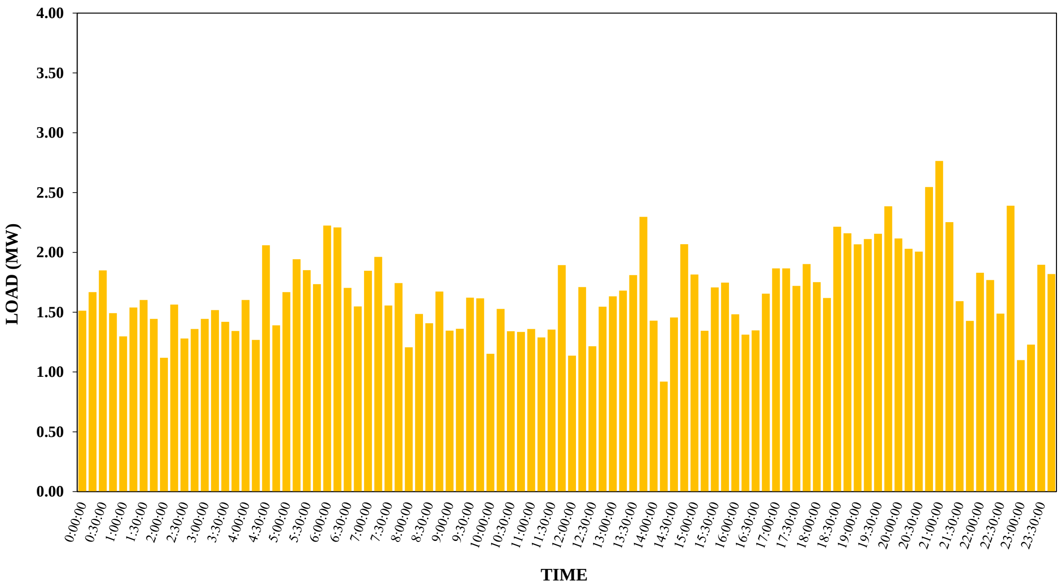



Figure 65 Load Profiles Wind Power Plant (April 28, 2021)

Load profiles were input into the DigSilent program to perform a load flow analysis and observe the state of the distribution system before the wind power plant starts generating electricity. The detailed analysis results are shown in Figure 66. The analysis results show that the average load throughout the day is approximately 1.5 MW. The electrical load will increase periodically, with the peak load occurring between 5:00 p.m. and 10:00 p.m. The peak electrical load is 2.76 MW at approximately 9:00 p.m. The voltage analysis of the distribution system shows that the voltage in the distribution system changes according to the electrical load. The higher the load, the lower the voltage in the distribution system. The average voltage throughout the day is approximately 1.00 PU. The details are shown in Figure 67.

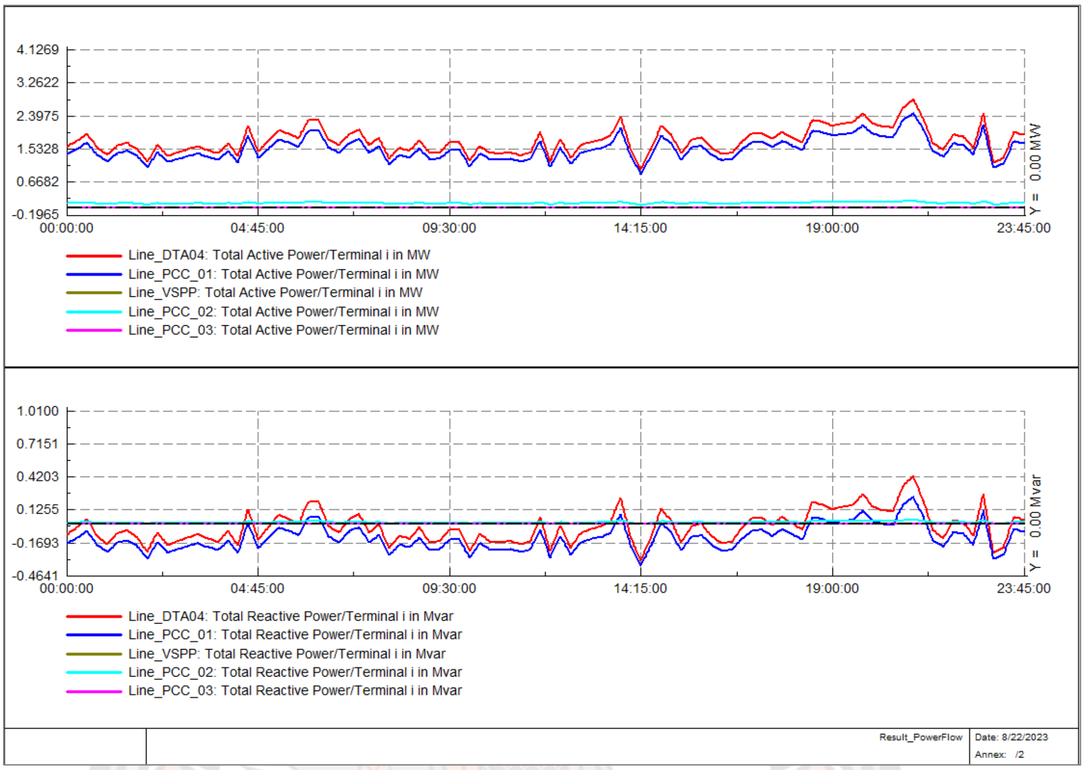



Figure 66 Output Base case Result Power Flow

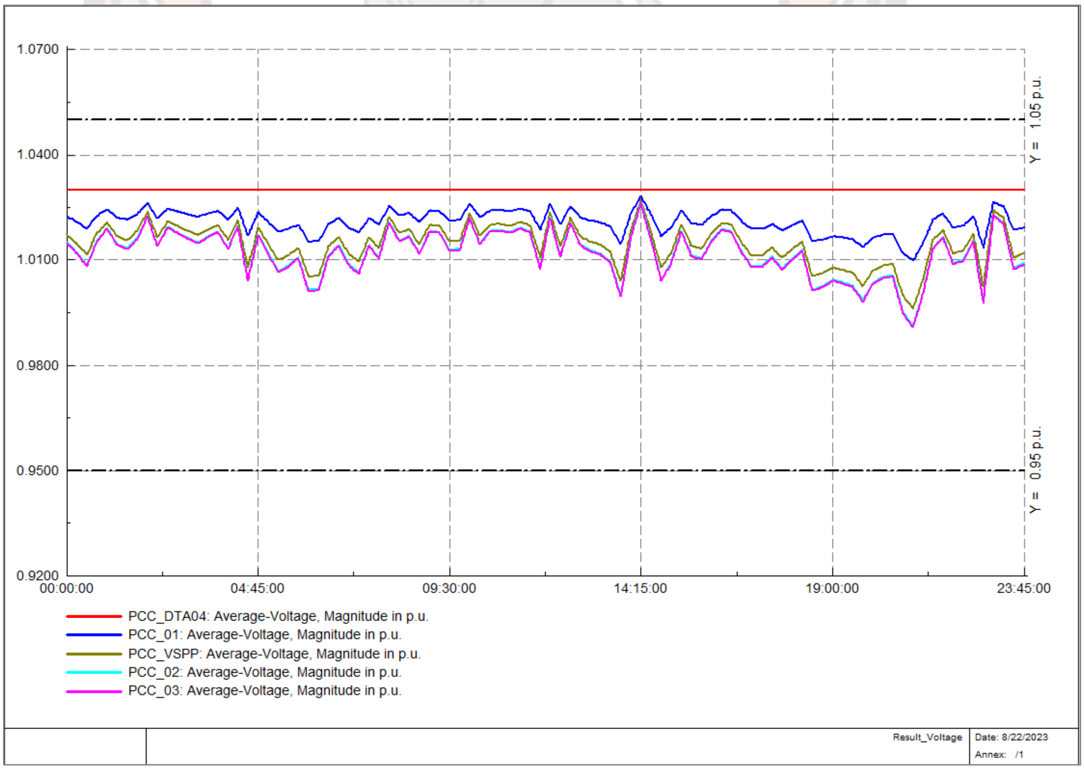



Figure 67 Output Base case Result Voltage

The analysis was conducted using the data of the lowest power generation of the wind power plant, which occurred on April 28, 1978. The data on the wind power plant output is shown in Figure 68. The DigSilent program was used to simulate the operation of the system and to design the system.

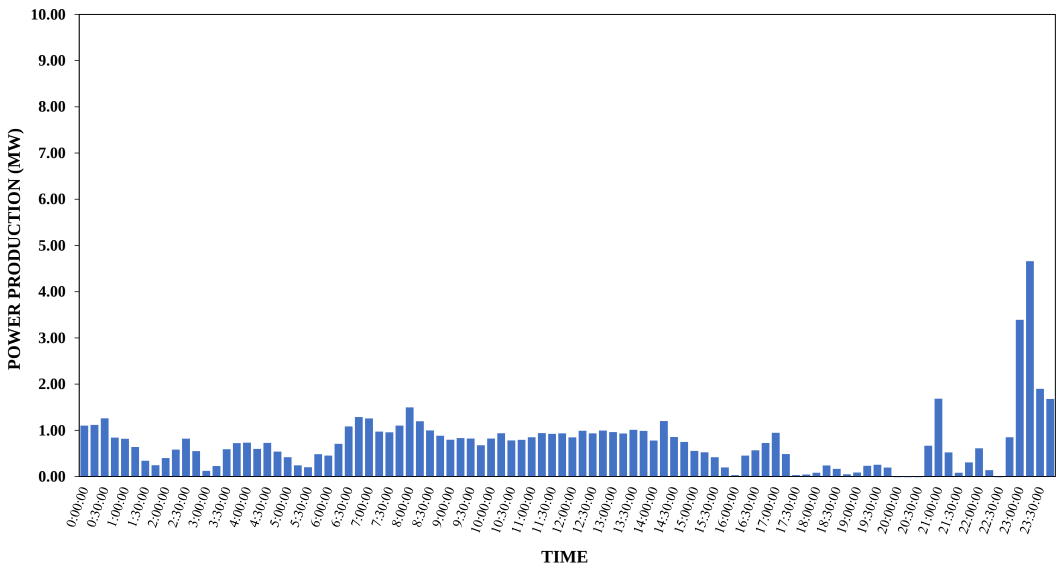



Figure 68 Wind Power Production Profiles (Power Min)

The DigSilent program was used to perform a load flow analysis (no storage) to analyze the voltage and power flow in the distribution system when the wind power plant is generating electricity and feeding it into the regional electricity authority's distribution system. The simulation results show that the voltage in the distribution system exceeds 1.05 p.u. at some times when the wind power plant is generating electricity and feeding it into the system. There is also some reverse power flow on the grid. The detailed simulation results are shown in Figures 69 and 70.

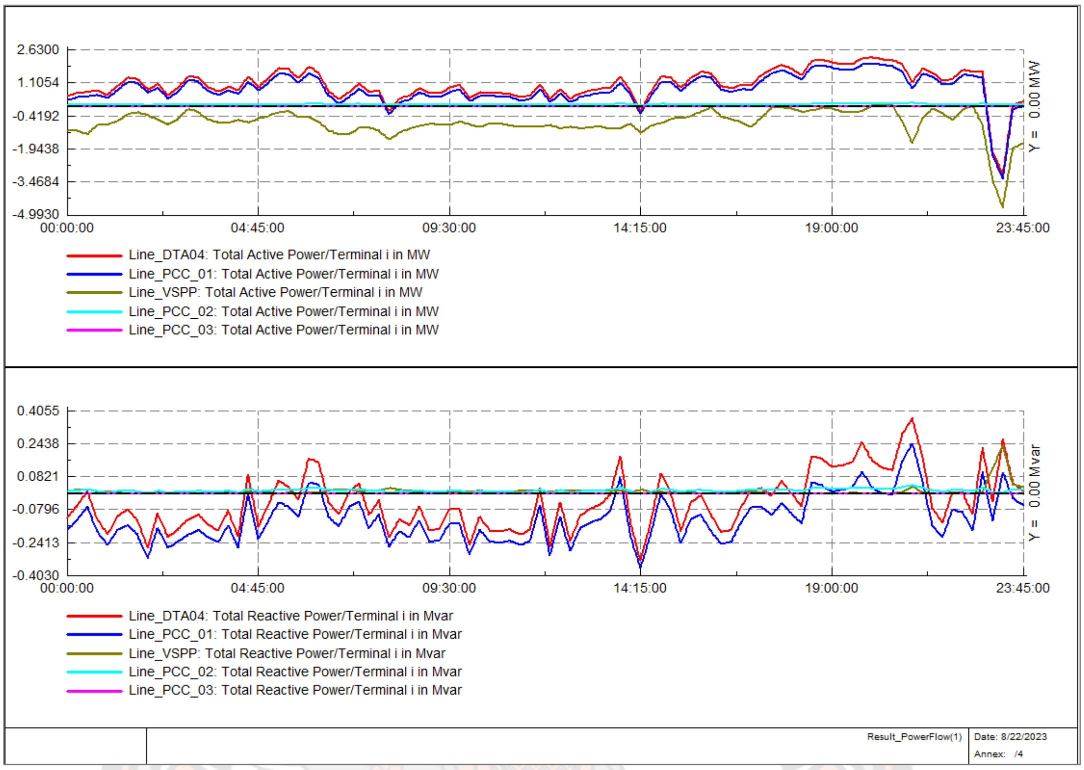



Figure 69 Output ADD VSPP Result Power Flow

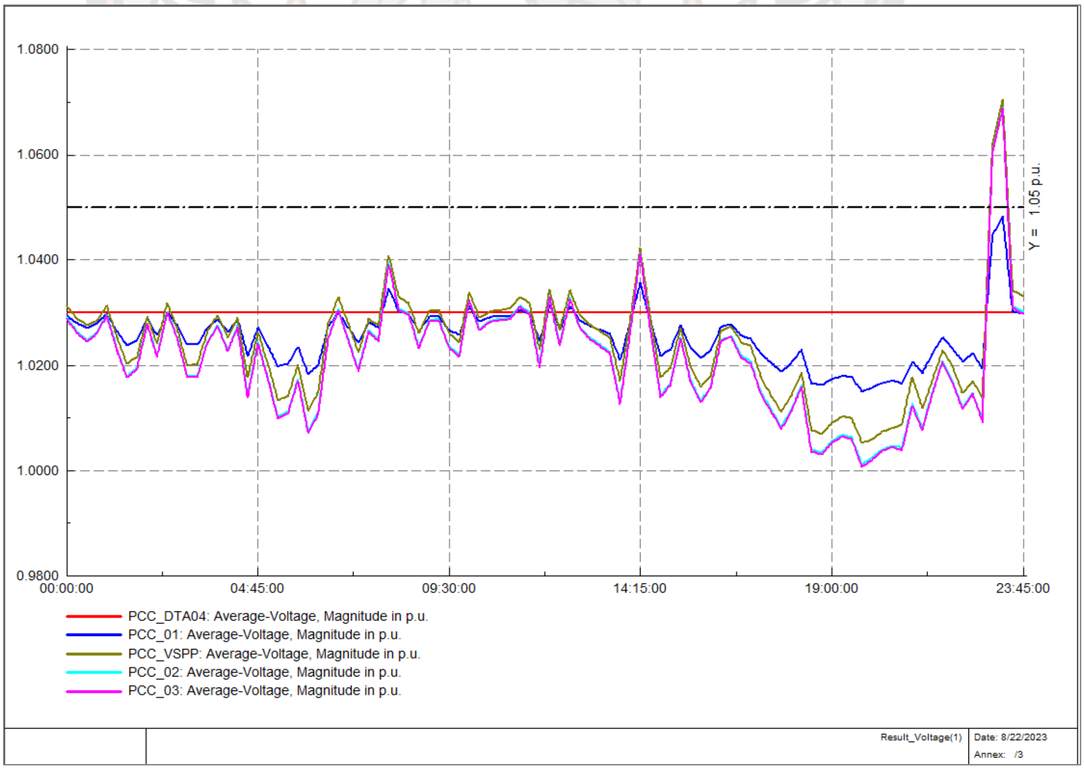



Figure 70 Output ADD VSPP Result Voltage

The parameters were input into the DigSilent program, including the BESS location and BESS profile, to perform the simulation. The storage profile was considered as follows:

- **Active Power:** Since the load flow data found that active power was flowing back into the Provincial Electricity Authority distribution system all the time, it was considered that the storage would charge and discharge according to the average active power.

- **Reactive Power:** DigSilent was configured to be calculated using mode voltage control at 1.045 PU.

A load flow analysis was performed to find the appropriate size of the energy storage system for the wind power plant. The operation was simulated to find the active power and reactive power values of the energy storage system that were appropriate and sufficient to reduce the overvoltage that occurred in the Provincial Electricity Authority distribution system and control the quality of electricity to comply with the Provincial Electricity Authority's grid connection code. The details of the results are shown in Figure 71.

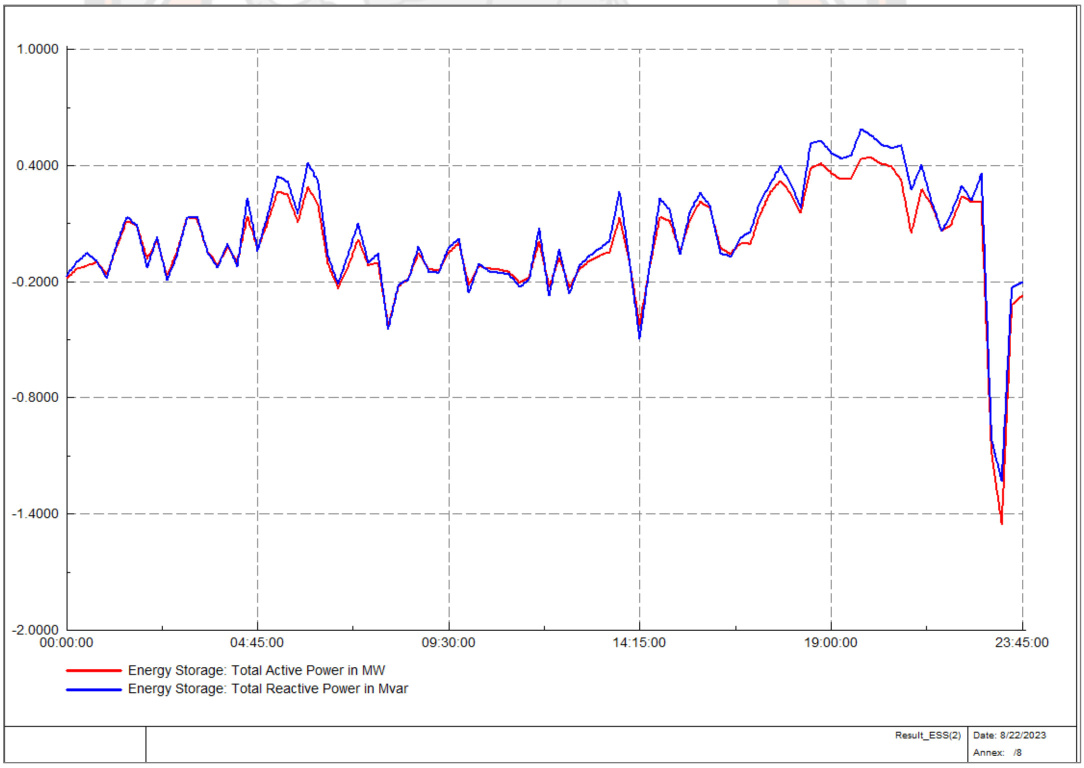



Figure 71 Storage Profile

From Figure 71, it can be seen that the maximum active power generated is approximately 0.45 MW. Therefore, the 5 MWh energy storage system designed is sufficient for the period when the wind power plant produces the least amount of power. In the simulation of the operation of the 8 MW wind power generation system using the Digsilent program, the storage profile value was input into the program to simulate the load flow analysis. The simulation of the operation of the wind power system together with the energy storage system found that the power generated by the wind power plant always flows back to the Electricity Generating Authority of Thailand's distribution system, and the stability of the system is increased. There is no longer any oscillation. Details are shown in Figure 72.

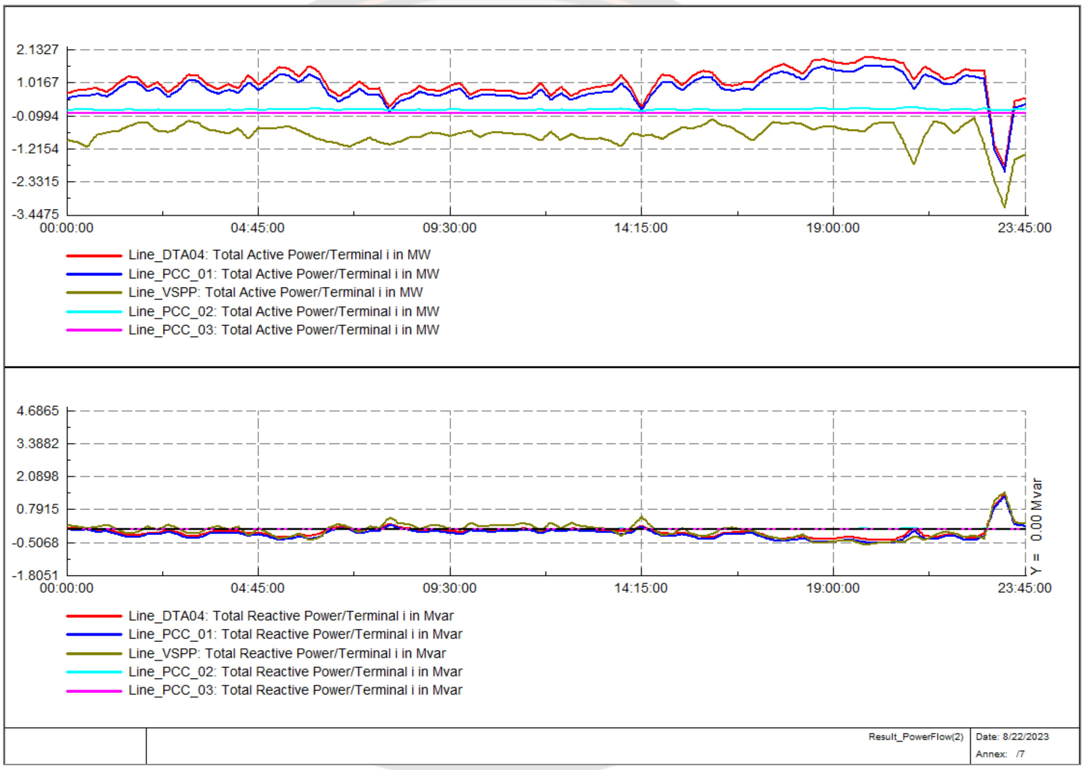



Figure 72 Output ADD BESS Result Power Flow

The operation of the wind power generation system with a 5 MWh energy storage system was then simulated to simulate the voltage in the system using the Digsilent program to run the load flow. The simulation results showed that the voltage was within the range of 1.045 PU. throughout the day. This resulted in no overvoltage in the Electricity Generating Authority of Thailand's distribution system, making the system more stable. Details are shown in Figure 73.

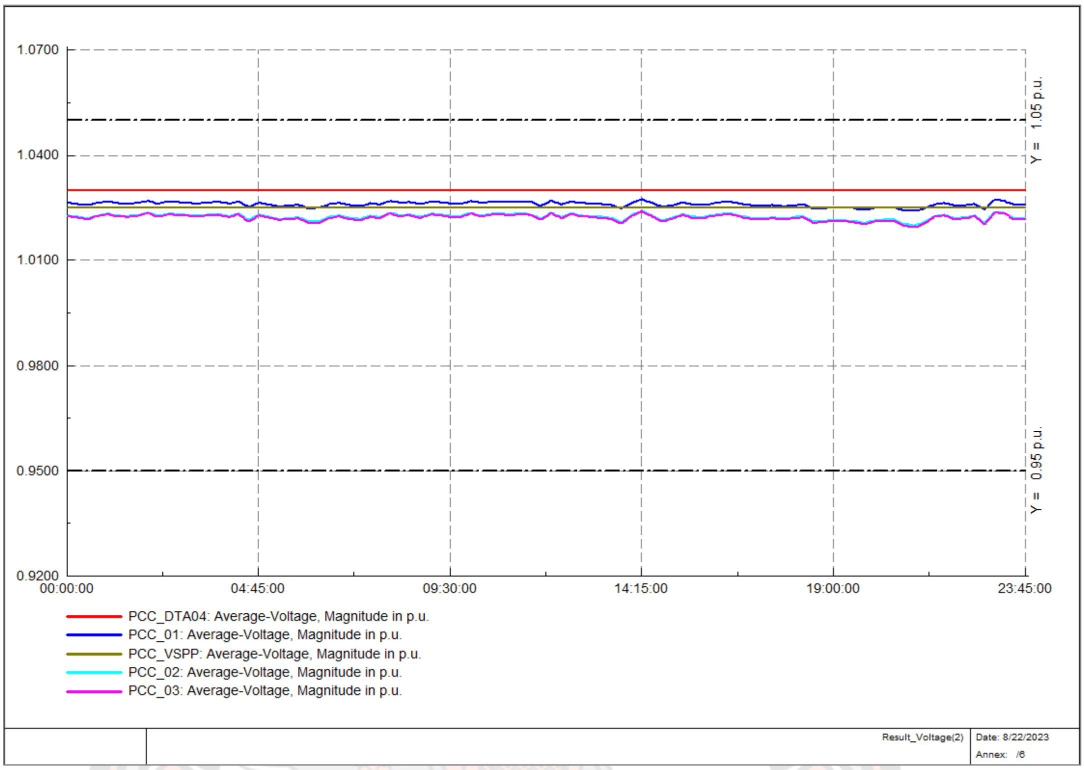



Figure 73 Output ADD BESS Result Voltage

An analysis of the operation of a wind power generation system with a 5 MWh energy storage system was conducted. The state of charge (SOC) was set to range between 20% and 100%. The system was then simulated for a whole day. The simulation results showed that the energy storage system could charge and discharge to adjust the voltage in the Electricity Generating Authority of Thailand's distribution system throughout the day. Details are shown in Figure 74.

