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Benefits of Battery Storage for Wind Power Plant

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Abstract

The fast growing expansion of wind energy increases the complexities in balancing generation and demand in the power system, with the integration of battery energy storage system (BESS) into the wind power system, the variation in wind power can be mitigated to dispatch constant power to the grid. In this study, the analysis has been conducted on two different model with combined operations of wind power and battery energy storage.

In Model-1, the analysis was conducted on hybrid wind-battery power system to investigate, the battery capacity required to deliver constant power dispatch to the grid over different time periods based on the wind profile, and see if it is economically beneficial to have a battery storage to deliver constant power over longer time periods. In Model-2, considering the electricity prices, the economic benefits of combined wind-battery storage system was developed. Considering the charging/discharging of the battery, the economic benefits of wind-battery storage system were based on the power production of the wind turbine. The economic benefits were obtained based on the analysis, by taking into account wind power forecast error, battery operation, costs associated with the loss of battery life, and maintenance. In both cases the power dispatch capability is decided under the conditions that state of charge of the battery is within safe range and that the battery power is maintained below its rating. Simulations of the mathematical models for both the cases are done in MATLAB.

The simulation results for Model-1 shows that, with longer time periods i.e: 6 months, 1 year, constant power dispatched to the grid is less as compared to the smaller time periods because, its directly related to storage size and power spilled and the variation in wind power generation. By increasing the storage size constant power dispatched to the grid can be increased but it is not economically beneficial. The simulation results for Model-2 shows that, the hybrid wind-storage system was not only economically beneficial as compared to the wind farm alone, but can also balance the deviation between the actual and forecast-ed output for the wind turbine to decrease the loss penalty.

Keywords: Battery energy storage, Wind power, Energy management, Renewable energy

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Introduction

Wind power is a rapidly growing and promising renewable energy source of electricity, with the increasing penetration of intermittent renewable energy, conventional energy sources such as thermal power plants are gradually being replaced by solar power, wind power and energy storage systems.With the increase in renewable energy resources in the electric power system there are certain challenges rise with it as well.

In the low carbon future, where the renewable energy sources are replacing the conventional energy resources one major challenge the power market is facing is the frequency regulation. Network frequency control ensures the continuous balance between the generation and power demand. In the case that the power demands exceeds the generation, the rotating speed of the synchronized generators throughout the network starts decreasing, which results in electrical frequency below set-point. Electrical frequency goes above its set-point in case the generation increases as compared to the power demand. For proper network operation and stability of the system the magnitude and the dynamics of the electrical frequency needs to be controlled[1]. Any power imbalance results in the frequency deviation which can be recovered from the power reserves which are activated to maintain electrical frequency with in required limit such as hydro power plants or thermal power plants[2].

The stochastic nature of the wind causes the wind farms (WFs) to be the non-dispatchable source of energy and limits the penetration of wind energy into the electric power system. In [3], the grid frequency deviation due to the wind fluctuations was investigated to shows that the wind power fluctuations from second-long to minute-long periods can result in significant grid frequency deviation. In [4], the severe impacts caused by the wind turbine fluctuations on the electric power system were investigated, which shows that wind farm fluctuation affects grid connections, power stability and power quality of the power system. Therefore, the problems related to the intermittent nature of the wind generation must be overcome to dispatch high wind power to the grid. There are two methods that can be used to mitigate the wind power fluctuations:

- In first method, wind power is smoothed without the use of energy storage systems, power smoothing methods are pitch control angle and wind generator rotor inertia regulation [5]. Although these methods have low investment cost but they do not ensure that the wind turbines (WTs) can will capture the maximum available energy [6].

- The second method is to smooth the wind power with the use of energy storage system such as battery, fly wheel, super-capacitor or super conducting magnetic energy storage (SCME). By using these types of energy storage systems the wind turbines (WTs) can harness the maximum available power and can be dispatchable to the electric power system.

Considering the energy storage systems available, batteries are utilised mostly because they are well-developed technology and because of their power and energy density. while integrating batteries with wind turbines, power control and system costs must be taken into consideration as well. In [7], a power dispatch method was proposed based on the state of charge (SOC) of the battery to control the power flow of the battery. The penetration level of wind power into the electric power system is compared with the conventional power system such as nuclear power plants and hydroelectric power, the wind farms are requited to deliver constant power to the grid at each dispatching interval by transmission system operator (TSO). In [8], a control method was introduced to dispatch constant power by averaging the wind power in each dispatching interval.