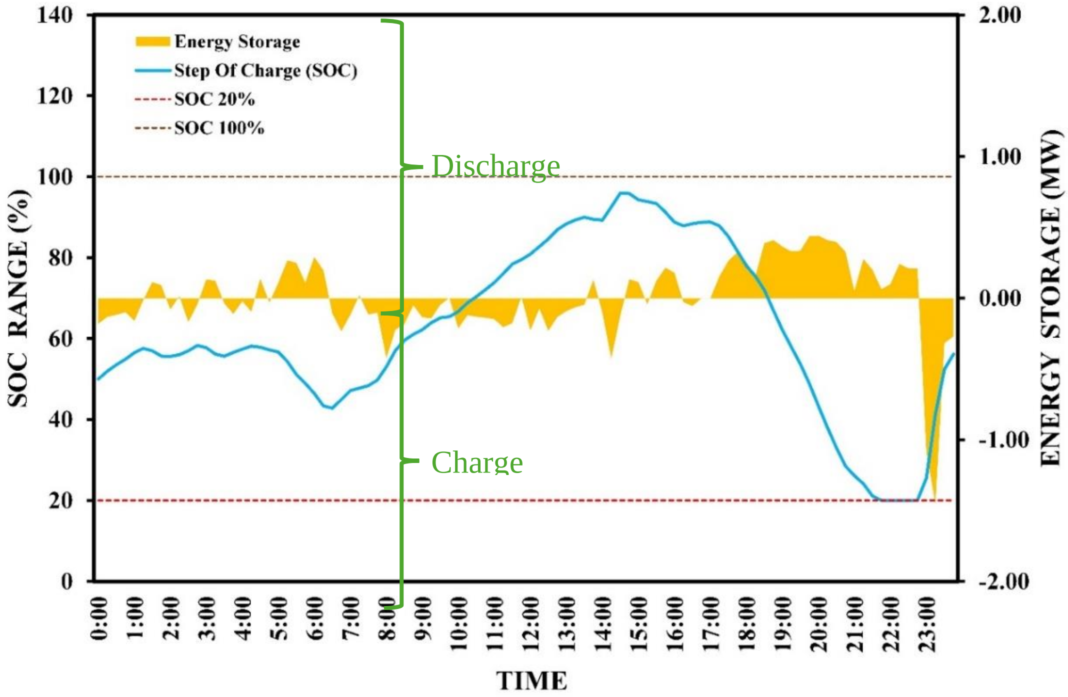



Figure 74 Energy Storage System Profiles

The two aforementioned situations are outlined to enhance comprehension of the nature of the proposed investigation. The integration of the 5 MWh Battery Energy Storage System (BESS) improved the wind farm's functioning by reducing the number of feeder trips. In general, power generation saw growth in all scenarios, with a notable rise in both high-power and low-power output. This technology demonstrates a remarkable improvement in power generation and consistent power supply to the grid. The analysis reveals that a 5 MWh Battery Energy Storage System (BESS) is suitable for an 8 MW commercial-scale onshore wind farm in Nakhon Ratchasima province, Thailand, irrespective of the prevailing meteorological conditions. By integrating Battery Energy Storage Systems (BESS) with the planned wind farm, the guarantee provided by the wind turbine manufacturer may be preserved. This integration has the potential to immediately decrease maintenance expenses and extend the lifespan of the wind turbines. As a result, the wind farm stands to benefit financially. However, the economic analysis conducted in this research did not provide satisfactory results since the major objective of the study was to minimize the number of feeder trips. We also recommend deploying a 5 MWh battery energy storage system (BESS) that includes a battery inverter and an energy management system. This would effectively stabilize the power quality and efficiently control the power output from both the wind farm and BESS, as shown in Figure 75.

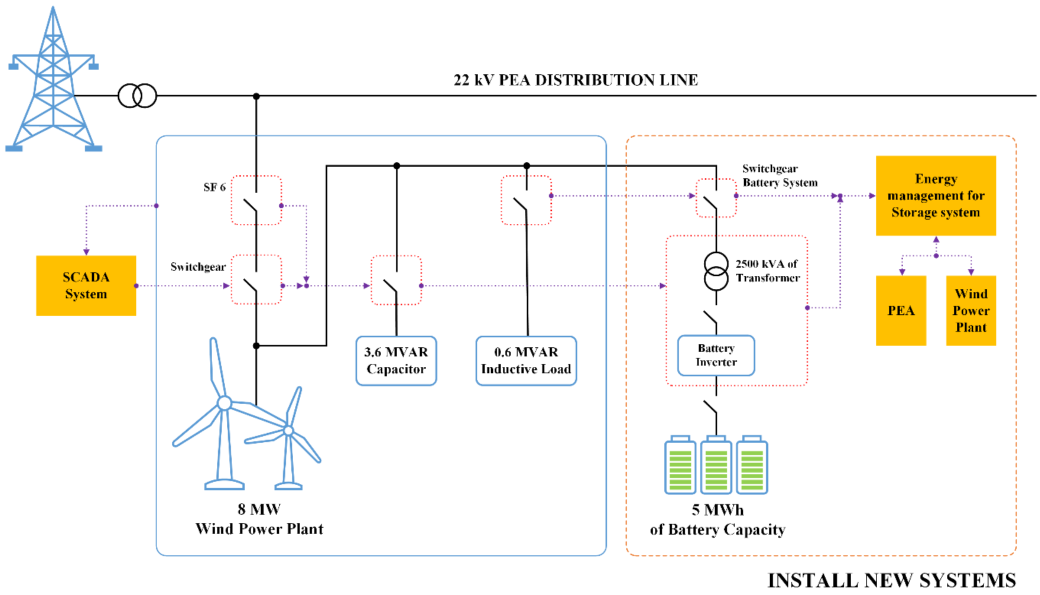



Figure 75 Schematic view of 8 MW wind farm with 5 MWh BESS under real-time operation.

Therefore, to determine the investment suitability of a wind power plant with a 5 MWh energy storage system, an economic analysis of the system was conducted to determine the suitability of installing an energy storage system for a wind power plant.

## 4.3 Inspection of the foundation structure of a wind turbine

Structural strength inspection of wind turbines will be conducted randomly by the Wind Energy Development Company's wind power plant, SubPlu 1. An 8 MW commercial-scale wind power plant is located in Dankhuntoth district, Nakhon Ratchasima province. Which is a wind power plant that has encountered problems and Korat Wind Energy Company's wind power plant is situated in Si Khiu district, Nakhon Ratchasima province. To analyze and compare the impacts that have occurred with the wind power plant. The details of the wind turbines inspected at both locations include 3 turbines at the Wind Energy Development Company's wind power plant and 2 turbines at the Korat Wind Energy Company's wind power plant, as shown in Table 8 and the wind turbine in Figure 76 - 78.

Table 8 The two wind power plants are detailed.

| Wind Power Plant | No. of Turbine | Diameter of Tower (m.) | Hight (m.) | Bland/Model |
|---|---|---|---|---|
| Wind Energy Development | 3 | 4.5 | 125 | GAMESA G114 - 2.0 MW |
| Korat Wind Energy | 2 | 4.67 | 137 | GAMESA G126 - 2.5 MW |

Figure 76 The Wind Power Plant of Wind Energy Development.

Figure 77 The Wind Power Plant of Korat Wind Energy

Figure 78 Structure and foundation of a wind turbine

#### 4.3.1 Results of crack mapping testing of the foundation of a wind turbine.

Inspecting the occurrence of a concrete crack at the foundation of wind turbines at both wind power plants, the impact of Pant Trip Wind Energy Development Company's, and the normal operation of Korat Wind Energy Company's. The results from the inspection revealed that the concrete cracks at the problematic wind turbines have over 68 cracks. The cracks were located around the base of the wind turbine, ranging from 0.1 to 1.0 mm in width. In contrast, the non-problematic power plants exhibited significantly fewer cracks, with a maximum of only 14 cracks observed, ranging from 0.1 to 0.2 mm in width. When considering the proportion of crack widths between wind power plants experiencing wind power plant trips compared to those operating normally, it amounts to 92%. Additionally, some crack widths exceeded the standard (ACI 224R-01). These are the consequences of wind power plant trip incidents. Measurement data is shown in Table 9.

Table 9 Crack mapping test results

| No. | Size of the cracks (mm.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | WED 01 | | WED 02 | | WED 03 | | KWE 01 | | KWE 02 | |
| | Width | Length | Width | Length | Width | Length | Width | Length | Width | Length |
| 1 | 0.2 | 22.0 | 0.2 | 25.0 | 0.2 | 15.0 | 0.1 | 40 | 0.2 | 36 |
| 2 | 0.1 | 26.5 | 0.2 | 26.0 | 0.2 | 15.0 | 0.1 | 38 | 0.2 | 37 |
| 3 | 0.2 | 15.0 | 0.2 | 24.5 | 0.1 | 15.0 | | | 0.2 | 42 |
| 4 | 0.1 | 15.0 | 0.2 | 23.5 | 0.2 | 15.0 | | | 0.2 | 44 |
| 5 | 0.2 | 15.0 | 0.1 | 12.0 | 0.1 | 15.0 | | | 0.2 | 44 |

Table 9  Crack mapping test results (Cont.)

| No. | Size of the cracks (mm.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | WED 01 | | WED 02 | | WED 03 | | KWE 01 | | KWE 02 | |
| | Width | Length | Width | Length | Width | Length | Width | Length | Width | Length |
| 6 | 0.2 | 14.5 | 0.2 | 11.0 | 0.2 | 15.0 | | | 0.2 | 45 |
| 7 | 0.2 | 5.0 | 0.3 | 27.5 | 0.2 | 15.0 | | | 0.1 | 45 |
| 8 | 0.2 | 15.0 | 0.2 | 27.0 | 0.2 | 15.0 | | | 0.1 | 12 |
| 9 | 0.2 | 14.0 | 0.2 | 25.0 | 0.3 | 15.0 | | | 0.2 | 17 |
| 10 | 0.2 | 15.0 | 0.2 | 9.0 | 0.1 | 15.0 | | | 0.2 | 46 |
| 11 | 0.2 | 15.0 | 0.2 | 15.0 | 0.2 | 15.0 | | | 0.2 | 45 |
| 12 | 0.2 | 14.0 | 0.2 | 15.5 | 0.3 | 15.0 | | | 0.2 | 47 |
| 13 | **0.5** | 14.5 | 0.3 | 15.0 | 0.2 | 15.0 | | | 0.2 | 35 |
| 14 | 0.2 | 14.0 | 0.3 | 14.5 | **0.5** | 15.0 | | | | |
| 15 | 0.1 | 14.5 | 0.3 | 14.5 | 0.2 | 15.0 | | | | |
| 16 | 0.1 | 11.0 | 0.2 | 14.5 | 0.2 | 15.0 | | | | |
| 14 | 0.2 | 15.0 | 0.2 | 14.0 | 0.2 | 15.0 | | | | |
| 18 | **0.4** | 15.0 | 0.3 | 15.0 | 0.2 | 15.0 | | | | |
| 19 | 0.2 | 15.0 | **0.4** | 15.5 | **0.4** | 15.0 | | | | |
| 20 | 0.2 | 14.0 | 0.2 | 12.0 | 0.2 | 15.0 | | | | |
| 21 | 0.2 | 14.5 | 0.2 | 15.5 | **0.6** | 15.0 | | | | |
| 22 | 0.1 | 14.5 | 0.2 | 16.0 | 0.2 | 15.0 | | | | |
| 23 | 0.2 | 14.5 | 0.2 | 16.0 | 0.3 | 15.0 | | | | |
| 24 | 0.3 | 14.5 | 0.2 | 16.5 | **0.4** | 15.0 | | | | |
| 25 | 0.2 | 14.5 | 0.3 | 15.0 | 0.2 | 15.0 | | | | |
| 26 | **0.4** | 15.0 | 0.2 | 14.5 | 0.2 | 15.0 | | | | |
| 27 | 0.2 | 15.0 | 0.2 | 14.5 | 0.3 | 15.0 | | | | |
| 28 | 0.2 | 15.0 | 0.3 | 15.0 | 0.2 | 13.0 | | | | |
| 29 | 0.1 | 14.0 | 0.1 | 5.0 | 0.2 | 8.0 | | | | |
| 30 | 0.1 | 14.0 | 0.2 | 15.0 | 0.2 | 14.5 | | | | |
| 31 | 0.3 | 14.0 | 0.2 | 14.5 | 0.2 | 14.0 | | | | |
| 32 | 0.2 | 14.5 | 0.3 | 15.0 | 0.2 | 15.0 | | | | |
| 33 | 0.2 | 12.0 | **0.4** | 15.0 | 0.2 | 16.0 | | | | |
| 34 | 0.2 | 15.0 | 0.3 | 15.0 | 0.2 | 16.5 | | | | |

Table 9 Crack mapping test results (Cont.)

| No. | Size of the cracks (mm.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | WED 01 | | WED 02 | | WED 03 | | KWE 01 | | KWE 02 | |
| | Width | Length | Width | Length | Width | Length | Width | Length | Width | Length |
| 35 | 0.3 | 14.5 | 0.2 | 15.0 | 0.2 | 17.5 | | | | |
| 36 | 0.3 | 15.0 | 0.3 | 14.5 | 0.2 | 16.5 | | | | |
| 37 | 0.2 | 14.5 | 0.2 | 9.0 | 0.2 | 16.5 | | | | |
| 38 | 0.2 | 14.0 | 0.1 | 15.0 | 0.3 | 17.5 | | | | |
| 39 | 0.2 | 14.0 | 0.3 | 15.5 | 0.3 | 16.5 | | | | |
| 40 | 0.1 | 15.0 | 0.1 | 15.5 | 0.3 | 15.5 | | | | |
| 41 | **0.7** | 14.5 | 0.2 | 15.0 | 0.2 | 15.5 | | | | |
| 42 | 0.2 | 14.0 | 0.2 | 15.5 | **0.4** | 15.0 | | | | |
| 43 | 0.2 | 14.0 | 0.2 | 14.5 | 0.2 | 15.0 | | | | |
| 44 | 0.1 | 8.0 | 0.2 | 14.0 | | | | | | |
| 45 | 0.2 | 14.5 | 0.3 | 15.0 | | | | | | |
| 46 | 0.2 | 14.5 | 0.2 | 15.0 | | | | | | |
| 47 | **1.0** | 14.5 | 0.2 | 15.0 | | | | | | |
| 48 | **0.4** | 14.0 | 0.2 | 14.0 | | | | | | |
| 49 | 0.2 | 14.0 | 0.2 | 15.0 | | | | | | |
| 50 | 0.2 | 14.5 | 0.2 | 14.5 | | | | | | |
| 51 | 0.3 | 10.0 | 0.2 | 15.0 | | | | | | |
| 52 | 0.2 | 14.5 | 0.3 | 14.5 | | | | | | |
| 53 | 0.2 | 14.5 | 0.2 | 15.0 | | | | | | |
| 54 | 0.2 | 14.0 | 0.2 | 15.0 | | | | | | |
| 55 | 0.2 | 15.0 | 0.2 | 14.0 | | | | | | |
| 56 | 0.3 | 14.0 | 0.2 | 14.5 | | | | | | |
| 57 | 0.2 | 14.5 | 0.2 | 11.0 | | | | | | |
| 58 | 0.2 | 14.5 | 0.3 | 15.5 | | | | | | |
| 59 | 0.2 | 15.0 | 0.2 | 15.0 | | | | | | |
| 60 | 8.0 | 15.0 | 0.2 | 8.0 | | | | | | |
| 61 | 0.3 | 15.0 | **0.4** | 15.0 | | | | | | |
| 62 | 0.2 | 15.0 | 0.2 | 15.0 | | | | | | |
| 63 | | | 0.2 | 11.5 | | | | | | |

Table 9  Crack mapping test results (Cont.)

| No. | Size of the cracks (mm.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | WED 01 | | WED 02 | | WED 03 | | KWE 01 | | KWE 02 | |
| | Width | Length | Width | Length | Width | Length | Width | Length | Width | Length |
| 64 | | | 0.2 | 10.0 | | | | | | |
| 65 | | | 0.2 | 15.5 | | | | | | |
| 66 | | | 0.2 | 15.0 | | | | | | |
| 67 | | | 0.2 | 15.0 | | | | | | |
| 68 | | | 0.1 | 12.0 | | | | | | |

**Remark:** The allowable crack width is 0.3 mm (ACI 224R-01).

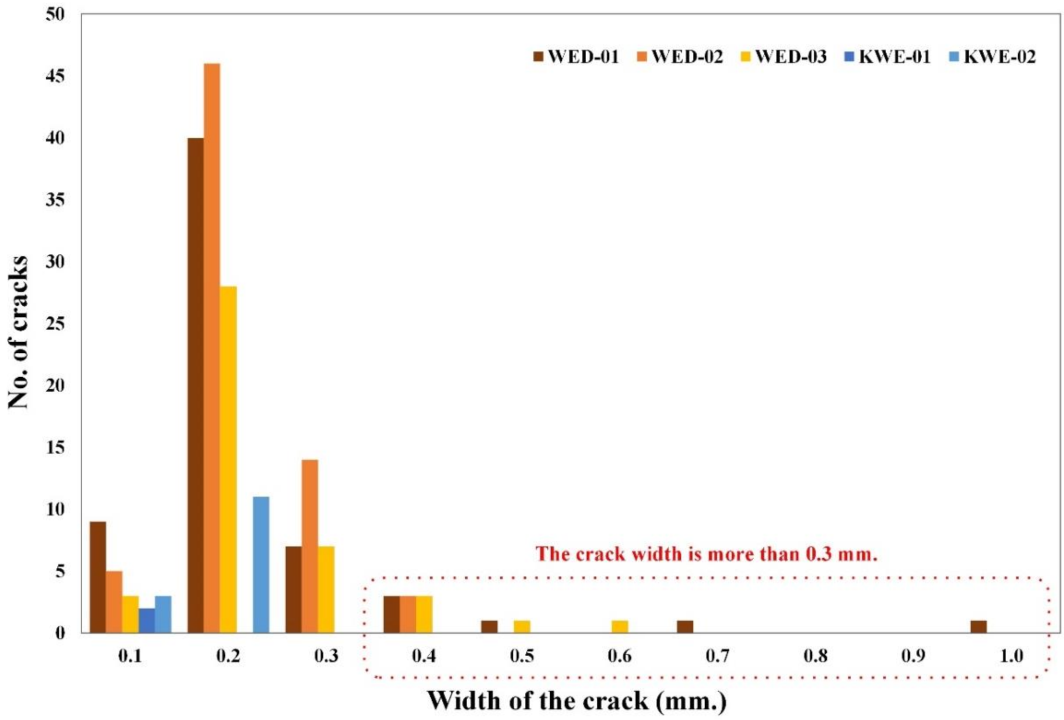



Figure 79 The width of the cracks at the wind turbine concrete foundation.

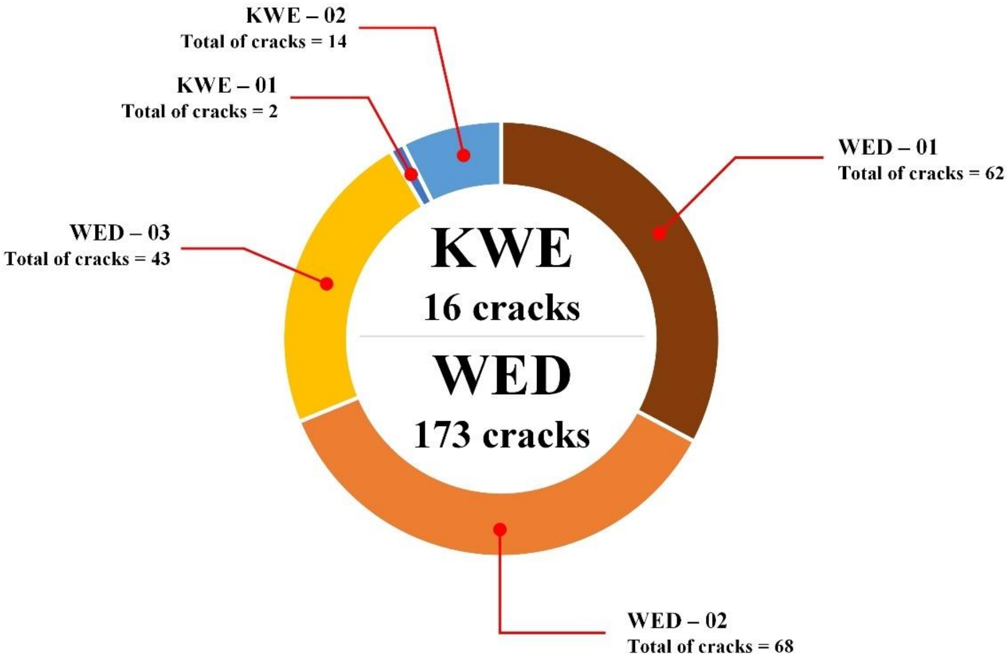



Figure 80 The proportion of measured cracks at the two wind power plants.

Results from the crack mapping test showed that the occurrence of plant trips at the wind power plant significantly increased the number of cracks in the foundations of the wind turbines. Additionally, the width of the cracks exceeded the specified standard. The allowable crack width is 0.3 mm (ACI 224R-01). According to the standard inspection, the cracks occurred on the surface of the concrete foundations but did not affect the structural strength of the concrete. Therefore, we can repair the crack issue using the concrete repair standard DPT 1901-51 (DPT: Department of Public Works and Town & Country Planning, Ministry of Interior), which involves applying mortar to fill the cracks. The mortar mix ratio must be controlled according to the standard or the manufacturer’s specifications, and a qualified engineer must closely supervise the repair. Figure 81 provides an example of crack repair.

Figure 81 an example of crack repair

**4.3.2 Results of non-destructive testing of concrete's compressive strength were conducted by the Rebound Hammer-Schmidt method.**

At both wind power plants, we conducted non-destructive testing of concrete compressive strength using the Rebound Hammer-Schmidt method, performing 10 random tests on each wind turbine concrete foundation. We found the Schmidt-Hammer readings to be consistent. When converting Schmidt Hammer readings to compressive strength, the measured values were approximately 567–700 ksc for Wind Energy Development Company's and Korat Wind Energy Company's, which were approximately 531–700 ksc. This is consistent with the design specifications for wind power plant foundations, which typically require 500 ksc for concrete foundations. Table 10 provides details.

Table 10 Schmidt Hammer test results

| No. | Compressive Strength (ksc) | | | | |
|---|---|---|---|---|---|
| | **WED 01** | **WED 02** | **WED 03** | **KWE 01** | **KWE 02** |
| N | 582 | >700 | >700 | 531 | >700 |
| N-W | 567 | 656 | >700 | 506 | 687 |
| W | 698 | >700 | >700 | 503 | 611 |
| W-S | 604 | >700 | >700 | 590 | >700 |
| S | 698 | >700 | >700 | 659 | >700 |
| S-E | 645 | >700 | >700 | 616 | >700 |
| E | 677 | >700 | >700 | 607 | >700 |
| E-N | 662 | >700 | >700 | 634 | >700 |

**Remark:** The design standards for wind turbine foundations are >500 ksc.

### 4.3.3 Results of evaluating a wind turbine's structure

The inspection and structural analysis of the wind turbine foundations, conducted to assess the annual wind turbine structure, revealed that Wind Energy Development Company's wind power plant, connected to a medium voltage distribution system and experiencing Power Plant Trip issues, had significantly more concrete cracks at the concrete foundation than Korat Wind Energy Company's plant, which is connected to a high voltage distribution system and operates normally. The cracks at Wind Energy Development accounted for up to 92%, with some exceeding permissible widths according to ACI 224R-90 standards. In contrast, Korat Wind Energy had only 18% cracks. Regarding the compressive strength testing of the concrete foundation, both wind power plants showed compressive strength values exceeding 500 ksc, consistent with the design specifications for wind power plant foundations. The summarized annual structural measurement is shown in Table 11.

Table 11 Summary of the measurement results

| **Measurement topic** | **Standard** | **The Result of Wind Energy Development** | | | **The Result of Korat Wind Energy** | |
|---|---|---|---|---|---|---|
| | | **WED 01** | **WED 02** | **WED 03** | **KWE 01** | **KWE 02** |
| **Crack measurement** | ACI 224R-90 (<0.30 mm) | Not pass | Not pass | Not pass | Pass | Pass |
| Compressive strength **measurement** | Design standards for wind turbine foundations (>500 ksc) | Pass | Pass | Pass | Pass | Pass |

## 4.4 Economics Analysis

The Subplu project is an 8 MWp wind farm. The details of the data used in the economic analysis of the system are shown in Table 12.

Table 12 General information about the Subplu project

| Topic | Details |
|---|---|
| Project owner company name | Wind Energy Development Co., Ltd. |
| Project location | Ban Huai Bong, Dan Khun Thot District, Nakhon Ratchasima Province |
| Installed capacity | 8 MWp |
| Wind turbine model and brand | Gamesa G114-2.0MW |
| Power purchaser | Provincial Electricity Authority |
| Power purchase duration | 10 years |
| Electricity selling structure | electricity tariffs + FT + Adder |
| Date of electricity sales | March 17, 2016 |

Economic analysis and evaluation to evaluate the results of the power generation system of a wind farm with a 5 MWh energy storage system, with the following details:

### 4.4.1 Cost and O&M

The goal of this investment cost-benefit assessment is to minimize the impact of Trip on stakeholders by considering the impact table mentioned above. The assumptions used for this investment cost-benefit assessment are as shown in Table 13.

Table 13 Assumptions used for investment cost-benefit analysis.

| Topic | Data | Source |
|---|---|---|
| Amount of energy lost due to Trip | 411,072 units per year | Analysis of power plant data after installing an energy storage system |
| Devices and value of wind turbine equipment that may be damaged in the event of a Trip | 1. Gear system: 6,400,000 THB per wind turbine<br>2. Brake system: 650,000 THB per wind turbine<br>3. Installation costs: 1,000,000 THB per unit | Manufacturers of wind turbines and asset appraisal companies |
| Increased maintenance and management costs for wind turbines | 1,440,000 THB per wind turbine to 2,880,000 THB per wind turbine | Manufacturers of wind turbines and service providers for maintenance and project management |
| Project value | 824,459,960 THB | Data from Wind Energy Development Co., Ltd. |
| Price of electricity per unit produced from a wind farm sold directly to the grid | 1. 1-10 years: electricity tariffs + FT + Adder<br>2. Years 11 and above: electricity tariffs + FT | in accordance with the terms of the power purchase agreement between Wind Energy Development Co., Ltd. and the Provincial Electricity Authority (PEA) |

### 4.4.2 Result of economic analysis

The economic evaluation of the 8 MW wind power plant with a 5 MWh energy storage system connected to the 22 kV medium voltage distribution system of the Provincial Electricity Authority was conducted by changing the investment budget ratio of the energy storage system to determine the suitability of the project. The optimal point to invest in the energy storage system for the wind power plant was found. The results of the analysis are shown in Table 14.

Table 14 the results of the economic

| Financial Parameter | Results | |
|---|---|---|
| | Wind Power Plant | Wind farm with 5 MWh BESS |
| **NPV (THB)** | 19,816,310 | 96,109,437 |
| **IRR** | 7.76 | 9.03 |
| **BCR** | 1.02 | 1.10 |
| **PB (Year)** | 17.4 | 13.9 |

When comparing systems without and with energy storage, the economic analysis results show that the investment costs of the wind power plant without energy storage system and the wind power plant with a 5 MWh energy storage system are 824,459,960 THB and 899,459,960 THB, respectively. The installation of the energy storage system increases the wind power plant's revenue by 2,825,000 THB per year, bringing the Internal Rate of Return (IRR) to 7.76% for the original wind power plant and 9.03% for the wind power plant with the energy storage system, which is higher than the original system. We analyzed the payback period (PB) and found that the wind power plant with the energy storage system has a shorter payback period. The details are shown in Figure 82.

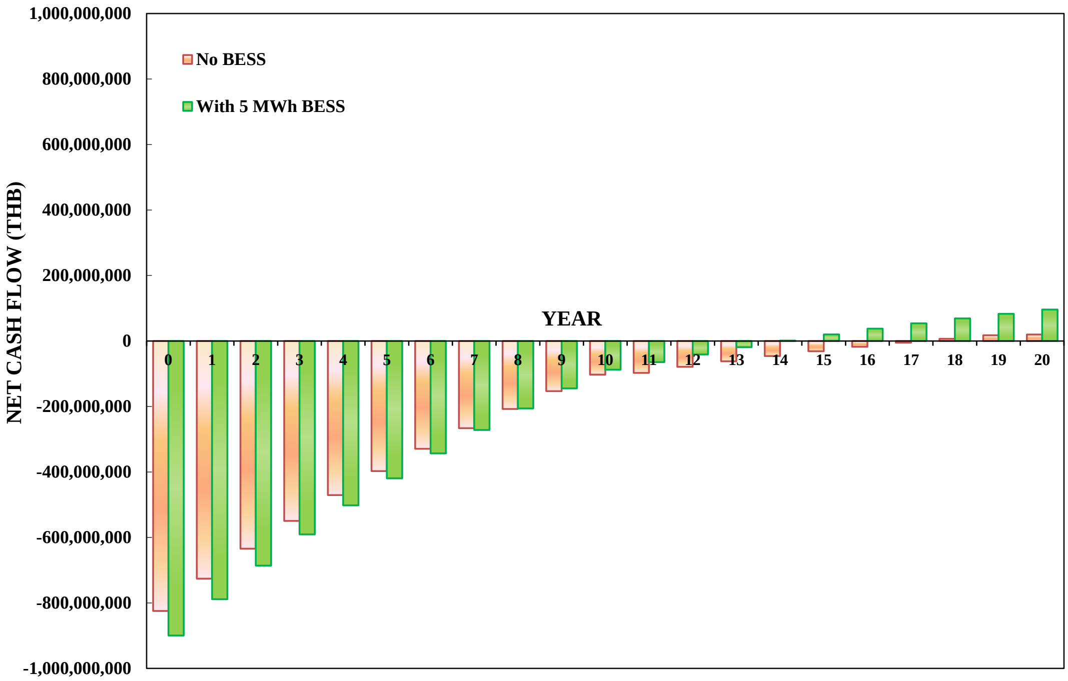



Figure 82 Cash flow analysis.

Figure 82 reveals that the wind power plant without the energy storage system has a payback period of 17.4 years, longer than the wind power plant with the energy storage system, which has a shorter payback period of 13.9 years. This is due to the increased revenue from the energy storage system, which helps the wind power plant operate at full efficiency and significantly reduces plant trips. However, due to the current high cost of battery systems, as of November 2023, the price of energy storage systems is 15,000 THB/kWh, with a lifetime of the energy storage system around 10 years, which is higher than the economic analysis results for wind power plants with energy storage systems. Therefore, the researcher carried out a sensitivity analysis to ascertain the suitable price for the energy storage system to be integrated into the system.

### 4.4.3 Sensitivity analysis

The analysis to determine the sensitivity and find the appropriate price for the energy storage system serves as information for wind power plants to use in deciding whether to invest in the installation of a 5 MWh energy storage system as designed. For the sensitivity analysis of the energy storage system, variables and parameters were used, with details shown in Table 15.

Table 15 Parameters for sensitivity study of Battery Energy Storage System.

| Parameter | Value | Unit |
|---|---|---|
| Discount Rate<br>(Information from the Bank of Thailand in 2023) | 7.36 | % |
| Wind power production increases when Energy Storage System is installed. | 411,072 | kWh/year |
| Investment in the cost of Energy Storage System<br>(Find out the price in November 2023) | 15,000 | THB/kWh |
| Wind power plant lifetime | 20 | Year |
| Energy Storage System lifetime | 10 | Year |
| Wind Turbine Performance Decline with Age*1<br>1) Newer wind turbine<br>2) Older wind turbine | <br>0.2<br>0.5 | <br>%/year<br>%/year |
| Devices and value of wind turbine equipment that may be damage from plant trip (change every 10 years)<br>1) Gear system<br>2) Brake system<br>3) Installation costs | <br>6,400,000<br>650,000<br>1,000,000 | <br>THB/Wind Turbine<br>THB/Wind Turbine<br>THB/Wind Turbine |
| Maintenance and management costs:<br>1) Wind turbine operation is normal.<br>2) Wind turbine is affected by plant trip | <br>1,440,000<br>2,880,000 | <br>THB/Year/ Wind Turbine<br>THB/Year/ Wind Turbine |
| Price of electricity<br>1) electricity tariffs + FT + Adder (Years 1-10)<br>2) Electricity tariffs + FT (Years 11 above) | <br>6.874<br>3.374 | <br>THB/kWh<br>THB/kWh |

**Remark:** *1 = Source: Driven Assessment of Wind Turbine Performance Decline with Age and Interpretation Based on Comparative Test Case Analysis

To see if it was possible to invest in a 5 MWh battery energy storage system (BESS), which can boost the electricity produced by a wind farm by over 411,072 kWh per year, an economic analysis was done. The economic assessment results of a 5 MWh BESS with different BESS investment budget ratios were used to find the best investment point for the BESS. The results of the assessment are shown in Table 16.

Table 16 Results of sensitivity studies

| Financial Parameter | PRICE of BESS 5 MWh | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% |
| NPV (THB) | 4,720,682 | 12,907,472 | 21,094,262 | 29,281,051 | 37,467,841 | 45,654,630 | 53,841,420 | 62,028,210 |
| IRR | 8.17 | 9.74 | 11.59 | 13.83 | 16.62 | 20.29 | 25.44 | 33.55 |
| BCR | 1.05 | 1.14 | 1.26 | 1.40 | 1.58 | 1.80 | 2.11 | 2.53 |
| PB (Year) | 17.2 | 13.3 | 10.8 | 10.2 | 8.6 | 6.8 | 5.1 | 3.7 |

The study's findings indicate that reducing the cost of the energy storage system results in an accelerated payback time and an increased return on investment. Figure 83 demonstrates the usefulness of the table in generating a graph that visually represents the correlation between the price of the 5 MWh energy storage system, the payback period (PB), and the benefit-cost ratio (BCR).

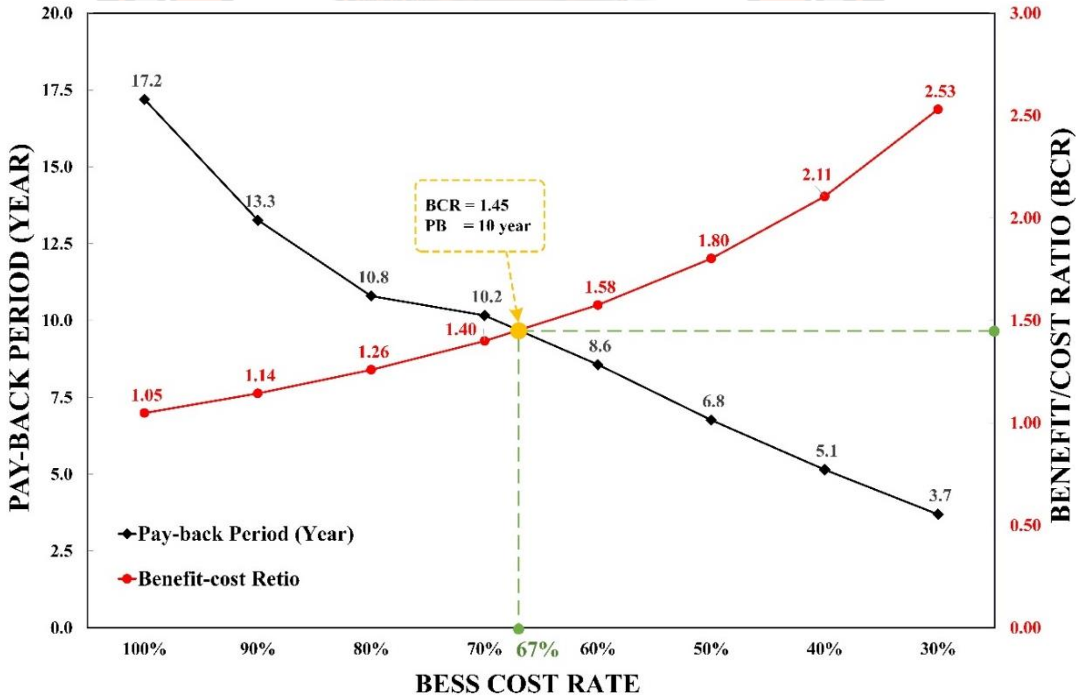



Figure 83 Results of the Analysis of the Investment Ratio of the BESS

The analytical findings indicate that the payback period for the energy storage system, with a 100% investment cost of 15,000 THB/kWh, is 17.2 years. This payback period is much longer than the current lifespan of energy storage systems, which is 10 years as of November 2023. Hence, it is now unsuitable for investment. We conducted a sensitivity analysis by considering other cost rates for energy storage systems, namely 90%, 80%, and 30% of the real electricity storage system pricing. Our findings indicate that the optimal investment cost ratio for energy storage systems is about 67%, equivalent to 10,000 THB/kWh. Implementing this strategy would lead to a payback time of under 10 years and raise the internal rate of return (IRR) to 14.54%, resulting in a benefit-cost ratio (BCR) of 1.45.Therefore, installing a 5 MWh energy storage system in conjunction with an 8 MW wind power plant found that a lower cost of the energy storage system leads to a shorter payback period and a higher return on investment. The BCR (benefit/cost ratio) is crucial in determining the payback period. Additionally, integrating the BESS with a wind power plant increases energy generation and reduces the plant trip period, which improves the BESS's return on investment. The installation of the energy storage system can also resolve feeder trip problems, improve power quality, increase power generation efficiency, and enhance power stability.

# CHAPTER V
# CONCLUSION

From ***The Study of Performance, Power Quality, and Stability Improvement of Wind Power Plant Connected with Medium Voltage Distribution Network***, The study targets Wind Energy Development Co., Ltd.'s Wind Farm SubPlu 1. An 8 MW commercial scale is located in Huaybong subdistrict, Dankhuntoth district, Nakhon Ratchasima province. This wind power plant is connected to the 22 kV distribution line of the Provincial Electricity Authority (PEA). The wind power plant has entered into a 10-year maintenance and management contract with the wind turbine manufacturer. The problem is that this wind power plant trips or shuts down more than 146 times per year. The wind turbine manufacturer's guarantee had already expired and made emergency stops work. Frequent emergency stops can cause significant damage to the wind power plant, particularly the wind turbine equipment, which can deteriorate faster due to transient loads when the emergency brake activates. Moreover, this could potentially result in structural damage to the turbine and the foundation. It also results in a loss of opportunity to generate and sell electricity. However, we used real operational data from the wind power plant and the PEA distribution network's GIS database to simulate the operation of a wind power plant with an energy storage system. We used DigSILENT Power Factory software version 15.1 (research license of Naresuan University, School of Renewable Energy Technology, Thailand) to design and develop an 8 MW wind power plant with an energy storage system (refer to purposes 1), analyze the impact on the foundations of wind turbines (refer to purposes 2), and conduct a technical and economic analysis of investment in the wind power plant with an energy storage system (refer to purposes 3). The conclusion to these research findings is divided into three parts, with the following details provided:

## 5.1 Design and develop wind energy storage system

The 8 MW wind power plant in Dan Khun Thot District, Nakhon Ratchasima Province, Thailand, experienced plant shutdown problems due to its connection to the 22 kV medium voltage distribution system of the Provincial Electricity Authority. This caused the voltage in the distribution system to exceed the overvoltage standard specified in the Grid Connection Code of the Provincial Electricity Authority. This affected the power quality in the distribution system and caused voltage dips, which resulted in feeder trips. Over the course of the year, the operational data collected from the wind farm reveals a noteworthy problem: feeder excursions, which occur 146 times a year and have a detrimental effect on electricity output. Overvoltage in the grid, a result of unaccounted grid demand and power generation from the wind farm, is the primary cause of these feeder excursions. We added a battery energy storage system (BESS) to the current configuration to solve this problem. BESS integration is not only necessary to cut down on feeder trips, but it is also essential for upholding the turbine manufacturer's warranty. This problem in the company having cost of insurance costs every year, and it also affects the revenue of the manufacturing company, which decreases by about 10% due to the need to limit the power capacity in some periods even though the wind power potential is high. This study analyzes wind power plants to find the appropriate size of the energy storage system to solve the problem of plant trips. The analysis Used DigSilent software to simulate the impact on the distribution system by simulating the size of the electrical load in the feeder where the wind power plant is connected by specifying the size of the electrical load be divided into two cases: Case 1 is high power production (July 25, 2021), and Case 2 is low power production (April 28, 1978). This will ensure that the analysis covers the entire operating range of the plant throughout the year and covers any potential impacts. This makes the designed system the most suitable for the target wind power plant. Analysis used the DigSilent program by running a load flow to see the conditions that occur in the distribution system before the production of electricity from the wind power plant. in cases of high power production. The average load that occurs throughout the day is approximately 2.0 MW. The maximum electrical load value is equal to 3.92 MW at approximately 23:00 PM. In cases of low power production, the average load throughout the day is approximately 1.5 MW. The peak electrical load is 2.76 MW at approximately 9:00 p.m. The voltage in the distribution system changes according to the electrical load. The higher the load, the lower the voltage in the distribution system. The average voltage throughout the day is approximately 1.00 PU.

Analyze the voltage and power flow (no storage) values that occur in the distribution system when electricity is generated from the wind power plant into the Provincial Electricity Authority distribution system. From the results of the simulation, the voltage values that occur in the distribution system exceed 1.05 PU. almost all day, and power flows back to the grid all the time. Then input the parameters into the DigSilent program, including the BESS location and BESS profile, to perform the simulation. Load flow analysis was performed to find the appropriate size of the energy storage system for the wind power plant. The operation was simulated to find the active power and reactive power values of the energy storage system that were appropriate and sufficient to reduce the overvoltage that occurred in the Provincial Electricity Authority distribution system and control the quality of electricity to comply with the Provincial Electricity Authority's grid connection code. The storage profile was considered to charge and discharge according to the average active power and was configured to be calculated using mode voltage control at 1.045 PU. The simulation's results indicate that the selected site is suitable for a 5 MWh BESS, and we set the State of Charge (SOC) value between 20% and 100%. The system was simulated for the entire day. The results of the simulation found that the energy storage system could charge and discharge to adjust the voltage in the Provincial Electricity Authority distribution system throughout the day. This ensures that there are no feeder trips. The BESS can send electricity to the grid without any feeder trips, ensuring consistent wind farm operation. On the other hand, optimizing the BESS involves managing the feeder trip rather than building it to continuously provide the grid with electricity during periods when wind power production is not present. The energy storage system can maintain and improve the power quality in the distribution system. It can manage the electricity generated by the wind turbines and keep the voltage in the distribution system within the standard specified by the Provincial Electricity Authority. When the data is analyzed, it is found that the wind power plant can generate 2.41% more electricity without the energy storage system. This means that it can generate 411,072 kWh/year more electricity. The payback period of the wind power plant with the energy storage system is about 7.48 years.

**5.2 Evaluate of wind foundation**

The analysis of wind turbine foundation impacts at the target wind power plant, connected to a medium-voltage distribution system, revealed that frequent emergency brake activations can directly damage the brake system and induce turbine vibrations, potentially compromising turbine and foundation structural integrity. Ensuring the safety of turbine towers, electrical components, and foundations is paramount. The Wind Energy Development Company conducts annual structural inspections, with a particular focus on reinforced concrete foundations that support. The inspection and structural analysis of wind turbine foundations aimed at assessing annual structural integrity showed significant differences between Wind Energy Development Company's plant and Korat Wind Energy Company's facility. Wind Energy Development, which experiences frequent power plant trips, exhibited extensive concrete cracking in its foundation—up to 92%, with some cracks exceeding allowable widths per ACI 224R-90 standards. In contrast, Korat Wind Energy, connected to a high-voltage system and operating normally, had only 18% cracks. Both plants demonstrated concrete compressive strengths exceeding 500 ksc, meeting the standards for wind power plant foundation design. Therefore, the goal is to lessen the impact of wind power plants shutting down or tripping. Enhance the quality of electricity and the stability of the distribution system for wind power plants experiencing issues. The wind power plant has the potential to operate efficiently. It can reduce the volatility of electricity production, thereby reducing the risk of structural damage to the wind turbines.

**5.3 Economic Analysis**

The economic analysis of the 5 MWh energy storage system was conducted by changing the investment budget ratio of the energy storage system to determine the suitability of the project. The optimal point to invest in the energy storage system for the 8 MW wind power plant connected to the 22 kV medium voltage distribution system of the Provincial Electricity Authority was found. The results of the analysis showed that the payback period will be shorter and the return on investment will be higher if the cost of the energy storage system is lower. When comparing systems without and with energy storage, the economic analysis results show that the investment costs of the wind power plant without an energy storage system and the wind power plant with a 5 MWh energy storage system are 824,459,960 THB and 899,459,960 THB, respectively. The installation of the energy storage system increases the wind power plant's revenue by 2,825,000 THB per year, bringing the Internal Rate of Return (IRR) to 7.76% for the original wind power plant and 9.03% for the wind power plant with the energy storage system, which is higher than the original system. We analyzed the payback period (PB) and found that the wind power plant with the energy storage system has a shorter payback period. The wind power plant without the energy storage system has a payback period of 17.4 years, longer than the wind power plant with the energy storage system, which has a shorter payback period of 13.9 years. This is due to the increased revenue from the energy storage system, which helps the wind power plant operate at full efficiency and significantly reduces plant trips. However, due to the current high cost of battery systems, the price of energy storage systems as of November 2023 is 15,000 THB/kWh, with a lifetime of around 10 years, which is higher than the economic analysis results for wind power plants with energy storage systems.

Therefore, the sensitivity analysis is conducted to determine the appropriate price for integrating the energy storage system into the system. We conducted a sensitivity analysis that took into account various cost rates for energy storage systems, specifically those that represent 90%, 80%, and 30% of the actual pricing of an electricity storage system. Our findings indicate that the optimal investment cost ratio for energy storage systems is about 67%, equivalent to 10,000 THB/kWh. Implementing this strategy would lead to a payback time of under 10 years and raise the internal rate of return (IRR) to 14.54%, resulting in a benefit-cost ratio (BCR) of 1.45. It is concluded that BESS alone failed to meet the economic benefit. When the BESS is integrated with a wind farm, energy generation increases, and the feeder trip period is minimized, resulting in the energy benefit from the wind farm favoring the return on investment of the BESS. Therefore, the installation of the energy storage system can solve the tripping problem of the system, improve the power quality in the distribution system, increase the power generation efficiency of the wind power plant, and enhance the power stability. It can also act as a backup system, such as by providing backup power during power outages, adjusting voltage, adjusting reactive power, etc. This will enable the wind power plant to reduce the cost of maintenance and management of the wind power project, reduce the risk of damage to the wind turbines, and generate more electricity more efficiently.

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# APPENDIX

# Appendix A Power quality enhancement for Thailand's wind farm using 5 MWh Li-ion battery energy storage system

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## Power quality enhancement for Thailand's wind farm using 5 MWh Li-ion battery energy storage system

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ABSTRACT

Several studies have stated that an increase in wind power plants and unpredictable wind energy generation face several issues during over-voltage. In this study, an operational 8 MW wind farm in Nakhon Ratchasima province faced severe annual feeder trips 146 times, which is not permissible according to the manufacturers. The feeder trips are mainly attributed to high grid voltage caused by low load demand. This study developed a Battery Energy Storage System (BESS) to minimise feeder trips using DigiSILENT and utilized the higher feeder trip period of September to optimise BESS capacity with a 10 % grid load. Notably, a 5 MWh BESS maintained the grid voltage within an allowable range compared to the 1–4 MWh (increment of 1 MWh) throughout the operational period. Furthermore, a 5 MWh BESS was tested during low and high wind periods to assess the stability of over-voltage management. We found that the 5 MWh BESS controlled over-voltage and prevented feeder trips, resulting in enhanced power generation on selective days with high feeder trips, low wind speed, and high wind speed, generating 28.34 MWh, 0.33 MWh, and 76.67 MWh, respectively, compared to conditions without BESS. Additionally, we recommend that the 5 MWh BESS can enhance wind farm power stability and uphold the manufacturer's warranty.