Storage systems has the ability to charge/discharge at high power and can be flexible based on the shifts in wind power generation, thereby increasing the economic profit of WFs. In [9], an optimal operation strategy for battery energy storage system (BESS) with the wind farm is investigated, where intraday energy imbalances and market prices with linear programming was used to identify the economically and technically optimal operation of wind-battery storage system. In [10], an optimal operations of wind turbines with BESS was investigated in intraday, day-ahead and secondary reserve markets using multi-stage stochastic programming model but taking into account the clearing prices and uncertainty in the wind power generation. In [11], real-time wind power fluctuation was analyzed to obtain the economic maximum charging/discharging power of battery storage system in every scheduling period. The authors aim was to minimize the deviation between the generation plan and actual integrated power of combined generation system based on quantization index (QI) clustering.

In this paper there are two different models that are studied:

- In Model-1, we determine the battery capacity required by the wind power system to deliver constant power dispatch based on the wind power profile and the wind turbines input over different time periods and investigate if it is economically beneficial to have BESS to deliver constant power over longer periods. To guarantee the wind-battery system works properly two constraints are applied: first is that the battery SOC should be kept with in safe ranger and the battery power should be kept lower then its rating.

- Model-2 investigates a model of combined wind-battery storage system considering the simulation experiment, which verifies the increase in profit for wind farm owners by using the battery storage. This study was based on the forcasted value of wind power, deviation in that forecast, charge/discharge of thew batteries, costs based of the BESS consumption and electricity prices. The aim for this model was to increase the WFs profit and decrease the deviation between the actual and forecasted wind power.

The study for both the models is conducted on a 16-MW WF with a real wind power data measured near Torsby, Sweden.

2

Theory

2.1 Wind Power:

In order to reduce the CO_2 emission, there is a a growing demand for the renewable power generation[12]. Wind turbine power plants represent the main energy resource being installed in Europe. These plants are installed to replace the existing generators or to increase the power generation capabilities. In this section, we will discuss the wind power plants.

2.1.1 Working Principle of wind turbine:

The Working principle of wind turbine is quite simple. Majority of wind turbines consist of three blades mounted on a tower. The turbines catch the wind energy with the propeller like blades, which act much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on one side of the blade. The low-pressure air pocket then pulls the blade towards it, causing the rotor to turn. This is called lift. The force of the lift is much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a turbine.

The wind power plant consists of number of components, which are shown in figure 2.1. The main component are wind turbine, nacelle, foundation and tower, foundation gives stability to the power plan and tower has the shape of cone and is often made of steel. The nacelle contains generator, gearbox, anemometer and electrical equipment. Size of the rotor blades and the tower varies between different models and the electrical systems can appear differently as well.

The turbine is connected to the primary shaft, also called the low speed shaft. This is then connected to the secondary shaft in the gear box where the series of gears increase the rotation of the rotor from about 7-18 revolution a minute to roughly 1800 revolutions per minute. Gearbox is connected to the generator which at a speed allows the generator to produce AC electricity. There are also turbines without the gearbox as well for low speed generators.

Another key component is the turbine controller, that keeps the rotor speed from exceeding a certain limit to avoid damage by high winds. The most common value of the wind speed to limit is between 12-15 m/s. An anemometer continuously measures wind speed and transmit the data to the controller. A parking brake, also housed in the nacelle, stops the rotor mechanically. Yaw motor is connected to the nacelle where the yaw drive changes the direction to keep the rotor in the direction of the wind to make it most efficient as possible.

Even though the power generated by the wind turbines depends upon the stochastic nature of wind speeds, the power generated by wind turbines are computed by:

$$P_{gen} = \frac{1}{2}\rho C_p(\lambda, \beta) A V_{wind}^3 \tag{2.1}$$

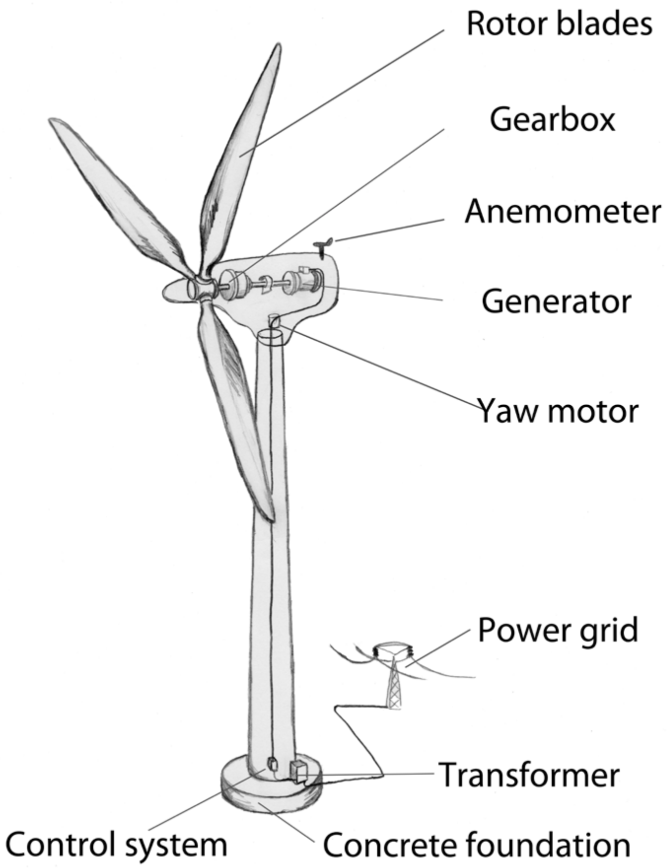

Figure 2.1: Construction of Wind Power Plant

Where A is the area swept by the blades of the turbine, ρ is the air density, V_{wind} is the speed of the wind and C_p is the power coefficient, which depends upon the pitch angle β of the blade and the tip speed ratio λ. The tip speed ratio can be computed by:

$$\lambda = \frac{V_{tip}}{V_{wind}} = \frac{\omega r}{V_{wind}} \tag{2.2}$$

In 2.2, V_{tip} is the blade tip speed and ω is the speed of the rotor while r is the radius of the blade. Normally the rotor speed ω is regulated by acting on the controller of the variable wind turbines to optimize the tip speed ration λ which in turn maximizes the coefficient C_p. If the wind turbine rotates too slow, the wind will pass without hitting the turbine blades and if the wind turbine is too fast it will be difficult for wind to pass through the rotor. Because of this, the wind turbines are designed to have an optimal tip speed ratio to extract the maximum amount of energy.

2.1.2 Operation Criteria of wind Turbines:

The power extracted from the wind is the cube of the wind speed as seen in eq:2.1, the power generation increases with the increase in wind speed. Since the power content is low and with the low wind conditions, wind turbines start only if the wind speed is around 3-4 m/s. Power generation reaches its rated power generation at wind speed around 9-15 m/s. The power output of a wind turbine is limited at higher speeds. This limitation in wind power from the turbines can be achieved in three different ways. Either by pitch control, stall control and active stall control[13]. At high wind condition, such as above 25 m/s , wind turbines will shut down. Figure 2.2 shows the basic function of pitch control and stall control, where the rotor blade is in sectional surrounded by the wind[13].

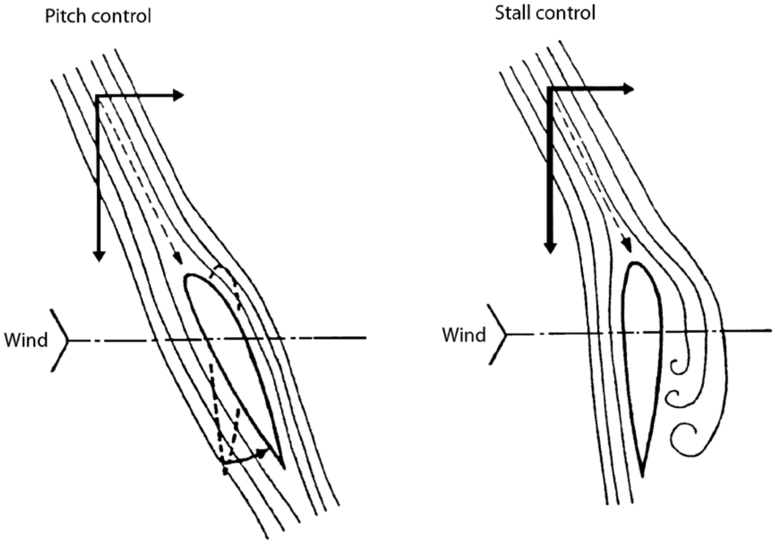

Figure 2.2: Pitch Control and Stall Control

Considering the pitch control in wind turbines, power flow in wind turbines is controlled by means of pitch angle of the blades, the blades are turned to or against the wind depending on a small or large power output[13]. The advantages and disadvantages of pitch control are explained below:

- The advantages of pitch control is that they give a good control over the power output as well as the possibility of emergency shutdown if needed, reduction in load with the increase in wind speed, they can assist in the start of wind turbine, another benefit is aerodynamical dampening and also a built-in braking.[13]

- The disadvantages of pitch control are that they make the system extra complex and increase the cost of the wind turbine with pitch mechanism and complex control systems[14]. The possibility of high fluctuations in power output when the wind speed varies fast and the power limitation varies fast with it as well.[13]

Stall regulation is the cheapest and the simplest control method to regulate power from the wind turbine and it is a passive wind control method[14]. The blades have a fixed angle and are set into a hub. The power flow in wind turbine is always controlled aerodynamically and are designed to slow the wind turbine if the wind velocity exceed certain value. It is not possible to manufacture blades that give stall limitation exactly when nominal power is reached instead the stall effect increases gradually to nominal wind speed, it generally increases from 8-9 m/s to nominal wind speed. At higher or nominal wind speeds, total power limitation is reached. when the wind power plant rotation speed is fixed there is no need to change the blade angle, in case the rotor speed increases proportionally with the wind velocity, it results in an optimal angle. The stall control is fairly slow and have less power variations as compared to the pitch control which is a faster method.[13]

- Some of the disadvantages of the stall control is such that there is a variation in maximum steady-state power of the wind turbine due to variation of temperature and air density. At lower wind velocity the power production is low, and if the the wind turbine goes into over-speed it must be stopped .