### 1. Introduction

Wind energy is a promising renewable energy source abundant in resources. In recent years, Thailand has seen significant growth in the installation of new wind turbines, aimed at reducing reliance on conventional energy sources [1,2]. According to the Alternative Energy Development Plan (AEDP), the rapid growth in wind turbine installations is projected to reach 3002 MW as Thailand possesses excellent wind energy potential and other renewable energy sources. Especially in Thailand's coastal areas, there is significant potential to reduce the substantial share of non-renewable energy-based power production. Additionally, the western and eastern mountainous areas have the second-largest potential for wind energy [3–5]. Although the potential for wind energy is high in

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Thailand, the intermittency and seasonal variation in wind speed significantly impact energy production. Fluctuations in energy production create imbalances in the power distribution line, leading to issues such as overvoltage or undervoltage, which result in feeder trips or necessitate shutting down the wind power plants [6,7]. Due to the absence of an energy storage system, high-penetration wind power plants are disconnected from the distribution system to maintain grid stability and the Distribution System (DS) unless power quality issues such as harmonic distortion, voltage, and frequency variations arise [8–11]. In this study, a detailed review was conducted to understand the necessity of energy storage for wind power plants. Various aspects were explored, including wind turbine placement optimisation, renewable energy integration, potential wind assessment, optimal placement and sizing of wind turbines, energy storage systems, wind power prediction, and the impact of wind power on power systems.

Kheder-Haddouche and Saheb-Koussa assessed the wind potential in the Mecheria region of Algeria and evaluated the cost of energy production by a wind farm. They utilized ten years of wind data to identify the windiest areas, conducted various wind turbine configuration tests to determine an efficient system, and performed 40 MW grid optimisation using HOMER software to assess the economic and environmental impact [12]. Hashem et al. developed a multi-objective optimisation method to determine the optimal sizing of wind turbines and energy storage systems, aiming to reduce the high penetration of intermittent wind power. They utilized the Equilibrium Optimizer (EO) algorithm and a Loss Sensitivity Factor (LSF) as indices of distribution system performance. These methods were applied simultaneously to minimise energy loss and voltage deviation while enhancing voltage stability [13]. Various analytical and optimisation techniques are accessible for enhancing wind power system performance and energy storage efficiency. Moon et al. introduced a weighted evaluation method to identify appropriate wind farm locations, annual wind speed, power generation capacity, and system sizing aligned with the Korean government's initiative to install 17 GW. Additionally, they utilized discrete Fourier transform and probability density models to optimise Energy Storage Systems (ESS) and maintain grid stability [14]. Yan et al. developed an optimal method for sizing the ESS using a steady-state model. In this study, the prediction of wind power establishing the developed system for commercial-grade use includes further operation and maintenance to identify the economically suitable EES for local grid stability [15].

Numerous studies have conducted analyses on power forecasting, error mitigation, long-term variability of wind speed, and wind power resource assessment to optimise the EES [16–19]. Yi et al. examined different operating strategies to optimise the EES capacity, EES lifetime, wind curtailment, and profits. Comparatively, the dynamic control strategy extended the EES's lifetime to 13.39 years, achieving a notably higher profit of 717,207.44 USD. Optimised EES maintains zero overcharging or discharging, making operations 81.85 % efficient, cost-effective, reliable, extending profit, and storing energy [20]. Felix et al. [21] performed an EES optimisation in hourly intervals to meet the electricity bidding in Australia. This study simulates one year of GIS data to generate power through various renewable energy sources. Following the simulation findings, they developed 55 MW battery storage systems capable of discharging over 12 h (110 MWh). The assistance of EES significantly reduced the LCOE by 13–23 %.

Flexi et al., researchers in Portugal have developed Battery Energy Storage System (BESS) integration strategies to reduce power curtailment while harnessing various renewable energy sources. This study utilises unit commitment and economic dispatch algorithms to optimise the system. The total load demand for the selected location stands at 35 MW, with installed capacities from thermal power plants, wind, hydro-geothermal, and waste-to-energy sources amounting to 47.6 MW, 12.6 MW, 1.4 MW, 3 MW, and 1.7 MW, respectively. As mentioned earlier, renewable energy sources often face challenges in providing stable power production due to climate variability. By integrating BESS with non-conventional energy systems, this approach significantly reduces the annual consumption of 1500 tons of oil. Sensitivity analysis reveals that integrating a 1500 KW and 6300 kWh BESS is a cost-effective solution for the examined location, leading to a remarkable 59 % reduction in renewable energy curtailment [22].

Xin et al. [23] developed a Battery Energy Storage System (BESS) to mitigate the uncertainty of wind production in China's varying climatic conditions. They conducted a day-ahead simulation using a Model Predictive Control (MPC) method, validated the results with real-time data, and found that integrating BESS significantly enhances grid stability and accuracy compared to a myopic controller. Furthermore, they discovered that BESS is economically viable with a reserve State of Charge (SOC) of 0.1, as any increase beyond this threshold results in reduced profitability.

In a separate study, Chen et al. [24] addressed wind energy curtailment in China's unpredictable climate. Without BESS, wind energy curtailment reached 40.16 % due to the high variation and unpredictability of wind speeds. To tackle this issue, Chen et al. developed an optimisation technique using a CPLEX solver, aiming to reduce wind energy curtailment and enhance the efficiency of China's wind energy production. This study employs a sodium-sulfur battery as BESS and Phase Change Material (PCM) to reduce the battery operating temperature during peak charging/discharging [25–27]. Utilized the removed temperature from the battery for building thermal applications and enhanced the battery's performance by reducing thermal stress. BESS and PCM reduced wind energy curtailment to 13.70 % and reduced conventional combined heat and power plant operation by 5 %, respectively.

Watson et al. developed a 2 MWh Battery Energy Storage System (BESS) for Canada's 10 MW research and development wind energy institute to reduce their reliance on the conventional grid during periods of low wind. The wind farm's annual energy production was 40 GWh, which was primarily exported to the grid. However, during low wind periods, the wind farm had to draw approximately 13 MWh from the grid to power the institute. This practice not only increased the grid load consumption but also led to low grid voltage levels. By implementing the BESS, the wind farm was able to reduce its grid dependence significantly. Specifically, during a 339-h low wind speed period, which accounted for approximately 63 % of the energy consumption, the BESS played a crucial role in stabilizing the institute's power needs and alleviating stress on the grid [28]. Ikni et al. examined lithium-ion BESS with a 300 MW offshore wind farm to maintain the grid frequency stable during the power fluctuation caused by unaccounted wind speed. Within 600 s, wind turbine power generations widely oscillate between 130 and 180 MW, which causes a mismatch in the grid frequency code. Incorporating a 30 MW lithium-ion, BESS remarkably maintained the grid feeding voltage and frequency code, reducing the feeder trip and power curtailment [29].

**Table 1**
Recent literature study of wind farms associated with BESS.

| Wind farm capacity | Location | Study platform | EES capacity | Description | Reference |
|---|---|---|---|---|---|
| 481.5 MW | Spain | MATLAB/Simulink | 50 MWh | BESS is used for wind turbine frequency matching to stabilise the grid voltage. | [33] |
| 3.6 MW | Taiwan | Simulation | 0.72 MW | Wind gusts, crescendos, and random wind strategies are employed to smooth wind power production. | [34] |
| 3 MW | India/Korea | Simulation | 500 Ah | A Neuro-fuzzy inference hybrid controller monitors the wind turbine and BESS for power filtering. | [35] |
| Two multi-MW | Greece | Simulation | 94 Ah | Wind speed and related data are collected from the EUNICE ENERGY GROUP (EEG) to optimise the BESS using the discrete wavelet transform method. | [36] |
| 160 MW | Iran | Analytical model (Simulation) | 21–80 MWh | Optimal BESS is calculated based on the one-year wind farm data, and different scenarios such as optimum method, total compensation, and no compensation are considered in optimising the BESS. | [37] |
| 5.950 MW | Cape Verde | Autoregressive Integrated Moving Average (ARIMA) | 9 MWh | A combination of ARIMA forecasting with BESS improved the grid reliability. | [38] |
| 60 MW and 45 MW | Mongolia and Sinkiang | Simulation | 2.01 MW and 1.34 MW | The proposed wind power prediction model aims to reduce power production errors using a modified statistical distribution model. | [39] |
| 9 MW | France | Simulation | 36 MWh | Simulation is conducted for four cases to optimise BESS capacity, minimise wind power curtailment, and improve BESS lifetime. | [40] |
| 100 kW | India | Simulation | 24 kWh | The Inherited Competitive Swarm Optimisation (ICSO) algorithm improves the BESS performance with wind turbine and load regulation. | [41] |
| 8 MW | Thailand | Power flow algorithm (DigSILENT simulation) | 5 MWh (Li-ion) | We collect wind speed and other site data from the 8 MW wind farm SubPlu 1 in Nakhon Ratchasima province, Thailand, to optimise the BESS capacity using DigSILENT.<br>Monthly prioritisation of feeder trips is conducted to determine the optimal solution for reducing overvoltage problems in the existing 8 MW wind farm.<br>A comparative study is performed for an 8 MW wind farm using with and without 5 MWh BESS. | Present study |

Dratsas et al. performed a feasibility study of incorporating the BESS for small islands to maintain grid stability and attain energy generation through non-conventional systems. The islands are primarily rich in wind energy, but the wind speed and power generation stability are not attractive compared to other renewable energy systems. During low wind periods, operators often compensate for power curtailments with diesel engines. Utilizing BESS as an auxiliary power generator reduces 42.75 % of the wind curtailments, amounting to 1442.8 MWh/year [30]. BESS are widely employed with wind turbines to avoid power curtailment and regulate the grid frequency. As mentioned earlier, wind power productions are unpredictable and fail to match the forecasted power generation, resulting in grid load mismatch and causing voltage flotation [31].

The wind farm maintained a power factor of unity for most of the period, depending on the availability of BESS capacity. The overall performance of the wind farm increased by 3.97 % compared to unsmoothed power feeding from the wind farm without BESS [32].

The above literature review and Table 1 emphasise the critical role of energy storage systems in enhancing the efficiency and reliability of wind power systems. The strategic placement and coordinated control of wind turbines and energy storage systems (ESS) in a distribution network are vital for maintaining stability and reliability during operation. Numerous studies have explored analytical and optimisation techniques to size and place energy storage systems effectively. These studies have demonstrated the efficacy of their approaches in reducing energy losses, managing congestion and voltage deviations, and enhancing the stability and controllability of wind power systems. Research findings consistently support the benefits of hybrid electricity generation systems, which combine wind energy and energy storage. Such systems prove advantageous for both the wind farm and the end-users within the distribution network. In the context of this study, a Battery Energy Storage System (BESS) was developed to mitigate fluctuations in electricity generation from an operational 8 MW commercial-scale onshore wind farm in Nakhon Ratchasima province, Thailand, as illustrated in Fig. 1 (a) and Fig. 1 (b). The primary purpose of developing the BESS is to reduce feeder trips by controlling the overvoltage and improving power quality through ramp control. The main objective of this study is as follows.

- Real-time data from an operational 8 MW commercial-scale onshore wind farm (Nakhon Ratchasima province, Thailand) is collected to analyse the nature of wind speed, wind directions and frequencies and the annual feeder trip.
- The high feeder trip period (September) is selected to optimise BESS capacity to simplify operations. DigSILENT simulation is performed with the lowest grid load of 10 %, varying BESS capacity from 1 to 5 MWh in 1 MWh increments.
- A comparative study is performed for wind turbine voltage and power productions using different BESS to optimise the suitable BESS for the operational wind farm.

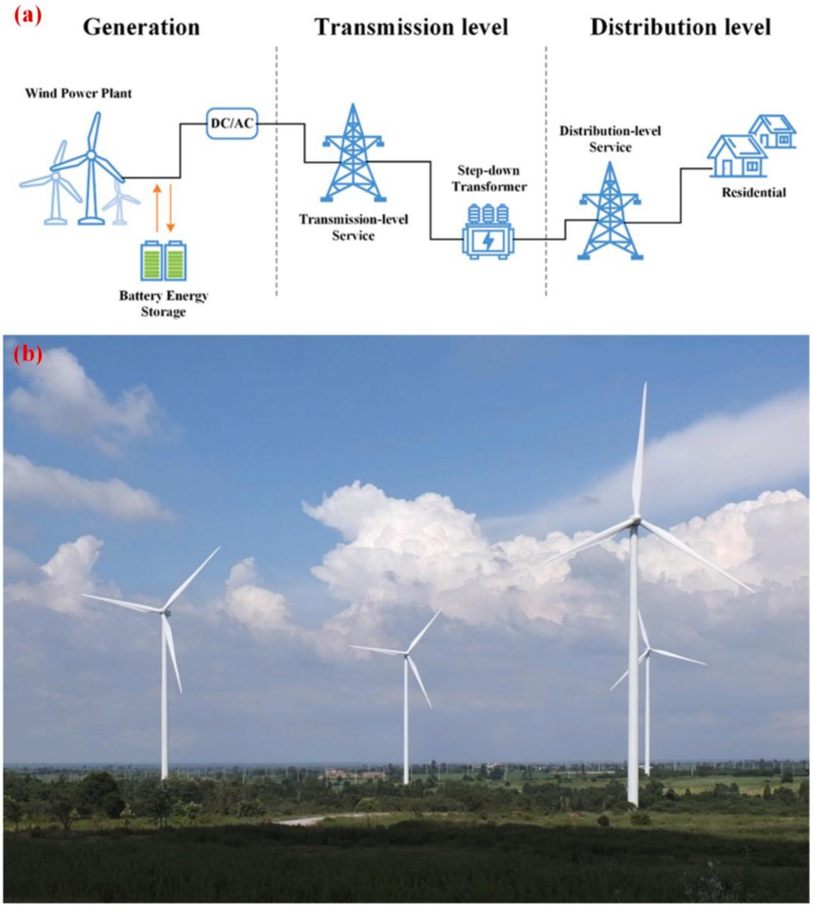


**Fig. 1.** (a) Conceptual diagram of BESS with wind power plant and (b) real-time view of 8 MW wind farm SubPlu 1, Nakhon Ratchasima province.

**Table 2**
Specification of wind turbine and BESS.

| Description | Range |
|---|---|
| Wind turbine type | Doubly Fed Induction Generator |
| Rated power | 2 MW |
| Cut-in wind speed | 2.5 m/s |
| Rated wind speed | 10 m/s |
| Cut-out wind speed | 25 m/s |
| Survival wind speed | 60 m/s |
| Battery type | Lithium Ion |
| BESS capacity | 5 MWh/2 MW |
| Depth of Discharge (DOD) | 90 % |
| State of Charge (SOC) | 95 % |

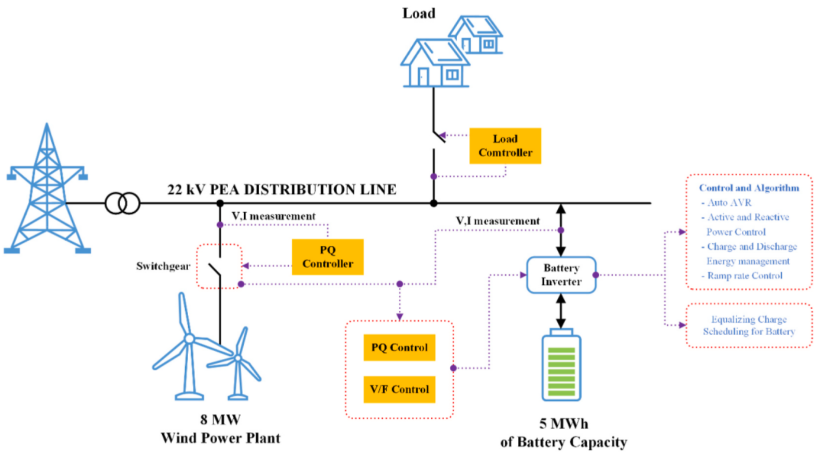


**Fig. 2.** Energy management system for BESS with a wind power plant.

- Further, the optimised BESS is performed for low and high wind speed periods to obtain the stability of the BESS in controlling the feeder trip and power generation.

## 2. Materials and methods

This study introduced a Battery Energy Storage System (BESS) for Wind Farm SubPlu 1, an operational 8 MW commercial-scale onshore wind farm located in Nakhon Ratchasima province, Thailand (refer to Table 2). The energy management system is designed to monitor the power production of the wind farm as well as the grid voltage. Over-voltage issues primarily arise under two conditions: when the wind turbine generates more power than expected and when there is a decrease in load demand. In both cases, the BESS effectively maintains the grid voltage within an allowable range, as specified by the Provincial Electricity Authority (PEA). By ensuring that the voltage fed into the grid remains within the permissible range, the stability of the power distribution system is preserved, and feeder trips are kept within the limits set by the wind turbine manufacturers. This integration of BESS with wind power plants not only enhances the stability of the system but also improves the overall power quality in the distribution network. For a visual representation, please refer to Fig. 2 for the schematic view of the wind farm with BESS and Fig. 3 for an overview of the research methodology.

### 2.1. Data collection and methods

Data collected from the wind farm and Provincial Electricity Authority (PEA) include wind speed, energy yield, downtime, fault descriptions and duration, forecasted energy production, grid outage time, customer stop time, grid regulator readings, and other relevant parameters. These data points are crucial for optimising the BESS, as illustrated in Fig. 3. Initially, key parameters such as wind power, wind speed, and various wind turbine specifications are fed into DigSILENT, considering different load scenarios of 100 %, 50 %, and 10 %. This analysis aims to understand the grid voltage under varying power consumption levels in the distribution system. Based on the grid voltage profiles obtained, further simulations are carried out with a negligible load of 10 %, varying the BESS capacity from 1 MWh to 5 MWh. This iterative process is crucial for optimising the BESS capacity and ensuring compliance with PEA regulations. A comparative study is conducted, analyzing grid voltage under different BESS capacities according to PEA regulations. Additionally, the optimised BESS configurations are tested under various operating conditions of wind turbines, including high feeder trips, low wind speeds, and high wind speeds. These tests assess the reliability of BESS in reducing annual feeder trips. The implementation of State of Charge (SOC) and Depth of Discharge (DOD) protocols is crucial for efficient BESS operation. When the grid voltage is high, BESS initiates charging to prevent overloading and reduce grid voltage, subsequently minimising feeder trips. Conversely, when BESS reaches 95 % capacity, it discharges power to the grid without causing voltage spikes, ensuring a stable power supply. This continuous charging and discharging process optimises power distribution, enhances wind turbine performance, and ultimately contributes to the overall efficiency and stability of the wind power plant. By breaking down the information into smaller, organized sections, the methodology becomes more digestible for readers.

#### 2.1.1. Simulations of BESS

To develop a prototype wind farm assisted with BESS, DigSILENT Power Factory Software is used for grid voltage stability, as

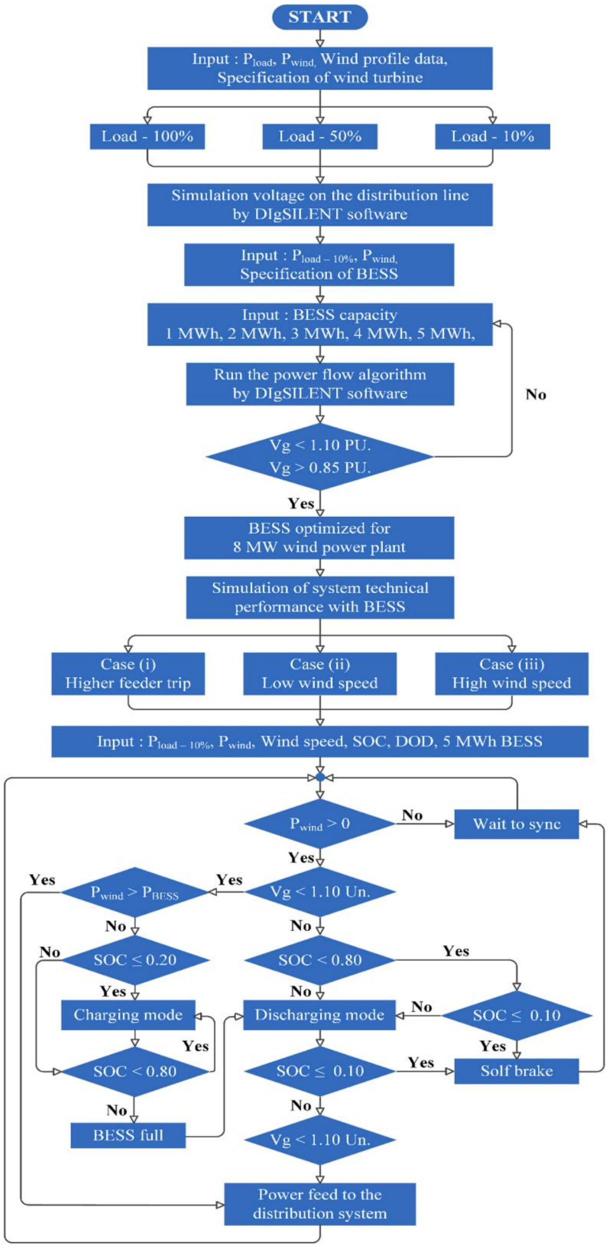


**Fig. 3.** Methodology of BESS optimisation for 8 MW wind farm.

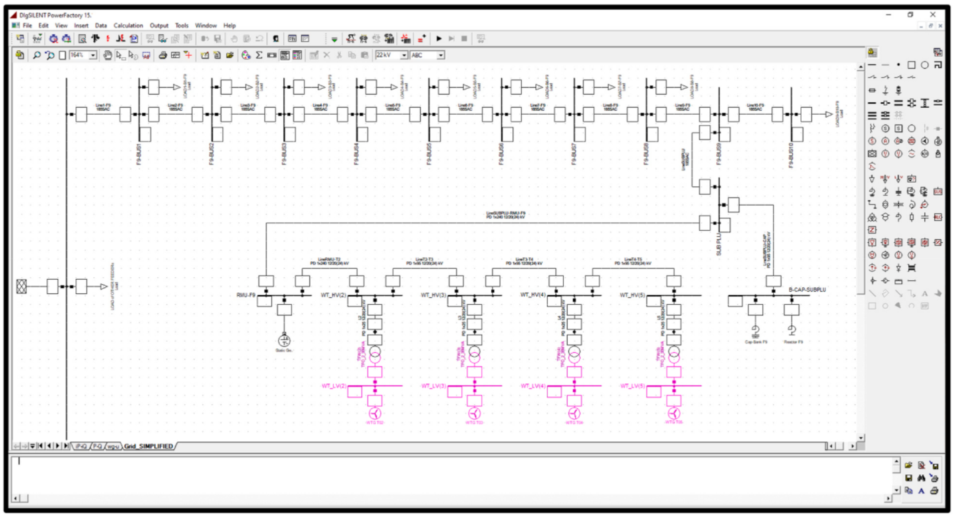

**Fig. 4.** Modelling of wind power plant with distribution network test system.

**Table 3**
The functions and details of BESS.

| Function | Details |
|---|---|
| Installed in conjunction with existing wind power plant. | It can be connected to the electrical circuit of the existing wind power plant to stabilise the grid. |
| Complies with the Regulation for Very Small Power Producers (VSPP). | Managed under the Regulation for VSPP.<br>If there is any non-compliance, it favours designing a plan with the least possible impact to propose an exemption from the Regulation for VSPP. |
| Complies with the grid connection code. | Overall, control complies with the grid connection code. |
| Prevents tripping. | BESS prevents tripping the wind power plant under various conditions within an acceptable range. |

shown in Fig. 4. The proposed system's medium voltage distribution system is divided into two parts: a medium voltage distribution test system connected with a wind power plant without BESS and a distribution test system connected with a wind power plant with BESS. DIGSILENT Power Factory software version 15.1 (research license of Naresuan University, School of Renewable Energy Technology, Thailand) simulates the voltage profiles of both systems. Furthermore, the wind farm's technical performance is analysed using the distribution system's voltage profile. Simulation is carried out with and without BESS to perform a comparative analysis. Table 3 presents the functions of the BESS."

**Feeder trip:** In this study, we develop a power flow algorithm to reduce the feeder trip using BESS. During the regular operation of the wind turbine, wind farm operators monitor various aspects, including continuous monitoring of line voltage. If the line voltage is less than 0.85 PU for 0.5 s or greater than 1.10 PU for 0.1 s or 0.2 PU for 0.1 s, the monitoring system finds the status of BESS and synchronises it with a wind turbine. Whenever the line voltage is less than 0.85 PU, BESS can discharge to the grid to increase the line voltage, but in this study, line voltage does not face less than 0.85 PU and residual voltage. Therefore, simulations analyse line overvoltage. If the BESS capacity remains to charge, a soft brake will be applied to synchronise the wind turbine and BESS. This power flow algorithm regulates wind turbine operations and reduces the feeder trip. BESS system controls the power feeding according to the regulated plant's parameters to follow the grid connection code. During the wind farm operation, if the power quality of the wind power plant is abnormal, Battery Management System (BMS) will synchronise the BESS with wind turbines to regulate the power feeding to the grid by using a soft brake/emergency brake. After that, the wind turbine will wait to sync at the grid connection point again. Fig. 5 shows the protection model for feeder trip and plant shutdown. The same wind farm operation without BESS leads to a feeder trip and emergency brake applied to protect the wind turbine.

The wind power plant has a protection system to control the power quality according to the grid connection code. It is divided into three main parts, namely under-voltage protection, over-voltage protection, and residual over-voltage protection, as listed in Table 4. The protection control system monitors the line voltage in wind farms without BESS. Wind turbines are disconnected from the grid whenever the voltage exceeds the permissible range. BESS stores excess energy from the wind turbines, controlling feeder trips and

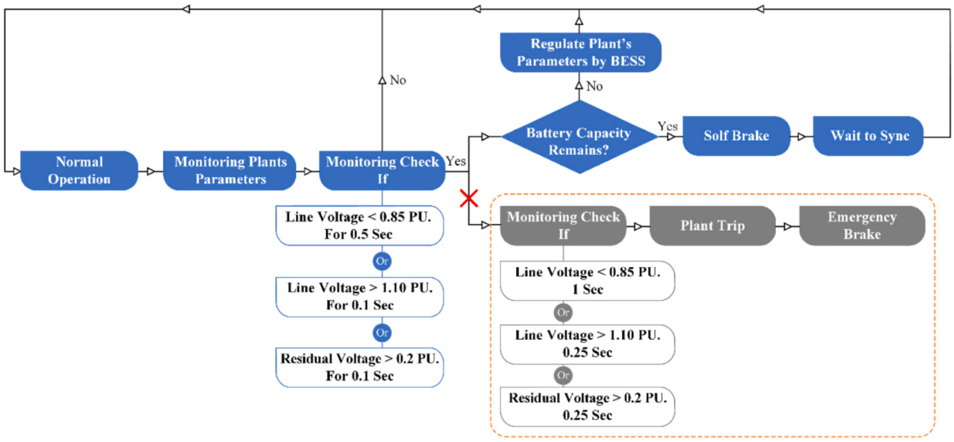


**Fig. 5.** Power flow algorithm to protect the feeder trip.

**Table 4**
The desired range of voltage for wind power plant.

| Protection Relay | Parameter | Time |
|---|---|---|
| Under Voltage Protection (27) | Line Voltage <0.85 PU | 1 Sec |
| Over Voltage Protection (59) | Line Voltage >1.10 PU | 0.25 Sec |
| Residual Over Voltage Protection (59 N) | Residual Voltage >0.2 PU | 0.25 Sec |

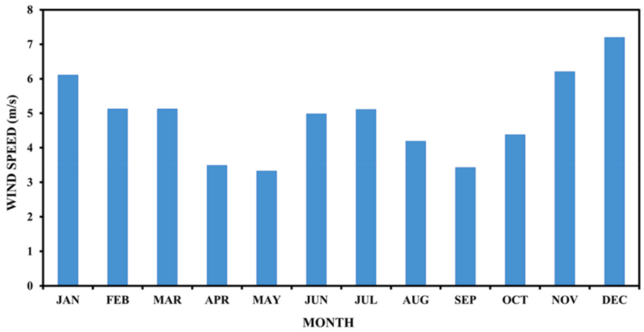


**Fig. 6.** Monthly wind speed distribution of Nakhon Ratchasima province, Thailand.

minimising wind power curtailments.

## 3. Results and discussions

The wind speed data from the 8 MW commercial-scale onshore wind farm were crucial for estimating the Battery Energy Storage System (BESS) capacity and conducting in-depth analyses, as depicted in Fig. 6. The monthly average wind speed analysis revealed the site's significant wind energy potential, with December registering the highest wind speed at 7.15 m/s. Conversely, May experienced the lowest wind speed at 3.3 m/s compared to other months. Notably, wind speeds in April, May, and September remained consistently below 4 m/s, marking these periods as low-wind seasons. In contrast, January, November, and December were identified as high-windy periods. The observed fluctuation in annual wind speeds necessitates the implementation of BESS to stabilise the

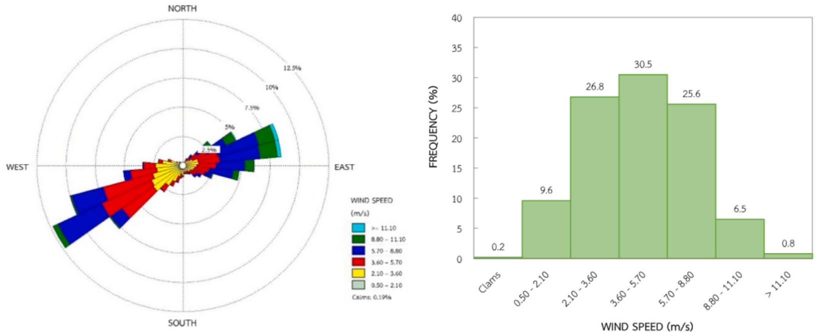


**Fig. 7.** Wind rose diagram and frequency of wind speed.

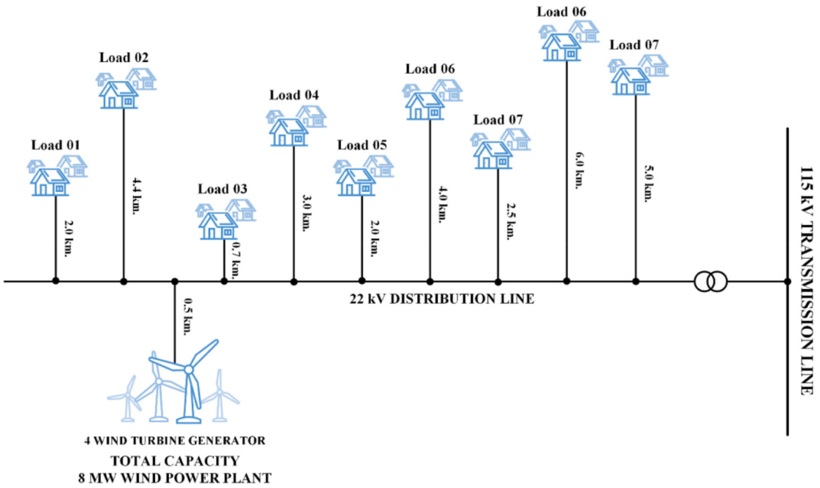


**Fig. 8.** Schematic view of 8 MW Windfarm distribution and transmission line.

distribution line without incurring penalties from the Provincial Electricity Authority (PEA) and grid authorities. The BESS system acts as a vital buffer, ensuring uninterrupted power supply during low-wind seasons and optimising energy distribution throughout the year.

Further, the annual wind speed is analysed using Lakes Environmental software to understand the nature and directions of wind flow, as shown in Fig. 7. The wind rose diagram in Fig. 7, displayed on the left-hand side, illustrates the annual wind speed directions. It is observed that winds predominantly blow from the south towards the west, indicating a higher frequency and extended periods in the north towards the east direction. Throughout most of the recorded period, wind directions were consistently in the southwest, surpassing other directions in frequency Fig. 6, right-hand side, represents the wind speed frequency; the higher frequency of 30.5 is achieved for 3.60–5.70 m/s, and the lowest frequency of 0.2 and 0.8, recorded for clams and wind speeds above 11.10 m/s, respectively. Apart from these, lower frequencies of 9.6 and 6.5 are achieved for 0.5–2.10 m/s and 8.80–11.10 m/s, respectively, and for the mid-high frequencies of 26.8 and 25.6 are achieved for 2.10–3.60 m/s and 5.70–8.80 m/s, respectively. Overall, it is found that for the selected location, the annual average wind speed is recorded to be 4.89 m/s, which shows that the eastern region of Thailand has a more significant potential for wind energy.

Fig. 8 shows the schematic view of an 8 MW wind farm on the 22 kV distribution and transmission line obtained from the Provincial Electricity Authority (PEA) since the Commercial Operation Date (COD). The wind farm is 0.5 km from the distribution line, and most loads are connected to the distribution line within the 0.7–6.0 km range before the transmission line.

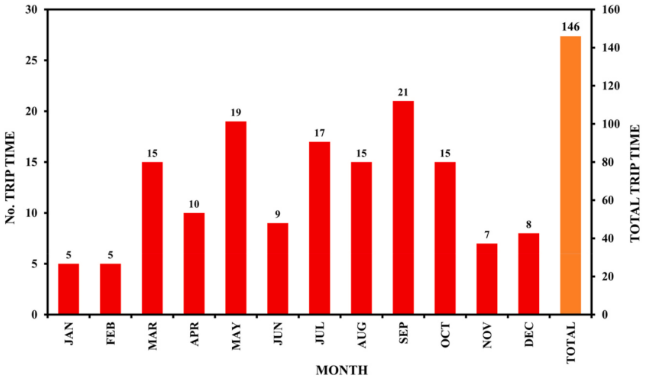


**Fig. 9.** Monthly feeder trip of 8 MW wind farm in 2021.

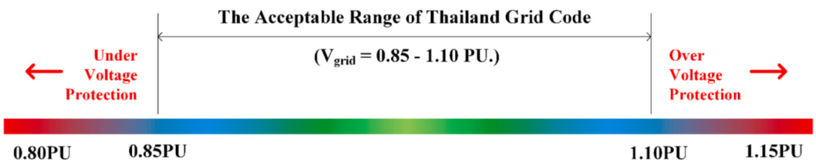


**Fig. 10.** Thailand's grid code for under, over, and acceptable voltage range.

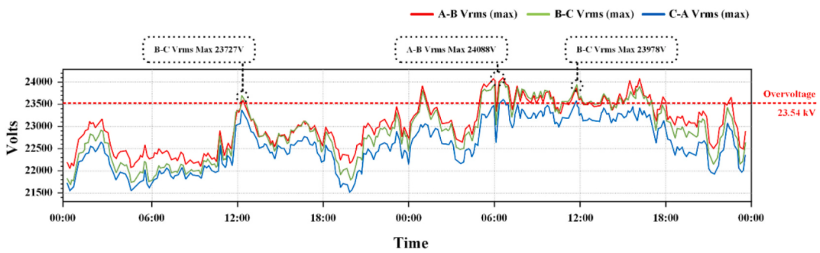


**Fig. 11.** Voltage profile of 8 MW wind farm (three phases) on 22 kV distribution line.

The primary challenge faced by the 8 MW wind farm is frequent feeder trips caused by unpredictable fluctuations in load demand and wind power production. These fluctuations lead to overvoltage and voltage dips, triggering feeder trips that halt the wind farm's operation. Unanticipated and increasingly frequent feeder trips render the entire system inefficient, especially considering that wind turbines come with a manufacturer's guarantee that feeder trips should not exceed 52 times per year. Based on the wind farm's operation data from 2021, the number of feeder trips exceeded the allowable limit. Fig. 9 illustrates the monthly variation in feeder trips recorded at the wind farm, providing crucial insights into the urgency of implementing a Battery Energy Storage System (BESS). The lowest number of feeder trips occurred in January and February, while the highest was observed in May and September, reaching 19 and 21 times, respectively. The total annual feeder trips amounted to 146 times, nearly double the permissible range, highlighting the pressing need for a solution to this issue. Fig. 10 shows the allowable voltage range of Thailand's grid code. The wind turbine's voltage feed is strictly monitored to maintain a stable frequency in the transmission and distribution system. Whenever the wind turbine voltage production is higher than 1.10 Vn, it is considered a harmful threat to the load, resulting in the protection control system automatically tripping the feeder, and the wind farm shuts until the grid voltages are within an allowable range. Due to massive disruption in feeder trips, wind farms faced several economic complications from grid authority and PEA.

In this study, the focus lies primarily on over-voltage faults as they are the predominant challenges encountered by the 8 MW wind

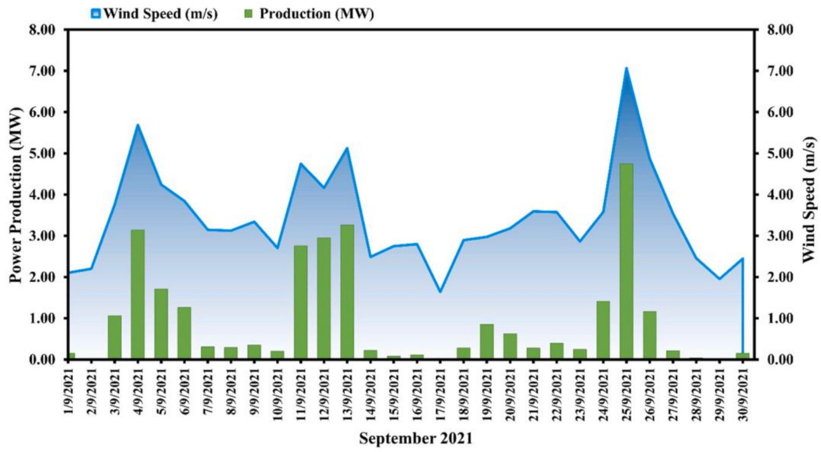


**Fig. 12.** Monthly average wind speed and power production (September 2021).

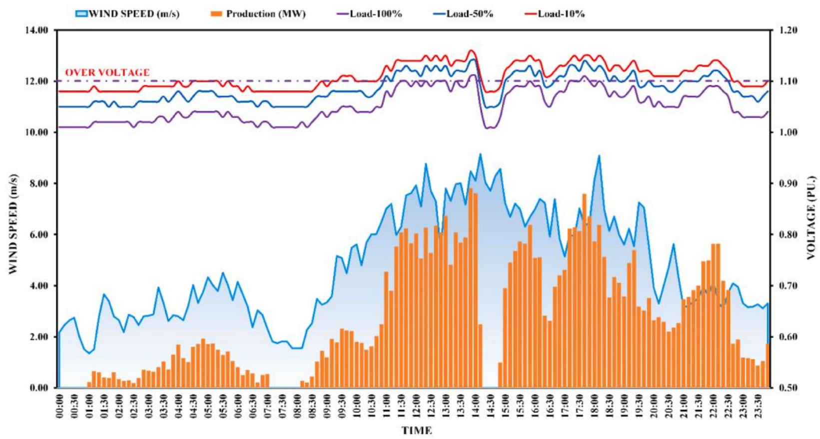


**Fig. 13.** Voltage profile on distribution system under different load conditions.

farm during its operational period. Over-voltage protection faults are prevalent, prompting an in-depth analysis compared to low and residual voltage faults. To gain a deeper understanding of the wind farm's characteristics, a specific day's three-phase voltage profile is presented in Fig. 11. Throughout the working day, slight oscillations were observed in all three phases. Notably, A-B Vrms and B–C Vrms experienced overvoltage conditions, peaking at 24088 V and 23978 V, respectively. In contrast, C-A Vrms maintained a stable voltage profile under overvoltage conditions throughout the day. Notably, whenever the other phases reached over-voltage levels, automatic feeder trips were triggered.

To address these over-voltage challenges, different Battery Energy Storage System (BESS) capacities were tested in real-time scenarios, focusing on three specific cases: periods of higher feeder trips, low wind speeds, and high wind speeds. These tests were conducted to develop effective strategies for controlling overvoltage faults and enhancing the wind farm's overall stability and performance.

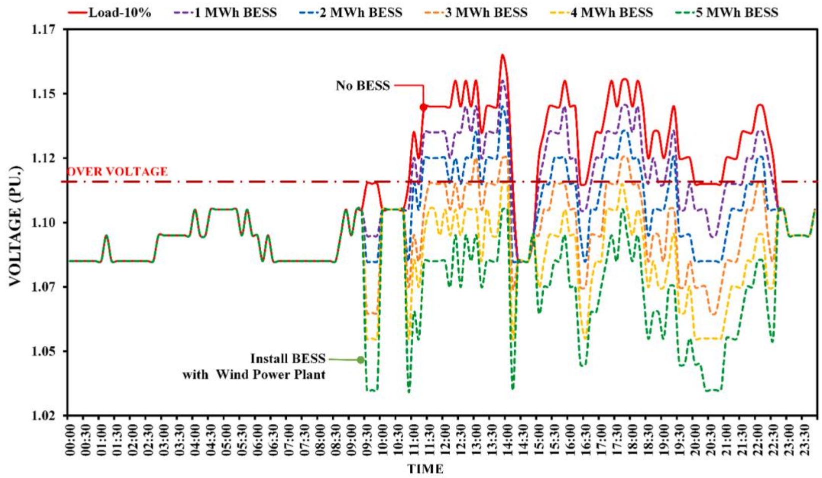


**Fig. 14.** Comparative analysis of grid voltage with different BESS.

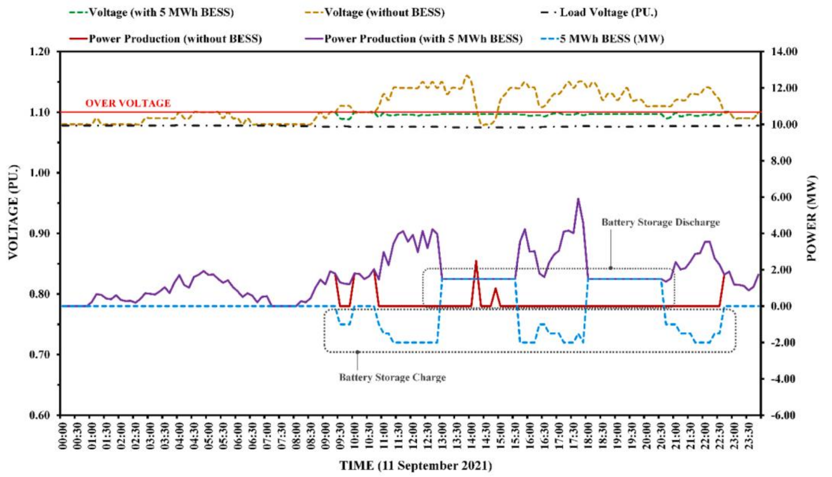


**Fig. 15.** The relationship between grid voltage and power production of 8 MW wind farm using with and without BESS (September 11, 2021).

### *3.1. Case (i): higher feeder trip period*

In Fig. 12, the wind speed and power production data for September are depicted. On most days, power production remains below 1 MW due to low wind speeds. The highest wind speed recorded was 7.07 m/s, correlating with a power production of 4.75 MW. However, the wind turbine's power generation often falls below the permissible limit defined by the Provincial Electricity Authority (PEA). When this occurs, the wind farm experiences higher grid voltage, surpassing the acceptable range. Consequently, the wind turbine fails to feed power into the grid, leading to feeder trips and shutting down the entire wind power plant operation. To gain insights into the nature of these feeder trips, a specific day with a recorded feeder trip was selected for simulation using DigSILENT, as shown in Fig. 13. The simulation was conducted under different load operating conditions of 100 %, 50 %, and 10 %. During 100 % load, the wind farm's voltage profile remained within the acceptable overvoltage range for most of the period. However, in practical

**Table 5**
Summarised view of grid voltage, power production, BESS capacity and production for using BESS and without BESS.

| Time | Grid voltage (PU.) | | | | | | Power (MW) | | | | | | BESS capacity (MW) | | | Energy production (MWh) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Without BESS | | | With BESS | | | Without BESS | | | With BESS | | | | | | Without BESS | | | With BESS | | |
| | Case (i) | Case (ii) | Case (iii) | Case (i) | Case (ii) | Case (iii) | Case (i) | Case (ii) | Case (iii) | Case (i) | Case (ii) | Case (iii) | Case (i) | Case (ii) | Case (iii) | Case (i) | Case (ii) | Case (iii) | Case (i) | Case (ii) | Case (iii) |
| 00:00 | 1.08 | 1.08 | 1.16 | 1.08 | 1.08 | 1.10 | 0.00 | 0.33 | 0.00 | 0.00 | 0.33 | 6.12 | 0.00 | 0.00 | −1.50 | 10.40 | 21.30 | 0.58 | 38.74 | 21.63 | 77.25 |
| 00:30 | 1.08 | 1.10 | 1.10 | 1.08 | 1.10 | 1.10 | 0.00 | 1.49 | 1.87 | 0.00 | 1.49 | 1.85 | 0.00 | 0.00 | 0.00 | | | | | | |
| 01:00 | 1.08 | 1.10 | 1.13 | 1.08 | 1.10 | 1.10 | 0.22 | 2.01 | 0.00 | 0.22 | 2.01 | 2.81 | 0.00 | 0.00 | −1.50 | | | | | | |
| 00:30 | 1.08 | 1.08 | 1.15 | 1.08 | 1.08 | 1.10 | 0.42 | 0.51 | 0.00 | 0.42 | 0.51 | 4.57 | 0.00 | 0.00 | −2.00 | | | | | | |
| 02:00 | 1.08 | 1.09 | 1.16 | 1.08 | 1.09 | 1.10 | 0.34 | 0.90 | 0.00 | 0.34 | 0.90 | 6.18 | 0.00 | 0.00 | −1.50 | | | | | | |
| 00:30 | 1.08 | 1.10 | 1.15 | 1.08 | 1.10 | 1.10 | 0.19 | 1.58 | 0.00 | 0.19 | 1.58 | 4.79 | 0.00 | 0.00 | −2.00 | | | | | | |
| 03:00 | 1.09 | 1.09 | 1.14 | 1.09 | 1.09 | 1.10 | 0.68 | 1.14 | 0.00 | 0.68 | 1.14 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 00:30 | 1.09 | 1.09 | 1.14 | 1.09 | 1.09 | 1.10 | 1.04 | 1.38 | 0.00 | 1.04 | 1.38 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 04:00 | 1.10 | 1.09 | 1.16 | 1.10 | 1.09 | 1.10 | 1.70 | 1.12 | 0.00 | 1.70 | 1.12 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 00:30 | 1.10 | 1.09 | 1.14 | 1.10 | 1.09 | 1.10 | 1.60 | 0.89 | 0.00 | 1.60 | 0.89 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 05:00 | 1.10 | 1.08 | 1.15 | 1.10 | 1.08 | 1.10 | 1.71 | 0.40 | 0.00 | 1.71 | 0.40 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 00:30 | 1.09 | 1.10 | 1.16 | 1.09 | 1.10 | 1.10 | 1.29 | 3.14 | 0.00 | 1.29 | 3.14 | 6.18 | 0.00 | 0.00 | −1.50 | | | | | | |
| 06:00 | 1.09 | 1.10 | 1.14 | 1.09 | 1.10 | 1.10 | 0.81 | 3.39 | 0.00 | 0.81 | 3.39 | 3.49 | 0.00 | 0.00 | −2.00 | | | | | | |
| 06:30 | 1.08 | 1.10 | 1.14 | 1.08 | 1.10 | 1.10 | 0.57 | 1.94 | 0.00 | 0.57 | 1.94 | 3.73 | 0.00 | 0.00 | −2.00 | | | | | | |
| 07:00 | 1.08 | 1.10 | 1.16 | 1.08 | 1.10 | 1.10 | 0.54 | 2.01 | 0.00 | 0.54 | 2.01 | 6.24 | 0.00 | 0.00 | −1.50 | | | | | | |
| 07:30 | 1.08 | 1.09 | 1.15 | 1.08 | 1.09 | 1.10 | 0.00 | 1.33 | 0.00 | 0.00 | 1.33 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 08:00 | 1.08 | 1.11 | 1.15 | 1.08 | 1.08 | 1.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 1.49 | 0.00 | −1.00 | 1.50 | | | | | | |
| 08:30 | 1.08 | 1.10 | 1.16 | 1.08 | 1.10 | 1.10 | 0.44 | 0.95 | 0.00 | 0.44 | 0.95 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 09:00 | 1.09 | 1.10 | 1.16 | 1.09 | 1.10 | 1.10 | 1.20 | 0.90 | 0.00 | 1.20 | 0.90 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 09:30 | 1.11 | 1.08 | 1.10 | 1.09 | 1.08 | 1.10 | 0.00 | 0.00 | 1.62 | 1.31 | 0.00 | 1.49 | −1.00 | 0.00 | 1.50 | | | | | | |
| 10:00 | 1.10 | 1.08 | 1.16 | 1.10 | 1.08 | 1.10 | 1.80 | 0.00 | 0.00 | 1.80 | 0.00 | 1.49 | 0.00 | 0.00 | 1.50 | | | | | | |
| 10:30 | 1.10 | 1.09 | 1.16 | 1.10 | 1.09 | 1.10 | 1.64 | 0.89 | 0.00 | 1.64 | 0.89 | 6.25 | 0.00 | 0.00 | −1.50 | | | | | | |
| 11:00 | 1.13 | 1.09 | 1.16 | 1.09 | 1.09 | 1.10 | 0.00 | 0.96 | 0.00 | 2.98 | 0.96 | 6.18 | −1.50 | 0.00 | −1.50 | | | | | | |
| 11:30 | 1.14 | 1.10 | 1.16 | 1.09 | 1.10 | 1.10 | 0.00 | 1.45 | 0.00 | 3.97 | 1.45 | 6.20 | −2.00 | 0.00 | −1.50 | | | | | | |
| 12:00 | 1.14 | 1.10 | 1.16 | 1.09 | 1.10 | 1.10 | 0.00 | 1.72 | 0.00 | 3.92 | 1.72 | 6.14 | −2.00 | 0.00 | −1.50 | | | | | | |
| 12:30 | 1.14 | 1.09 | 1.15 | 1.09 | 1.09 | 1.10 | 0.00 | 1.37 | 0.00 | 3.19 | 1.37 | 6.01 | −2.00 | 0.00 | −1.50 | | | | | | |
| 13:00 | 1.15 | 1.09 | 1.14 | 1.09 | 1.09 | 1.10 | 0.00 | 1.03 | 0.00 | 1.49 | 1.03 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 13:30 | 1.14 | 1.09 | 1.14 | 1.09 | 1.09 | 1.10 | 0.00 | 0.84 | 0.00 | 1.49 | 0.84 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 14:00 | 1.15 | 1.11 | 1.13 | 1.09 | 1.08 | 1.10 | 0.00 | 0.00 | 0.00 | 1.49 | 0.18 | 1.49 | 1.50 | −1.00 | 1.50 | | | | | | |
| 14:30 | 1.08 | 1.08 | 1.13 | 1.09 | 1.08 | 1.10 | 0.00 | 0.50 | 0.00 | 1.49 | 0.50 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 15:00 | 1.12 | 1.08 | 1.12 | 1.09 | 1.08 | 1.10 | 0.00 | 0.00 | 0.00 | 1.49 | 0.00 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 15:30 | 1.14 | 1.08 | 1.12 | 1.09 | 1.08 | 1.09 | 0.00 | 0.00 | 0.00 | 1.49 | 0.00 | 2.02 | 1.50 | 0.00 | −1.50 | | | | | | |
| 16:00 | 1.14 | 1.08 | 1.12 | 1.09 | 1.08 | 1.09 | 0.00 | 0.00 | 0.00 | 2.99 | 0.00 | 2.14 | −2.00 | 0.00 | −1.50 | | | | | | |
| 16:30 | 1.11 | 1.08 | 1.12 | 1.09 | 1.08 | 1.10 | 0.00 | 0.05 | 0.00 | 1.60 | 0.05 | 2.32 | −1.00 | 0.00 | −1.00 | | | | | | |
| 17:00 | 1.13 | 1.08 | 1.11 | 1.09 | 1.08 | 1.09 | 0.00 | 0.02 | 0.00 | 3.05 | 0.02 | 1.74 | −1.50 | 0.00 | −1.00 | | | | | | |
| 17:30 | 1.14 | 1.08 | 1.11 | 1.09 | 1.08 | 1.09 | 0.00 | 0.43 | 0.00 | 4.02 | 0.43 | 1.53 | −2.00 | 0.00 | −1.00 | | | | | | |
| 18:00 | 1.14 | 1.08 | 1.11 | 1.09 | 1.08 | 1.09 | 0.00 | 0.05 | 0.00 | 1.49 | 0.05 | 1.75 | 1.50 | 0.00 | −1.00 | | | | | | |
| 18:30 | 1.12 | 1.08 | 1.11 | 1.09 | 1.08 | 1.10 | 0.00 | 0.30 | 0.00 | 1.49 | 0.30 | 1.89 | 1.50 | 0.00 | −1.00 | | | | | | |
| 19:00 | 1.12 | 1.09 | 1.13 | 1.09 | 1.09 | 1.10 | 0.00 | 1.30 | 0.00 | 1.49 | 1.30 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 19:30 | 1.12 | 1.08 | 1.13 | 1.09 | 1.08 | 1.10 | 0.00 | 0.49 | 0.00 | 1.49 | 0.49 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 20:00 | 1.11 | 1.08 | 1.12 | 1.09 | 1.08 | 1.10 | 0.00 | 0.12 | 0.00 | 1.49 | 0.12 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 20:30 | 1.11 | 1.08 | 1.13 | 1.09 | 1.08 | 1.10 | 0.00 | 0.41 | 0.00 | 1.49 | 0.41 | 1.49 | 1.50 | 0.00 | 1.50 | | | | | | |
| 21:00 | 1.12 | 1.09 | 1.15 | 1.09 | 1.09 | 1.10 | 0.00 | 0.68 | 0.00 | 2.43 | 0.68 | 1.49 | −1.00 | 0.00 | 1.50 | | | | | | |
| 21:30 | 1.13 | 1.09 | 1.15 | 1.09 | 1.09 | 1.10 | 0.00 | 1.15 | 0.00 | 2.44 | 1.15 | 5.76 | −1.50 | 0.00 | −1.50 | | | | | | |
| 22:00 | 1.14 | 1.10 | 1.16 | 1.09 | 1.10 | 1.10 | 0.00 | 1.58 | 0.00 | 3.54 | 1.58 | 6.19 | −2.00 | 0.00 | −1.50 | | | | | | |
| 22:30 | 1.12 | 1.08 | 1.16 | 1.09 | 1.08 | 1.10 | 0.00 | 0.00 | 0.00 | 2.28 | 0.00 | 6.25 | −1.50 | 0.00 | −1.50 | | | | | | |
| 23:00 | 1.09 | 1.09 | 1.16 | 1.09 | 1.09 | 1.10 | 1.19 | 1.12 | 0.00 | 1.19 | 1.12 | 6.25 | 0.00 | 0.00 | −1.50 | | | | | | |
| 23:30 | 1.09 | 1.09 | 1.16 | 1.09 | 1.09 | 1.10 | 0.87 | 0.90 | 0.00 | 0.87 | 0.90 | 6.25 | 0.00 | 0.00 | −1.50 | | | | | | |

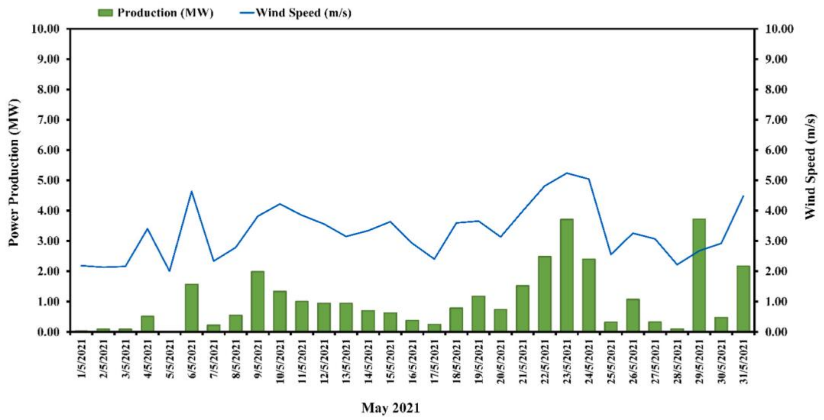


**Fig. 16.** Monthly average wind speed and power production (May 2021).

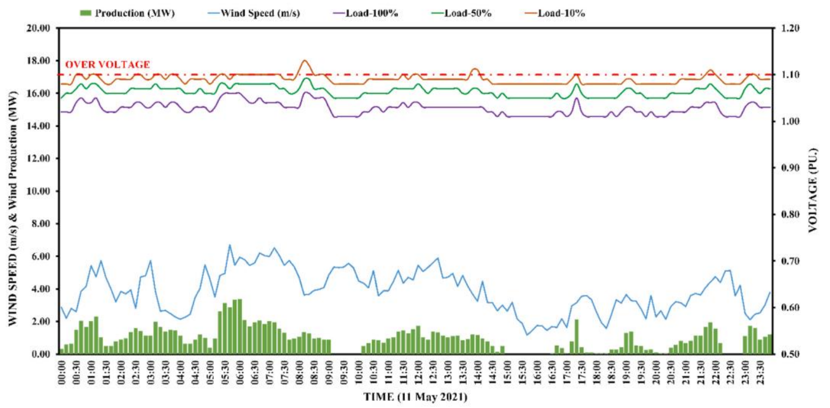


**Fig. 17.** Selected feeder trip day from May with different load conditions.

scenarios, maintaining a constant 100 % load on the distribution line is unfeasible. When the load is reduced to 50 % and 10 % on the distribution line, overvoltage issues arise as early as 09:30, leading to the wind farm being compelled to halt power production to prevent further grid instability.

Further, to optimise the BESS capacity, a 10 % load is considered the highest feeder trip for a wind farm, and the simulation is performed using a different capacity of BESS. At 09:25, over-voltage is identified, and the feeder starts tripling and isolating the wind power production. Implementation of BESS clearly shows that grid voltage is under the over-voltage range. However, 1 MWh, 2 MWh and 3 MWh BESS are not favouring throughout the working day, and they are not suitable for 10 % grid load consumption as the grid voltage is higher than 1.10 PU, as shown in Fig. 14. Notably, 4 MWh BESS controls the over-voltage protection better than 1–3 MWh BESS; however, during the 13:45 to 14:05 and 17:30 to 17:40 period, 4 MWh BESS failed to control the grid feed voltage. Considering complete protection against the feeder trip, a 5 MWh BESS is optimised to maintain the grid feeder voltage. Comparatively, a 5 MWh BESS controls the grid voltage within or under the 1.10 PU, resulting in the feeder trip being neglected throughout the working day.

In Fig. 15, an insightful comparison between an 8 MW wind farm with and without a 5 MWh Battery Energy Storage System (BESS) is presented. As previously mentioned, the 5 MWh BESS plays a crucial role in regulating power fed into the grid during over-voltage periods. The BESS system effectively stores excess power and maintains the grid voltage within an allowable range, preventing feeder trips and ensuring uninterrupted power supply. In the absence of BESS, the wind farm experiences multiple feeder trips, disrupting power supply from 09:30 to 10:00, 10:55 to 14:10, and 14:25 to 14:40. However, with the implementation of a 5 MWh BESS,

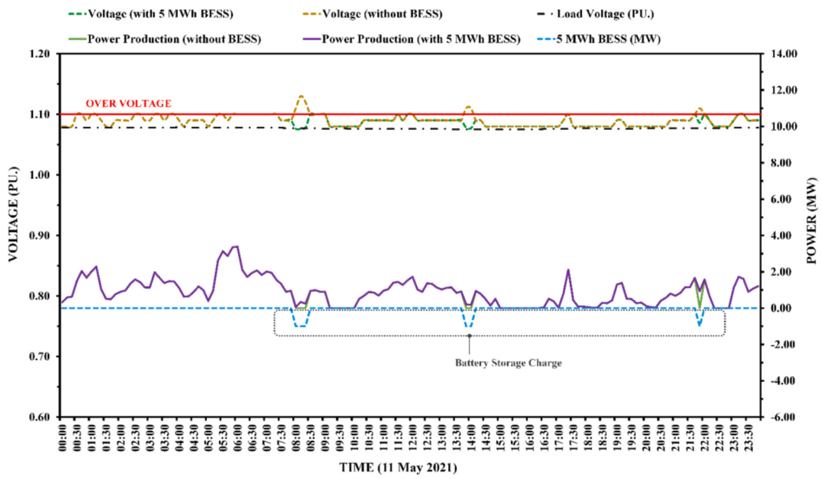


**Fig. 18.** The relationship between grid voltage and power production of 8 MW wind farm using with and without BESS (May 11, 2021).

continuous voltage feeding to the distribution line is achieved. This minimizes wind farm power curtailment, eliminates penalties from the Provincial Electricity Authority (PEA), enhances annual income, and ensures long-term system reliability. One of the significant advantages of the BESS is demonstrated during over-voltage periods. With BESS in operation, power production reaches 6 MW, effectively utilizing the excess power by initiating battery charging. Charging continues until the BESS reaches 90 % capacity. Between 13:00 and 15:40, the BESS discharges 1.5 MW to the grid, ensuring stable voltage levels. During the discharge period, wind farm operation is temporarily halted to maintain grid stability. In this study, BESS is optimised to control the feeder trip and not to store the entire overvoltage period of wind power production. BESS capacity needed to increase to store the entire wind power production, which could not be economically favorable. The second charging peak is noted between 15:30 and 18:00 and discharged from 18:00 to 20:30. Overall, it was found that BESS maintained the uninterrupted power feed to the grid and increased power production without tripping the feeder. Table 5 shows that with the help of BESS, a wind turbine can generate a power production of 38.74 MWh, whereas without BESS, it is 10.40 MWh and, comparatively, 3.7 times lower than with BESS. As mentioned earlier, wind power productions are unpredictable compared to other renewable energy systems, and it is found that when the wind turbine and BESS are not functioning, the grid voltage is nearly stable for the entire period of operations. As conventional energy generators can be easily optimised with the grid power consumption. The necessity of BESS in this study is to control the fluctuating wind power production and protect the wind turbine from feeder trips.

### 3.2. *Case (ii) low wind speed period*

The second-highest feeder trip occurred in May; on the other hand, the lowest wind speed occurred in the same month, as shown in Fig. 16. Due to low wind speed, the average power generation of the entire month is 1.04 MW, which is lower than other months, though the over-voltage causes the 19 times feeder trip. Low wind potential and higher feeder trip deteriorate the power feed during May to the grid. A selective feeder trip day from May shows the grid voltage is higher than the PEA allowable range, as shown in Fig. 17. Overall, three times overvoltage occurred during the operational hours of the wind turbines, and noticeably, it occurred during the low wind power production period. Secondly, the grid voltage is closer to the over-voltage range for most of the operating period. The over-voltage during the low wind potential period is due to low load consumption from the grid. Grid load consumption depends on the end-user, which cannot be modified, but incorporating a 5 MWh BESS can regulate the overvoltage during power production. It could reduce the feeder trip and harvest the energy produced by the wind turbine. Facing a higher feeder trip during the low wind period could minimise the economic benefit of the wind farm. It is found that a 5 MWh BESS initiates the charging mode when the grid voltage is high, resulting in the 8 MW wind farm producing the power without any interference, as shown in Fig. 18. However, in this case, BESS initiated only charging mode due to low wind speed and less power production, and the BESS did not reach the SOC (95 %) beneficial feeder trip is reduced three times. Noticeably, 0.33 MWh power production enhanced as compared to without BESS.

### 3.3. *Case (iii) high wind speed period*

As mentioned earlier, over-voltage occurs due to low load consumption and high-power production; for the selected location, December records to be the highest wind potential period with an average and peak wind speed of 7.2 m/s and 9.5 m/s, respectively, as

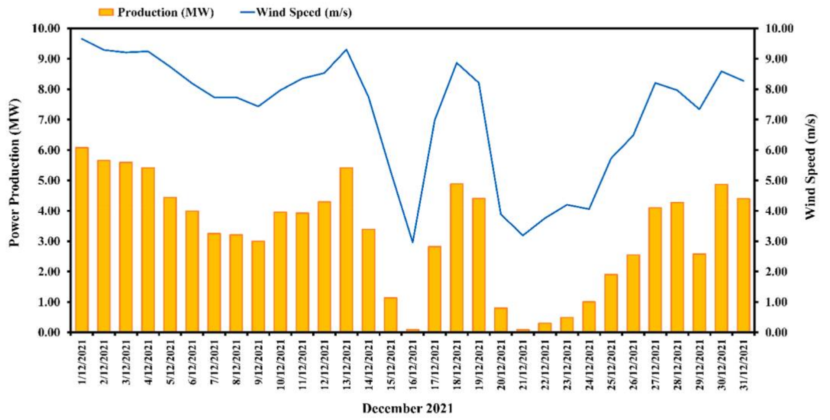


**Fig. 19.** Monthly average wind speed and power production (December 2021).

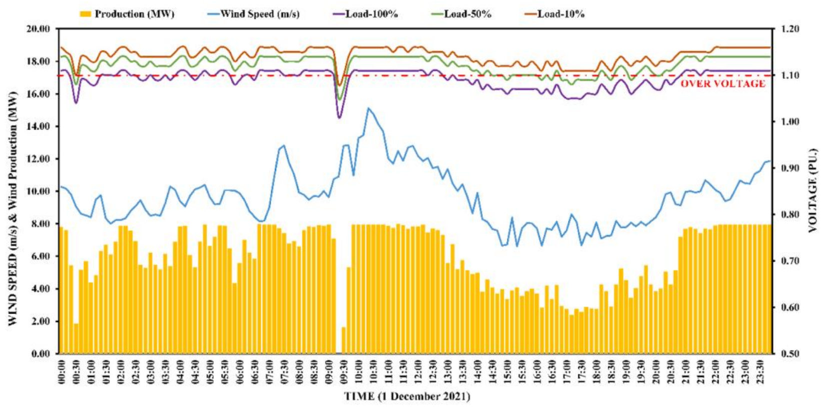


**Fig. 20.** Selected feeder trip day from December with different load conditions.

shown in Fig. 19. Furthermore, the study identified that the occurrence of feeder trips exhibits a strong negative correlation with wind speed and power production but a strong positive correlation with grid load. To delve deeper into this correlation, a specific day with selective feeder trips was chosen for analysis, as shown in Fig. 20. For instance, on December 1st, 2021, most of the wind farm's operational period power production hovering around 8 MW, corresponding to sustained wind speeds greater than or close to 10 m/s the rated wind speed of the selected wind turbine. However, even though high production was achieved on this day, the wind farm failed to feed power to the grid due to feeder trips, primarily caused by elevated grid voltage. Notably, despite the occurrence of feeder trips, the BESS played a pivotal role. During this specific day, the BESS was fully charged five times and discharged stored energy to the grid four times, as indicated in Fig. 21. During BESS discharge, stabilized power was seamlessly fed into the grid without increasing grid voltage. Consequently, the power generation of the 8 MW wind turbine increased to 77.25 MWh on this day, marking a staggering 133 times increase compared to scenarios without BESS. This illustrates the significant impact of BESS in enhancing power generation and system stability, even during challenging operational conditions. The above-mentioned three cases are summarised in Table 5 to understand the nature of the proposed study better. Integrating the 5 MWh BESS enhanced the wind farm operation by reducing the feeder trip. Overall, power generation increased for all cases, particularly for high-speed and high-feeder trip periods. This technique shows an excellent enhancement in power production and stabilized power feeding to the grid. It is concluded that a 5 MWh BESS is suitable for an 8 MW commercial-scale onshore wind farm in Nakhon Ratchasima province, Thailand, for all climatic conditions. Integrating BESS with the proposed wind farm will maintain the wind turbine manufacturer warranty, which could directly reduce the

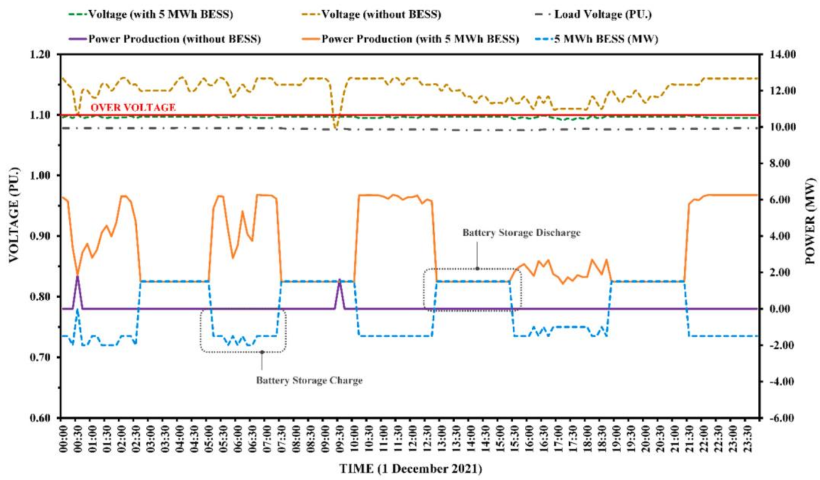


**Fig. 21.** The relationship between grid voltage and power production of 8 MW wind farm using with and without BESS (December 1, 2021).

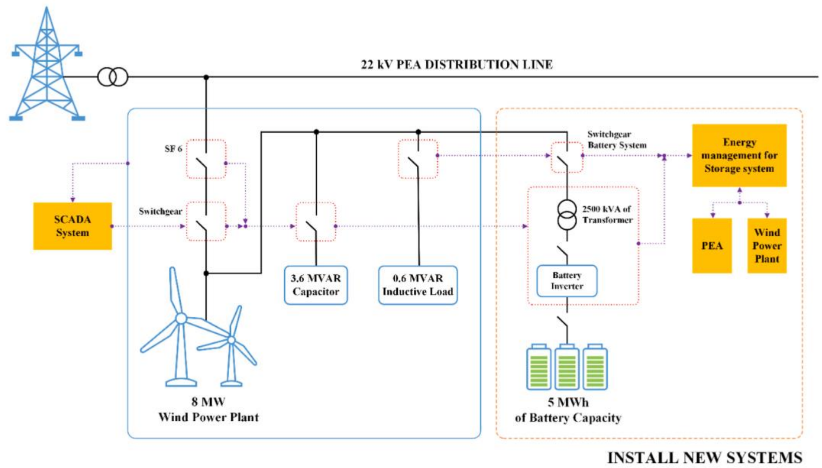


**Fig. 22.** Schematic view of 8 MW wind farm with 5 MWh BESS under real-time operation.

maintenance cost and increase the wind turbine's lifetime, resulting in economic favours for the wind farm. However, a detailed economic analysis did not perform in this study as the study's primary aim focuses on reducing the feeder trip. Further, it is recommended to implement the 5 MWh BESS with a battery inverter and energy management system to stabilise the power quality and manage the power production from the wind farm and BESS, as shown in Fig. 22.

## 4. Conclusion

The operational data from the 8 MW wind farm throughout the year highlights a significant issue: feeder trips, occurring 146 times annually, severely impacting power generation. The primary cause behind these feeder trips is overvoltage in the grid, resulting from unaccounted grid load and power production from the wind farm. Notably, in September alone, there were 21 instances of feeder trips, constituting nearly 50 % of the total annual occurrences and surpassing the limits set by the wind turbine manufacturers. To address this challenge, a Battery Energy Storage System (BESS) was integrated into the existing setup. The incorporation of BESS is not only vital for reducing feeder trips but also crucial for maintaining the warranty provided by the turbine manufacturers. In the optimisation process, this study considered a minimal grid load of 10 % and tested various BESS capacities ranging from 1 MWh to 5 MWh, with incremental steps of 1 MWh. Simulation results for a high feeder trip period revealed that BESS capacities of 1 MWh and 2 MWh managed to maintain voltage stability but failed during 24 h of selective day operations. Subsequently, BESS capacities of 3 MWh and 4 MWh exhibited improved stabilization compared to their smaller counterparts; however, feeder trips persisted despite these improvements. The simulation results conclude that the selected location is optimal for a 5 MWh BESS, demonstrating zero feeder trips. To ensure stable wind farm operation, the optimised BESS capacity is utilized during periods of low wind speed. This results in a 5 MWh BESS capable of supplying voltage to the grid without any feeder trips. However, optimising the BESS is for controlling the feeder trip and not for designing it to provide uninterrupted power to the grid during no wind power production periods. We recommend using a 5 MWh BESS to maintain grid stability with controlled voltage feed and to support wind turbine maintenance and service. A detailed economic analysis will be conducted in our future studies using with and without BESS.

## Data availability statement

Data will be made available on request.

## CRediT authorship contribution statement

**Rattaporn Ngoenmeesri:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Sirinuch Chidaruksa:** Writing – original draft, Conceptualization. **Rabian Wangkeeree:** Writing – original draft, Conceptualization. **Chatchai Sirisamphanwong:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization.

## Declaration of competing interest

All authors declare no conflict of interest.

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# Appendix B Performance Evaluation of Thailand's 8 MW Wind Farm Feeder Trip, Energy Generation, and Loss Using 5 MWh BESS—A Statistical and Economic Approach

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RESEARCH ARTICLE

## Performance Evaluation of Thailand's 8 MW Wind Farm Feeder Trip, Energy Generation, and Loss Using 5 MWh BESS–A Statistical and Economic Approach

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**ABSTRACT** In this study, an operational 8 MW wind farm was analyzed through a statistical approach to determine the wind speed and feeder trip correlation with energy loss and energy production. In December, a higher wind potential was recorded; however, a higher feeder trip was recorded during the low wind potential period of October, with a maximum duration of 1800 min. The box plot and histogram show that a higher feeder trip occurred at a wind speed of 4-6 m/s, indicating that grid voltage and load consumption were the major causes of the feeder trip. The Pearson Correlation method expressed a similar trend for feeder trips associated with energy losses that had a strong positive correlation compared to feeder trip time. To improve the stability of the wind farm's power generation, a 1-5 MWh battery energy storage system was studied to determine its impact on the grid voltage at the wind farm and the load terminals. It was found that 411071.84 kWh is enhanced for a 5 MWh battery energy storage system compared to the conventional wind farm. This enhancement in power production shows a positive correlation of grid voltage at the factory, village 1, wind farm, village 2, and village 3 with a range of 0.703, 0.873, 0.665, 0.894, and 0.896, respectively. Further, the economic analysis of the 5 MWh battery incorporation increased the annual revenue to 2825585 baht with a payback period of 7.79 years and a return on investment of 0.10 years.

**INDEX TERMS** Feeder trip, energy generation, energy loss, statistical analysis, economic benefit, payback period.

**NOMENCLATURE**

| | |
|---|---|
| ADALINE | ADAptive Linear Neuron. |
| ASFR | Aggregated System Frequency Response. |
| BCR | Benefit-Cost Ratio. |
| BESSs | Battery Energy Storage Systems. |
| DTA04 | Voltage at Factory. |
| EL | Energy Loss. |
| EP | Energy production. |
| E-o-L | End-of-Life. |
| FL | Fuzzy Logic. |
| FT-No | Feeder Trip Number/count. |
| FT-T | Feeder Trip Time. |
| GA | Genetic Algorithm. |
| IQR | Interquartile Range. |
| IRR | Internal Rate of Return. |
| Li-ion | Lithium-ion. |
| MPC | Model Predictive Control. |
| NASA | National Aeronautics and Space Administration. |
| NPC | Net Present Cost. |

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| | |
|---|---|
| NPV | Net Present Value. |
| PCC | Point of Common Coupling. |
| PCC_01 | PCC voltage at Village 1. |
| PCC_02 | PCC voltage at Village 2. |
| PCC_03 | PCC voltage at Village 3. |
| PF | Power Factor. |
| PP | Payback Period. |
| Q | Quartile. |
| RESs | Renewable Energy Sources. |
| SD | Standard Deviation. |
| Va-Red/VRB | Vanadium-Redox/Vanadium-Redox Battery. |
| VSPP | Very Small Power Producer. |
| wb | With BESS. |
| wob | Without BESS. |
| WS | Wind Speed. |
| $X_i$, $Y_i$ | individual wind power production/ loss (X) and feeder trip (Y). |
| $\bar{X}$, $\bar{Y}$ | means of wind power production/loss and feeder trip. |

## I. INTRODUCTION

Environmental pollution has become a significant concern in modern society, and 220 Mt of $CO_2$ is produced during electrical and heat energy conversion. Renewable Energy Sources (RESs) are efficient for reducing fossil fuel consumption and directly controlling pollution [1], [2]. Several RESs in practice among wind energy generation have gained popularity as they have high energy density and require less area for implementation [3], [4]. Although wind energy is an abundant resource, it fails to meet the load requirements owing to discontinuous power generation and over/low voltage productions. Voltage fluctuations occur on the variability of wind speed and are directly dependent on natural occurrence [5]. Several factors affect wind speed, such as atmospheric pressure, geographical conditions, seasonal changes in sunlight, hurricanes, and wind shear. These occurrences are not controllable, but it is predictable to solve voltage fluctuations during the grid feed [6]. Apart from natural occurrences, voltage fluctuations occur due to poor load management. During peak load demand periods, if unexpected load consumption occurs, the higher current drawn from the distribution and transmission line decreases the grid voltage. A higher grid voltage occurs when the estimated load demand is not met during the higher wind speed period [7], [8].

In most cases, the voltage regulator maintains the grid voltage within the allowable range. However, voltage regulators cannot handle sudden fluctuations in wind speed and load consumption, resulting in a lagging Power Factor (PF) [9], [10]. Battery Energy Storage Systems (BESSs) have been widely employed to overcome voltage fluctuations and reduce active power curtailment. The BESS regulates the grid frequency and smoothens the output power by storing excess energy from wind turbines [11], [12]. Subsequently, the BESS discharged when the grid voltage was lower than the predicted/actual range. The BESS favors the maintenance of grid balancing, grid resilience, and peak power shaving [13]. However, integrating a BESS with wind turbines cannot resolve the grid frequency mismatch without a proper response system. To optimize the BESS capacity, a history of the load and energy profiles is required [14].

Furthermore, wind turbine operating characteristics such as wind speed, seasonal wind variation, and other maintenance charts are required. Based on these analyses, the BESS capacity was determined using advanced energy-management systems. Prioritizing BESS's charging and discharging characteristics could reduce the active power curtailment and favor an attractive Payback Period (PP) of the system [15]. Further, this study reviewed BESS-associated wind turbines to understand their economic viability.

Optimizing BESS's capacity is a significant challenge in wind energy systems, as it requires real-time operational parameters of a wind turbine, grid network, and its distortion during distribution. Second, they determine the impact of BESS operations on grid stability and network performance [16]. The dual-power ramp strategy controls the required amount of power injected into the grid and reduces the BESS capacity [17]. ADAptive Linear Neuron (ADALINE) effectively tracks the wind farm's power production and responds quickly to power fluctuation. A dual constraint implementation to ADALINE protects against the unexpected increase/decrease in the combined power output of BESS and wind farms. This technique smoothens the 99 MW wind farm power production using a 12.13 MWh BESS [17]. Following this, multi-layer optimization techniques were developed by Jannati and Foroutan [18], considering the discontinuous/intermittent nature of wind power production. The flexible ADALINE method uses linear prediction and particle swarm optimization algorithms to monitor power production. The power feed was controlled without deteriorating the grid frequency and excess energy stored in the BESS. To compensate for the voltage fluctuation, the heuristic algorithm tracks the charging and discharging characteristics of the BESS, which helps extend its operation and lifetime.

Liu et al. [19] developed complex modeling and control strategies to understand BESS operations' nonlinear and stochastic nature, as the power and energy density are inversely proportional. Multi-objective optimization is crucial in monitoring the BESS's power and energy density, and the Model Predictive Control (MPC) mechanism regulates BESS charging and discharging to the grid. It was found that 30% of the power feed to the grid is increased, and controlled thermal management for BESS increases the operational lifetime compared to the existing BESS. Song et al. [20] developed a multi-objective optimization algorithm and categorized the process into initialization, evaluation, selection, and reproduction. This technique uses the BESS degradation rate and thermal effects to assess the system performance. Population size, crossover rate, and mutation rate play a crucial role in the operation of the

Genetic Algorithm (GA) and Fuzzy Logic (FL) to reduce uncertainty. The developed algorithm provides energy savings, increases utilization of renewable energy, and reduces peak load demand by 23.7%, 18.5%, and 15.3%, respectively.

Several studies have stated that the DIgSILENT PowerFactory is a reliable and efficient tool for optimizing BESS capacity and distributed power generation using a dynamic simulation [21], [22], [23]. It is mainly used to perform a simple analytical model and load-shedding approaches for a quick response in frequency regulation. Emon et al. [24] performed Aggregated System Frequency Response (ASFR) modeling to monitor the frequency deviation, frequency nadir, and rate of change of frequency to improve grid frequency stability using BESS. Subsequently, ASFR combined with the second-order approximation method evaluates the frequency nadir using actual frequency data and concludes that the required capacity of BESS is 0.5-2.5% of wind turbine rated capacity. Comparatively, this technique recommends the lowest BESS capacity among the methods by maintaining the system frequency response. As mentioned earlier, optimizing the capacity of BESS is a significant task, especially regarding the economic aspect, as an increase in the capacity of BESS increases the return on investment. Several studies state that BESS internal losses, such as performance degradation, thermal-oriented operational stress, and improper power management, affect system efficiency [25], [26], [27].

Youseef et al. [28] generated the actual power generation from PV and wind; input parameters are obtained from the National Aeronautics and Space Administration (NASA), and real-time resources are used for biomass. Lithium-ion (Li-ion) and lead-acid batteries are used to store excess energy from the above-mentioned renewable energy generators. Notably, lead-acid batteries show a lower initial investment than Li-ion; however, operating costs are high. Net Present Cost (NPC) is high for PV/wind/biomass integrated with lead-acid batteries. On the other hand, PV/wind, PV/biomass, and PV-alone with Li-ion show higher NPC. Subsequently, Niaz et al. [29] optimized the BESS for the Tehran, Iran location to minimize power curtailment and maintain the grid frequency. Historical data on wind farms, load profiles, and other environmental parameters were collected from the Iranian Renewable Energy Organization to train the developed model. To assess the economic impact on the system, power curtailments of 25%, 50%, 75%, and 100% were performed using a 50 MW/600 MWh BESS. It was found that operating the renewable energy system with 100% BESS mode failed to reduce the power curtailment. Renewable energy generation, including PV, wind, and biomass, is used to optimize the BESS under various operating conditions on an island.

Similarly, Niaz et al. developed a hybrid energy storage system for a standalone system in a rural area of Egypt, and the examined renewable energy generator faces 8% to 12% power curtailment. It was found that the BESS reduced power curtailment by 5 %, which increased revenue by 7%. The PV and wind turbines generate 9874.71 kWh for the Ras Ghareb location, and the BESS with water electrolyzer power generation reached 16,984.51 kWh. For the Mersa Matrouh and Aswan regions, annual energy generation was enhanced by 26.62% and 27.28 %, respectively. The Mersa Matrouh and Aswan regions attained higher economic benefits than Ras Ghareb owing to seasonal variation in renewable energy generation [30].

The economic viability of BESS integration varies depending on the location and the local grid power purchasing agreement. Lobato et al. [31] evaluated the economic viability of BESS for a 30 MW wind farm in the Spanish market. In this case, Li-ion and Vanadium-Redox (Va-Red) are used to evaluate the economic feasibility as BESS initial investment cost and efficiencies are not the same, but end-of-life (EoL), EoL efficiency, and number of cycles per day are the same. Although the integration of BESS favors the wind farm to deliver smooth power output, it did not result in a remarkable economic change. The reason for this non-drastic improvement is that the international coordination of automated frequency restoration and stable system operations is under construction.

From the above literature and Table 1, integrating BESS favors smoothing the power delivery, improving the grid stability, and reducing the power curtailment. The performance of the BESS with a wind farm varies depending on the local grid load profile and energy generation, which makes optimizing the capacity of the BESS a necessary measure to attain a higher efficiency of the system. Second, the economic viability of BESS integration is different for each location, and it is truly dependent on the local grid power purchasing agreement. To the author's knowledge, no study has been conducted on optimizing the BESS for Thailand's wind farm on economic aspects. Considering this research gap, in this study, BESS optimized following our previous study [32], and the power generation was statistically analyzed to determine the reliability of the developed system. Furthermore, economic feasibility was determined under real-time operating conditions.

## II. MATERIALS AND METHODS

### A. STATISTICAL ANALYSIS

Statistical methods are widely used to uncover the patterns and trends of systems. This study analyzed wind farm power generation and losses using annual wind speed and feeder trip data.

#### 1) WIND SPEED

The discontinuous wind speed pattern was analyzed using a box plot and histogram view every month to determine the root cause of power deterioration. Box plots are presented in whiskers and Interquartile Range (IQR). In the wind speed data, 50% of high values are shown as IQR split into three segments: Q1, Q2/median (horizontal partition of the box), and Q3. The IQR bottom box represents 25% of the wind speed from 50% of IQR; the median and Q3

**TABLE 1. Recent literature of renewable energy system with energy storage.**

| Location | Renewable energy generator capacity | BESS capacity | Energy benefit with BESS | BESS cost | Payback period | Reference |
|---|---|---|---|---|---|---|
| United Kingdom | - | 1.25 GWh | £0.040/kWh | 200 £/kWh | 14 years | [33] |
| China | Wind 200 MW<br>PV 50 MW | 125 MWh | - | - | - | [34] |
| Germany | - | 20 MWh | - | - | 9.25 years | [35] |
| China | PV 1 MW | 3.78 MWh | - | 1800 yuan/ kWh | 6.9 years | [36] |
| China | Wind 20.745 MW<br>PV 17.338 MW | Li-ion 14 GWh<br>VRB 15.6 GWh | Li-ion<br>0.086 yuan/MWh<br>VRB<br>0.144 yuan/MWh | Li-iom ESS<br>2000 yuan/kWh<br>VRB ESS<br>3000 yuan/kWh | - | [37] |
| South Africa | PV/Wind microgrid | 30 kW | $0.847/kWh | $74,609 | - | [38] |
| United Nations | PV 8.67 kW | 7 kWh | $0.34$/kWh | $25,099 | - | [39] |
| Italy | PV 40 kW | 145 kWh | - | 450 €/kWh | - | [40] |
| Cyprus | PV 2.89 MW<br>Wind 1.15 MW | 2.31 MWh | 0.1838 €/kWh. | - | - | [41] |
| Thailand | PV 3.9 kW | 32 kWh | 0.245 $/kWh | $134 / kWh | - | [42] |
| - | PV 1.523 MW<br>Wind 1.785 MW | 360.2 kWh | - | $0.5187 M | - | [43] |
| Egypt | PV 126.14 kW<br>Wind 100 kW | - | 0.118 $/kWh | $ 65,015 | - | [44] |
| Span | Wind 30 MW | 2.5 MWh | - | 11,000 €/MWh | - | [31] |
| China | Wind and PV | 6860.91 kWh | - | - | - | [45] |
| China | Wind 99 MW | 10 MW / 0.3 MWh | - | - | - | [46] |
| China | Wind 2 MW | 1 MWh | 0.0340$/kWh | 123,000 $ | 3.5 years | [47] |
| China | Wind 153 MW | - | - | 946,100 yuan | - | [48] |
| China | Wind 360 kW<br>PV 260 kW | 700 kWh | - | - | - | [49] |
| China | Offshore wind | Pumped storage<br>240 MW | - | 243,000 CNY | - | [50] |
| Canada | Wind 200 kW | 100 kWh | - | - | - | [51] |
| China | Wind | Lithium 6.80 MWh<br>Flywheel 0.3204 MWh<br>Supercapacitor 0.1026 MWh | - | 7.5647x10$^5$ CNY | - | [52] |
| China | Wind 22 MW | Battery 10.44 MWh<br>Supercapacitor 10 MWh | - | Battery<br>930 yuan/kW<br>Supercapacitor<br>12400 yuan/kW | - | [53] |
| Libya | Wind 30 kW<br>PV 30 kW | Hydrogen storage | 0.137 $/kWh | Electrolyzer<br>900 $/kW<br>Compressor<br>1800 $/kW | 7 year | [54] |
| United States | Offshore Wind<br>350 MW | Compressed Air Energy Storage (OCAES) 200 MW | $0.22/kWh | $1457/kW | - | [55] |
| Thailand | 8 MW | 5 MWh | 411071.84 kWh/year | Wind farm = 103,057,495/MW<br>BESS = 15,000 baht/kWh | 7.89 years | Present study |

are 50% and 75%, respectively. Apart from the box, the lower and upper whiskers denote the minimum and maximum wind speeds of Q1-1.5×IQR and Q3-1.5×IQR, respectively. The Histogram view is a summarized representation of the dataset frequency for wind speed. It is widely used to analyze the frequency distribution of continuous datasets. The X-axis and Y-axis represent the wind speed and frequency distribution of the wind speed, respectively.

### 2) FEEDER TRIP

The primary issue in wind farms is the feeder trip, which disconnects wind turbine power generation from the distribution system. Unpredicted and lack of power distribution attributed to feeder trips. Feeder trip patterns were analyzed using a histogram to understand the nature of the selected wind farm operations against load consumption. Feeder trip frequency distributions were categorized into different scenarios concerning the wind speed of the location, the wind turbine's operational time, and the feeder trip's total duration.

#### 3) POWER PRODUCTION AND POWER LOSS

Pearson correlation is widely used to assess the strength and direction of two linear variables as expressed in Eq. (1). In this case, a correlation between the power production and feeder trip and how the feeder trip increased the power loss was studied. Furthermore, the different capacities of BESS with 8 MW wind farm annual power generation were studied to understand the benefit of BESS integration. The correlation coefficient is expressed in the range of $-1$ to $+1$, where $-1$ and $+1$ indicate a strong negative and positive correlation between the two variables, respectively, and 0 indicates no correlation.

$$Pearson\ correlation,\ r = \frac{\sum \left(X_i - \bar{X}\right)\left(Y_i - \bar{Y}\right)}{\sqrt{\sum \left(X_i - \bar{X}\right)^2 \sum \left(Y_i - \bar{Y}\right)^2}} \quad (1)$$

where, $X_i, Y_i$ = individual wind power production/loss (X) and feeder trip (Y). $\bar{X}, \bar{Y}$ = means of wind power production/loss and feeder trip.

#### 4) LOW AND HIGH LOAD PROFILE

Feeder trips occur during low- and high-voltage periods due to load demand fluctuations. To determine the relationship between the feeder trip and the voltage profile, a Pearson correlation was performed on the specific periods of low- and high-load profiles of the wind farm. A comparative correlation between the voltage profiles with and without BESS was conducted for both load profiles.

### B. ECONOMIC ANALYSIS

Economic analysis is predominant in convincing policy-makers, stakeholders, and individuals to install wind energy systems. It is well known that wind energy systems efficiently deliver renewable power generation with an attractive return on investment. Under certain circumstances, wind energy systems fail to meet economic benefits, especially when the system is not commissioned correctly as per the local grid regulations. In this case, an 8 MW wind turbine is commissioned following the Thailand grid regulations; however, unexpected load demand increases power curtailment. Second, active power curtailment raised concerns about wind turbine manufacturers' warranties owing to higher feeder trips. As per the wind turbine manufacturer, feeder trips must not exceed 52 times a year; unfortunately, they reach 146 times. In our previous study, different capacities of BESS were approached to reduce the feeder trip, and the same methodology was followed for this study.

Furthermore, the economic viability of the proposed BESS with wind turbine power generation was discussed. The major parameters used to evaluate the economic benefits of the proposed system were **Net Present Value (NPV), Internal Rate of Return (IRR), Benefit-Cost Ratio (BCR), and Payback Period (PP).** A description of the selected 8 MW wind farm is listed in Table 2.

**TABLE 2. General information about the Subplu project.**

| Content | Description |
|---|---|
| Project shareholder | Wind Energy Development Co., Ltd. |
| Project location | Ban Huai Bong, Dan Khun Thot District, Nakhon Ratchasima Province, Thailand |
| Installed capacity | 8 MWp |
| Wind turbine model | Gamesa G114-2.0MW |
| Power purchaser | Provincial Electricity Authority (PEA) |
| Power purchase duration | 10 years + 10 years |
| Electricity selling structure | electricity tariffs + FT + Adder |
| Date of plant operation | March 17, 2016 |

## III. RESULTS AND DISCUSSIONS

An 8 MW wind farm from Nakhon Ratchasima Province, Thailand, has been operational since March 17, 2016. The Provincial Electricity Authority of Thailand commissioned the wind power plant to minimize conventional power generation and mitigate grid power demand. Wind energy is discontinuous/intermittent in power generation and predictable. However, it is not easy to maintain a balanced grid power flow because it directly relies on the power consumption in the grid. Figure 1 shows the annual box plot of wind speed for the 8 MW wind farm in Nakhon Ratchasima Province, Thailand. The cross-lined box represents 50% of the wind speed every month, and the lower and higher 25% of wind speeds are shown as whiskers. An increase in the length of the horizontal box indicated a wide variation occurring at 50% of the wind speed. In January, a higher box length was recorded, starting from 3.54-8.39 m/s, which means that 50% of the wind speed lies between these ranges. An increase in the box length did not effectively favor attaining high power generation, although it was better than that in March, April, May, and September. A box plot such as the IQR must attain a smaller box length in a higher wind speed region for effective power generation.

This state indicates that the oscillation of wind speed is lower for 50% of the monthly wind speed, and it attained a higher wind speed, resulting in stable power generation. Comparatively, March, April, May, and September contain small box lengths, but they attain lower power generation in the lower wind speed region. During December, 50% of the wind speed was recorded to be 5.46-9.12 m/s, and the median/Q2 is 7.57 m/s, making this month have a high potential for energy generation. Following December, a similar wind speed pattern was recorded in July and June. December, July, and June were categorized as having the highest potential periods. November, January, August, and February are moderate potential periods, and March, April,

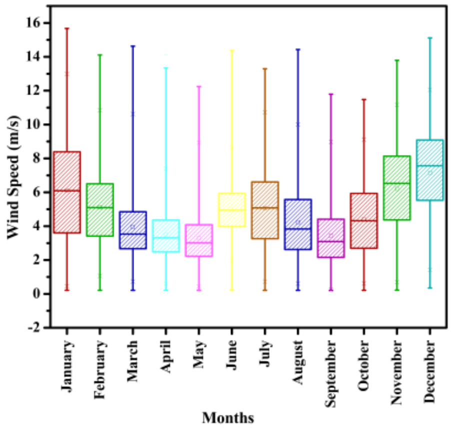


**FIGURE 1.** Box plot representation of annual wind speed for an 8 MW wind farm.

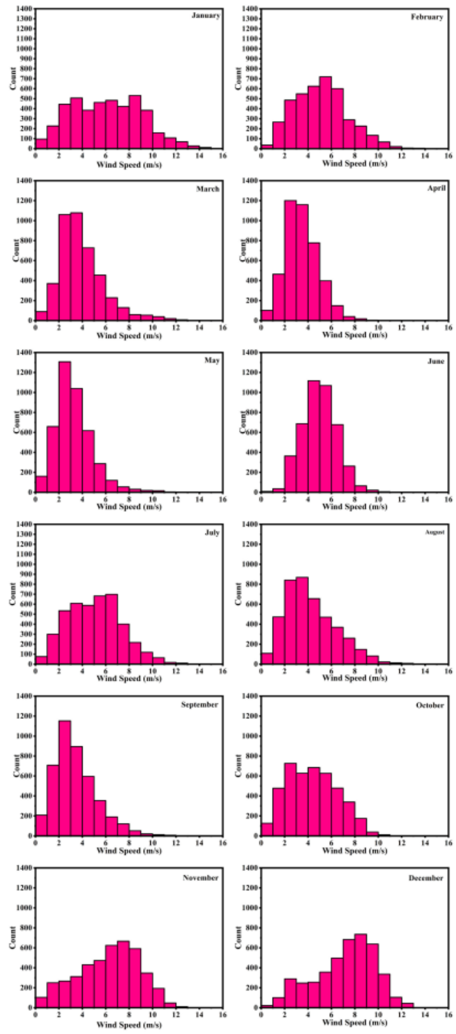


**FIGURE 2.** Histogram view of annual wind speed for an 8 MW wind farm.

May, September, and October are low potential periods for wind-power generation.

In a standardized way, commercial wind farms monitored by Supervisory Control and Data Acquisition (SCADA) measure the wind speed by 10 minutes to obtain a manageable dataset [56], [57]. To further understand the nature of wind speed, monthly categorized annual wind speeds were analyzed using a histogram. The high wind potential period of December attained a higher wind speed of 7-9 m/s more than 650 times. Following that, the second highest period of July showed a wind speed of 6-7 m/s more than 680 times. Between 3-7 m/s, the wind speed was sustained more than 500 times. After 7 m/s, the wind speed failed to maintain a higher frequency count and was slowly reduced. Comparatively, a higher frequency count of more than 1100 times was recorded for June with a wind speed of 4-5 m/s. However, June failed to compete in terms of higher power production with December and July due to fluctuations in wind speed, as shown in Figure 2. January gained a stable wind speed compared to other months; however, the frequency of the wind was not as high as that of the months mentioned above. Notably, 4 m/s and 9 m/s wind speeds were recorded for more than 500 frequency counts. The primary benefit of the January wind speed is that more than 400 counts are recorded at 2-9 m/s separately, which is predominant in producing moderate power with a lower oscillation. Subsequently, November recorded similar wind patterns with 7-9 m/s for more than 590 counts. August marked a sudden sweep in wind speed after 5 m/s and attained less than 400 counts, while February had the least wind power conversion potential in a moderate wind speed period. As mentioned earlier, March, April, May, September, and October are low potential periods, as it can be seen that during March, a wind speed of 6 m/s failed to maintain a higher count. Secondly, a higher frequency count recorded with a low wind speed could not generate higher power, resulting in April, May, September, and October yielding less power following March. This wind speed histogram exhibits a wind pattern based on the frequency count. Overall, December and July recorded higher frequencies of high wind speeds.

Apart from the wind speed, the feeder trip plays an energetic role in deteriorating the wind turbine power fed to the grid. Feeder trips occur because of low and high voltages, and they mainly depend on the nature of the grid voltage. Secondly, annual feeder trips that are higher than 55 times increase the security and warranty issues of the wind turbine. In the selected wind farm, the yearly feeder trip reached 146 times, nearly threefold higher than the manufacturer's guidelines. Figure 3 depicts a detailed view of each month's feeder trip count and duration. It was found that January, February, November, and December recorded lower and higher feeder trips in September and May. The feeder trip during September and May was due to the low wind potential that failed to generate higher power to feed the grid.

On the other hand, the maximum feeder trip duration reached 1800 min in October owing to the low wind speed. In general, integrating BESS with wind farms will not eliminate feeder trips; however, the rate of feeder trips will be reduced. In the general thumb rule, a higher wind speed is attributed to the feeder trip to avoid overvoltage; however, in this case, wind speeds greater than or equal to 14 m/s faced three feeder trips, and 12-14 m/s did not face the feeder trip. Notably, wind speeds of 4-6 m/s and 6-8 m/s faced 58 and 35 times higher feeder trips, respectively. This feeder trip indicated that the voltage in the grid played a significant role in tripping the feeder to protect the grid. In a 24-hour wind farm operational period, higher feeder trips were noted between 06:00 and 09:00, which is 33 times, and following that, 15:00 and 18:00 faced 26 times.

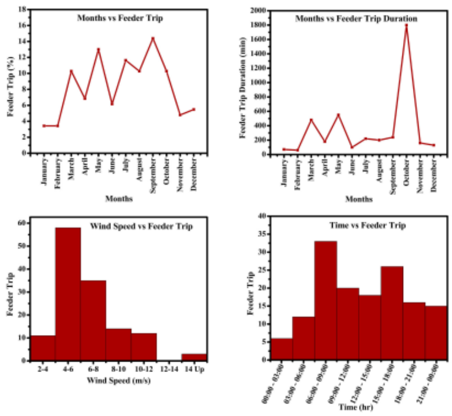


**FIGURE 3.** Annual feeder trip of an 8 MW wind farm.

The Pearson correlation method was used to understand further the nature of wind speed, the feeder trip count, time duration, energy production, and energy loss. Figure 4 shows that wind speed (WS) strongly correlates negatively with feeder trip count (−0.67576) because higher feeder trips occurred for 4-6 m/s. Secondly, the increase in wind speed has a moderate and weak negative correlation with the feeder trip time duration (FT-T) and energy loss (EL), which are −0.3012 and −0.2287, respectively. An increase in wind speed generates higher power, and it has been found that wind speed has a strong positive correlation (0.7426) with energy production (EP). It is well known that an increase in the feeder trip count (FT-No) increases the energy loss; in this case, the feeder trip count and energy loss have a moderate positive correlation (0.4992). However, the feeder trip duration has a very strong positive correlation with the energy loss, which is 0.9543. The feeder trip count affects the manufacturer warranty claim but is attributed to a moderate correlation with energy loss. An increase in the duration of the feeder trip time increases energy loss and deteriorates the wind farm's performance. The feeder trip duration was worse than the feeder trip count regarding energy loss. To further understand the variability/dispersion of the data used in Figure 4, the standard analytical tool of Standard Deviation (SD) was applied to each variable independently. The deviation of the mean value for wind speed, feeder trip count, and energy loss were 1.2, 5.5, and 9.9, respectively. The annual wind speed and feeder trip counts are dispersed less from the mean value, and the energy loss deviates moderately. However, feeder trip duration and energy production are widely dispersed from the mean values of 283.1 and 695.28, respectively. The reason behind the massive variability in feeder trip duration is that October, March, and May reached maximum durations of 1070, 460, and 410 min, whereas February and January reached maximum durations of 60 and 70 min, respectively. Following this, similar SD patterns were observed for energy production due to high annual energy production fluctuations. Higher SD values were recorded for energy production and feeder trip duration. As mentioned above, the BESS reduces the feeder trip and its duration but cannot feed uninterrupted power to the grid. Following our previous study [32], annual energy generation for different BESS was performed for comparison.

Wind farms without BESS energy generation have a very strong positive correlation with all BESS capacities, as shown in Figure 5. The difference between the annual energy generation with and without the BESS reached a maximum of 2.4 %. A strong positive correlation exists between BESS capacity and the absence of BESS. To further understand the magnitude and dispersion of energy generation, the SD was calculated for wind farms with and without BESS. The wind farm without BESS SD value is 695.28, which is 0.33, 1.41, 3.57, 5.90, and 7.65 SD higher than 1-5 MWh BESS, respectively. An increase in the BESS capacity shows a higher dispersion in energy generation owing to the controller feeder trip duration and count. Second, shifting the wind farm energy generation to meet the load demand favors using more wind farm energy generation. Therefore, it is concluded that 5 MWh BESS with wind farm operations is efficient.

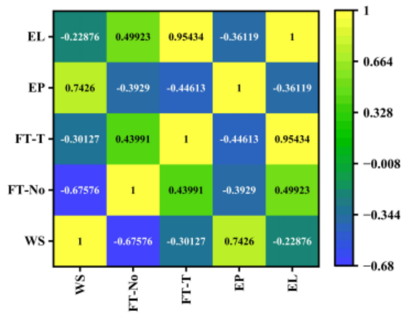


**FIGURE 4.** Pearson Correlation for 8 MW wind farm energy profile and feeder trip.

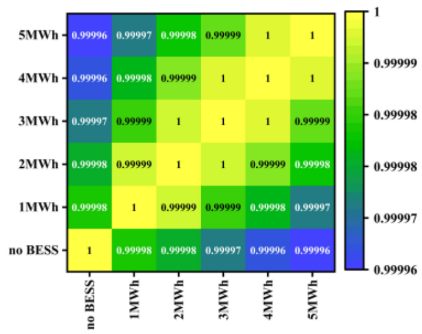


**FIGURE 5.** Pearson correlation coefficient of 8 MW wind farm using with and without BESS.

This 8 MW wind farm is located within the boundaries of residential villages and industrial areas. This mixed-load consumption zone creates grid voltage issues due to load consumption's unpredictable and discontinuous/intermittent nature. Figure 6 shows the high-load profile correlation plot for grid load consumption and voltage at the wind farm, which is represented as Very Small Power Producer (VSPP), three villages Point of Common Coupling (PCC_01, PCC_02, and PCC_03), and factory (DTA04). The wind farm's nearest connecting load consumption hubs are PCC_02 and PCC_01, which show a very strong positive correlation of 0.989 and 0.998 without BESS (wob). However, DTA04 exhibited a strong negative correlation, which means that the grid voltage at the factory was much lower than the voltage at the wind farm. A significant voltage difference was noted between DTA04 and the villages (PCC_01, PCC_02, and PCC_03).

DTA04 with PCC_01 has a strong negative correlation with a factor of −0.474, which means that the voltage at the factory is lower than that in the village because of high load consumption. Comparatively, other villages also faced a similar trend, with correlations of −0.472 and −0.473. However, the voltage ranges are identical for all the villages, and the correlations are nearly perfectly positive and very strong. That indicates wind farm power generation and grid voltage face complexity in operation without BESS. The load with BESS (wb) depicts correlations of 0.351, −0.983, −1, and −1 for DTA04, PCC_01, PCC_02, and PCC_03, respectively. The grid voltages are within the allowable range for all three villages compared to those without BESS.

On the other hand, PCC_01 (wob) with PCC-01 (wb) has a 0.127 less positive correlation, followed by PCC_02 and PCC_03 with 0.106 and 0.104 correlation differences, respectively. Apart from the villages, wind farms and DTA04 also contained correlation differences of 0.335 and 0.297, respectively. An 8 MW wind farm with a 5 MWh BESS effectively maintained the grid voltage at the wind farm and across the load consumption regions. Table 3 shows the mean and SD for different load consumption regions and wind farms. The SD for BESS clearly defined the deviations; however, it is minor to note that the dataset used in this statistical analysis was in the form of pu to simplify the analysis.

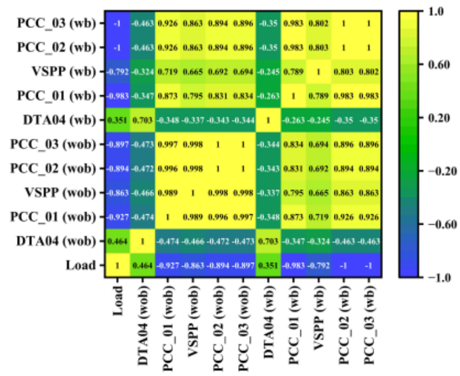


**FIGURE 6.** Pearson correlation of grid high-load period and different points of grid voltage in the transmission system with and without BESS.

To further understand the benefits of 5 MWh BESS, a low-load demand period was used to analyze the correlation between different regions of the consumer's voltage profile as shown in Figure 7. In this case, the load demand negatively correlated with DTA04 without BESS. On the other hand, PCC_01, PCC_02, and PCC_03 have fewer negative correlations compared to the high load profile. The low voltage at the consumer end causes this massive disruption in correlation. The voltage magnitudes from the wind farm to DTA04, PCC_01, PCC_02, and PCC_03 had positive correlations of 0.322, 0.997, 0.999, and 0.999, respectively. This correlation shows that the voltage magnitudes of the villages and factories follow similar trends to wind farms. The reason behind the same correlation factor of PCC_02

**TABLE 3.** Statistical analysis of grid high load period and different points of grid voltage in the transmission system using with and without BESS.

| Parameter | Mean | SD |
|---|---|---|
| Load | 2.04571 | 0.55134 |
| Factory without BESS (DTA04 (wob)) | 1.03 | 1.43576E-7 |
| Village 1 without BESS (PCC_01 (wob)) | 1.04818 | 0.0049 |
| Wind farm without BESS (VSPP (wob)) | 1.07586 | 0.00895 |
| Village 2 without BESS (PCC_02 (wob)) | 1.07239 | 0.01007 |
| Village 3 without BESS (PCC_03 (wob)) | 1.07201 | 0.01018 |
| Factory with BESS (DTA04 (wb)) | 1.03 | 1.02062E-7 |
| Village 1 with BESS (PCC_01 (wb)) | 1.02291 | 9.81486E-4 |
| Wind farm with BESS (VSPP (wb)) | 1.02493 | 3.78418E-5 |
| Village 2 with BESS (PCC_02 (wb)) | 1.02154 | 0.00129 |
| Village 3 with BESS (PCC_03 (wb)) | 1.02118 | 0.0014 |

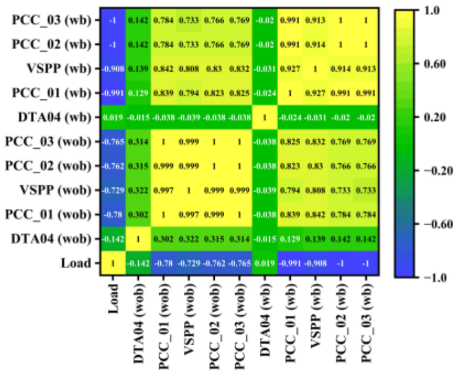


**FIGURE 7.** Pearson correlation of grid low-load period and different points of grid voltage in the transmission system with and without BESS.

and PCC_03 with the wind farm indicates that the load consumption was less than that of DTA04. In addition, the PCC_01 power transmission line is affected by the DTA04 owing to its high energy consumption. The map of the three villages, wind farm, and DTA04 power transmission network is shown in the Appendix (Figure 8). Second, DTA04 with PCC_01, PCC_02, and PCC_03 showed weak positive correlations within 0.302, 0.315, and 0.314, respectively. DTA04 with other energy consumer villages had a strong negative correlation for the high load profile; however, in this case, the PCC_01, PCC_02, and PCC_03 voltage magnitudes were lower than DTA04, resulting in a weak positive correlation. The integration of 5 MWh BESS for a low-load profile demonstrates that the voltage magnitudes of PCC_01, PCC_02, and PCC_03 are in phase with DTA04.

The wind farm voltage magnitude with three village energy consumers has a very strong positive correlation within the ranges of 0.927, 0.914, and 0.913. Notably, the grid voltage in different consumer regions is stabilized with the help of BESS. The SD of the voltage magnitude across the distribution system maintained similar trends, following a high-load profile, as listed in Table 4. Furthermore, it was concluded that 5 MWh BESS efficiently regulates the voltage magnitude for both low- and high-load periods.

**TABLE 4.** Statistical analysis of grid low load period and different points of grid voltage in the transmission system using with and without BESS.

| Parameter | Mean | SD |
|---|---|---|
| Load | 1.66793 | 0.35095 |
| Factory without BESS (DTA04 (wob)) | 1.03 | 1.43576E-7 |
| Village 1 without BESS (PCC_01 (wob)) | 1.02548 | 0.00551 |
| Wind farm without BESS (VSPP (wob)) | 1.02396 | 0.01036 |
| Village 2 without BESS (PCC_02 (wob)) | 1.02144 | 0.01095 |
| Village 3 without BESS (PCC_03 (wob)) | 1.02116 | 0.011 |
| Factory with BESS (DTA04 (wb)) | 1.03 | 1.02062E-7 |
| Village 1 with BESS (PCC_01 (wb)) | 1.02596 | 7.17721E-4 |
| Wind farm with BESS (VSPP (wb)) | 1.02497 | 2.6427E-5 |
| Village 2 with BESS (PCC_02 (wb)) | 1.02244 | 8.24175E-4 |
| Village 3 with BESS (PCC_03 (wb)) | 1.02216 | 8.97478E-4 |

**TABLE 5.** Basic parameters of wind farm, BESS, and power purchase details.

| Parameters | Value |
|---|---|
| Wind farm initial investment | 824459960 baht/8MW |
| BESS | 75,000,000 baht/5MWh |
| Annual energy production without BESS | 17071670.58 kWh |
| Annual energy production with BESS | 17482742.42 kWh |
| Discount rate | 7.36 % |
| Wind turbine power purchase | 20 years |
| Feed-in tariff | 6.874 baht/kWh (0-10 years) and 3.374 baht/kWh (11-20 years) |

## IV. ECONOMIC ANALYSIS

An economic analysis was performed for an 8 MW wind farm with and without BESS. Subsequently, a varying cost analysis is performed for only BESS (without a wind farm) to understand the impact on the payback period when the BESS is associated with the wind farm. In Thailand, the power purchase agreement for the wind farm includes two different feed-in tariffs: 6.874 baht/kWh for up to ten years and 3.374 baht/kWh for the remaining ten years, as listed in Table 5. The discount rate is 7.36% as per Thailand's financing regulations. Operation and maintenance (O&M) costs include feeder trip penalties and energy loss, which are applied throughout 20 years of plant operation. Table 6 presents a detailed view of energy generation, O&M, and discounted energy generation. Over 20 years of wind farm

**TABLE 6.** Basic parameters of wind farm, BESS, and power purchase details.

| Year | Discount factor (%) | Feed-in tariff (baht) | Without BESS | | | | With BESS | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Energy generation (kWh) | Energy generation (baht) | O&M (baht) | Discounted energy generation (kWh) | Energy generation (kWh) | Energy generation (baht) | O&M (baht) | Discounted energy generation (kWh) |
| 1 | 0.931 | 6.874 | 17,071,671 | 117,345,542 | 11,520,000 | 15,901,333 | 17,482,742 | 120,171,127 | 5,760,000 | 16,284,224 |
| 2 | 0.868 | 6.874 | 17,037,527 | 117,110,851 | 11,635,200 | 14,781,604 | 17,447,777 | 119,930,784 | 5,817,600 | 15,137,533 |
| 3 | 0.808 | 6.874 | 17,003,452 | 116,876,629 | 11,751,552 | 13,740,723 | 17,412,881 | 119,690,923 | 5,875,776 | 14,071,589 |
| 4 | 0.753 | 6.874 | 16,969,445 | 116,642,876 | 11,869,068 | 12,773,139 | 17,378,056 | 119,451,541 | 5,934,534 | 13,080,706 |
| 5 | 0.701 | 6.874 | 16,935,506 | 116,409,590 | 11,987,758 | 11,873,689 | 17,343,300 | 119,212,638 | 5,993,879 | 12,159,598 |
| 6 | 0.653 | 6.874 | 16,901,635 | 116,176,771 | 12,107,636 | 11,037,576 | 17,308,613 | 118,974,213 | 6,053,818 | 11,303,352 |
| 7 | 0.608 | 6.874 | 16,867,832 | 115,944,418 | 12,228,712 | 10,260,340 | 17,273,996 | 118,736,264 | 6,114,356 | 10,507,401 |
| 8 | 0.567 | 6.874 | 16,834,096 | 115,712,529 | 12,350,999 | 9,537,835 | 17,239,448 | 118,498,792 | 6,175,500 | 9,767,498 |
| 9 | 0.528 | 6.874 | 16,800,428 | 115,481,104 | 12,474,509 | 8,866,206 | 17,204,969 | 118,261,794 | 6,237,255 | 9,079,697 |
| 10 | 0.492 | 6.874 | 16,766,827 | 115,250,141 | 44,799,254 | 8,241,872 | 17,170,559 | 118,025,270 | 6,299,627 | 8,440,330 |
| 11 | 0.458 | 3.374 | 16,733,294 | 56,453,113 | 12,725,247 | 7,661,502 | 17,136,218 | 57,812,458 | 81,362,623 | 7,845,984 |
| 12 | 0.426 | 3.374 | 16,699,827 | 56,340,207 | 12,852,499 | 7,122,000 | 17,101,945 | 57,696,833 | 6,426,250 | 7,293,491 |
| 13 | 0.397 | 3.374 | 16,666,427 | 56,227,526 | 12,981,024 | 6,620,488 | 17,067,741 | 57,581,439 | 6,490,512 | 6,779,904 |
| 14 | 0.370 | 3.374 | 16,633,095 | 56,115,071 | 13,110,835 | 6,154,291 | 17,033,606 | 57,466,276 | 6,555,417 | 6,302,481 |
| 15 | 0.345 | 3.374 | 16,599,828 | 56,002,841 | 13,241,943 | 5,720,922 | 16,999,539 | 57,351,344 | 6,620,971 | 5,858,678 |
| 16 | 0.321 | 3.374 | 16,566,629 | 55,890,836 | 13,374,362 | 5,318,071 | 16,965,540 | 57,236,641 | 6,687,181 | 5,446,125 |
| 17 | 0.299 | 3.374 | 16,533,496 | 5,779,054 | 13,508,106 | 4,943,586 | 16,931,609 | 57,122,168 | 6,754,053 | 5,062,624 |
| 18 | 0.279 | 3.374 | 16,500,429 | 55,667,496 | 13,643,187 | 4,595,473 | 16,897,745 | 57,007,923 | 6,821,594 | 4,706,128 |
| 19 | 0.259 | 3.374 | 16,467,428 | 55,556,161 | 13,779,619 | 4,271,872 | 16,863,950 | 56,893,908 | 6,889,809 | 4,374,735 |
| 20 | 0.242 | 3.374 | 16,434,493 | 55,445,048 | 46,117,415 | 3,971,058 | 16,830,222 | 56,780,120 | 6,958,708 | 4,066,678 |

**TABLE 7.** Annual revenue, IRR, BCR, PP, and NPV for an 8 MW wind farm.

| Parameter | Wind farm without BESS | Wind farm with 5 MWh BESS |
|---|---|---|
| Annual revenue (THB) | 117,345,542.07 | 120,171,126.57 |
| IRR | 7.74% | 7.74% |
| Payback Period (Year) | 7.79 | 7.89 |
| NPV (THB) | 579,908,919 | 662,613,032 |
| BCR | 1.51 | 1.60 |

operation, energy generation declined from 17071671 kWh to 16434493 kWh, and for BESS, from 17482742 kWh to 16830222 kWh. The association of BESS was found to enhance 411071 kWh/year by reducing feeder trips. Second, feeder trips significantly impact the O&M cost, resulting in wind farms with 5 MWh BESS being twice as low as those without BESS. This enhancement in O&M and energy generation results in higher discounted energy generation. An increase in energy generation greatly impacts annual revenue, with benefits of 2825584.5 baht/year. Following the annual income, the IRR attained 7.74% for both wind farms with and without BESS, as listed in Table 7. Advantageously, PP with a difference of 0.10 years is noted compared to without BESS. This study indicates that integrating a 5 MWh BESS with an 8 MW wind farm potentially enhanced the power output and economic benefits. The PP of the BESS is strongly dependent on the wind farm feeder trip and reduction in energy loss. Apart from BESS integration by a wind farm, if the Provincial Electricity Authority (PEA) installed the BESS separately to improve the grid voltage, BESS would face severe negative impacts in terms of economic benefits.

IRR and BCRs in negative terms and lower than 1, resulting in PP reaching 26.5 years, which is higher than BESS lifetime

**TABLE 8.** Sensitivity analysis of a varying BESS investment price for independent installation by PEA.

| Financial Parameter | Variation in BESS investment cost | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% |
| NPV (THB) | 40,802,665 | 33,302,665 | 25,802,665 | 18,302,665 | 10,802,665 | 3,302,665 | 4,197,334 | 11,697,334 |
| IRR | -7.88 | -6.97 | -5.91 | -4.64 | -3.08 | -1.08 | 1.63 | 5.68 |
| BCR | 0.51 | 0.56 | 0.62 | 0.70 | 0.80 | 0.93 | 1.11 | 1.38 |
| PP (Year) | 26.5 | 23.9 | 21.2 | 18.6 | 15.9 | 13.3 | 10.6 | 8.0 |

as listed in Table 8. In this case, the BESS discharged energy calculates the economic benefit. Furthermore, to understand the sensitivity of the PP, variable BESS cost rates are used, such as 90%, 80%, 70%, 60%, 50%, 40%, and 30% from the BESS actual price. It was found that PP for BESS, with a 40% cost rate, nearly reached the life expectancy of BESS, and a 30% cost rate reached 8 years. Overall, it was concluded that 5 MWh BESS with an 8 MW wind farm attained attractive PP and economic benefits compared with the independent installation of BESS (without wind farm authorities).

## V. CONCLUSION

In this study, an 8 MW operational wind farm was statistically analyzed using real-time PEA and wind farm data. The main objective of this study is to evaluate the root cause of feeder trips by statistically analyzing the data to avoid O&M costs. Furthermore, a detailed economic analysis was conducted for wind farms with and without BESS. The significant findings of the statistical and economic analyses are as follows.

- The box plot shows that December, July, and June are categorized as having high potential, and March, April, May, September, and October have low potential for wind energy generation.
- A histogram view depicts that 7-9 m/s and 4-5 m/s wind frequencies were noted more than 650 times and 1100 times for December and June, respectively, although a lower frequency count of December delivered a higher energy yield owing to the high wind speed.
- The higher wind speed period of December obtained a low feeder trip; however, October reached 1800 times, which yielded a low energy conversion.
- Wind speed has a weak and moderate negative correlation with feeder trips, and feeder trips are mostly correlated with load consumption and grid voltage. A higher correlation difference was noted for 5 MWh BESS owing to the higher energy yield than that without BESS.
- For high- and low-load demand periods, without BESS, a higher voltage difference was noted between the DTA04 and the wind farm. Integration of the BESS regulated the voltage across all energy consumer ends within the allowable range.
- An 8 MW find farm with BESS attained a PP of 7.89 years, whereas the wind farm alone was 7.79 years. The annual revenue for the wind farm with and without BESS was 117,345,542.07 baht and 120,171,126.57 baht, respectively.
- BESS integration by an individual DTA04/PEA reached 26.5 years of PP, which is 2.65 times higher than the life expectancy of the BESS.
- Furthermore, it is recommended that the BESS be integrated with renewable energy sources to improve energy generation capability and attain an attractive PP.

## APPENDIX

See Figure 8.

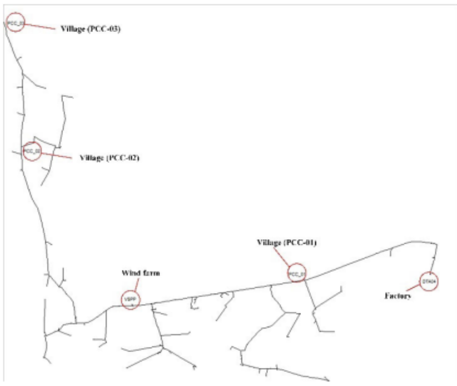


**FIGURE 8.** Geospatial view of the wind farm, three villages, and factory.

## DATA AVAILABILITY

Data and system configuration models are available on request.

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