The benefit of using active stall control is that it offers advantages of both the pitch control and stall control. the rated power level can be achieved precisely, due to the pitch control blades without the effects of the difference in velocity or air density because of stall control. Similarly, by using the stall control the uncertainties in the rated power level can also be avoided because of the pitch control. Active stall control provides power control, we can also use the blade pitch system to accelerate the blades from idling to operational speed and back to safe idling in case of functional error or grid loss[15].

The control methods of wind turbine are chosen depending on the type of wind power plants. Active stall control and stall control is used mostly when the wind power plant is constructed with the fixed rotor speed. Pitch control is used when the wind power plant is constructed with the variable rotor speed but nowadays, all large wind turbines have pitch control and variable rotor speed.

2.1.3 Types of Wind turbines:

There are two basic types of wind turbines the horizontal axis wind turbines (HAWT) and vertical axis wind turbine (VAWT). Most of the wind turbines have a horizontal axis design with the blades that rotate around a horizontal axis as shown in figure: 2.1. Horizontal axis wind turbine (HAWT) is basically of two types. One is upwind turbines where the wind hits the blade before the tower and the other is downward wind turbine where the wind hits the tower before the blade. Upwind turbines and downwind turbines both include a yaw drive and motor, components that turn the nacelle to keep the rotor facing the wind when its changes its direction.

Vertical axis wind turbines(VAWT) exists in smaller scale as compared to HWAT and one model is shown in figure: 2.3, they further divided into two main types based on their designs. One is drag-based, or Savonius, and the other is lift-based or Darrieus. Savonius turbines generally have rotors with solid vanes that rotate about a vertical axis. Whereas Darrieus turbines have a tall vertical air foil style which resembles in shape of an eggbeater.

When comparing both HAWT and VAWT, HAWT extracts more power from the wind. They can also operate on higher wind speeds. Moreover, they are more efficient. They require a streamline wind conditions where a constant stream and wind direction is available. As a disadvantage , They require high maintenance. On the other hand, VAWT rotating axis of the blade is perpendicular to the direction of the wind. VAWT are small in size and therefore, extract less power from the wind and they can't be build at a higher altitude because they are not robust and breakdown easily.

2.2 Energy storage systems(ESS):

With the increase in the share of wind power in the electrical grid it points towards the major challenge that implies with the wind power integration in the grid. For the wind power plants to function as the conventional power plants, energy storage systems can be added in combination with the wind power plant. On one hand, by adding energy storage(ES) device with the wind power plant, not only increase the storage of power and energy but also when integrated into to the grid, it makes it more

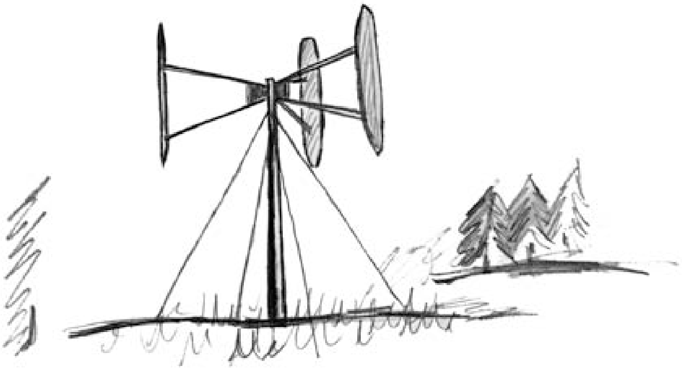

Figure 2.3: Vertical Axis Wind Turbine (VAWT)

controllable, predictable and less variable[16].

On the other hand, energy storage can provide the several service such as grid frequency regulation, forecast accuracy improvement and power gradient reduction[17], and have specific requirements on the energy storage system(ESS); while some of these applications require high power density. Others require low power density[17]. There are many types of energy storage systems available in the market. Despite all of them can be associated with the wind power plants, not all of them are suitable. After the extensive study of their properties, they are tabulated below in table 2.1. A deeper knowledge Battery energy storage systems(BESS) is gained from [19]. We will have a brief look at few of these technologies below:

- **Super-capacitors**
  Super-capacitors are the very high capacitance energy storage device. They are used for storage which is undergoing frequent charge and discharge cycles at a very high current and short duration. Its efficiency is considered around 95% longer life time which allows thousands of cycles without considerable loss of energy storage capacity. Super-capacitors are suitable for applications in the wind industry where they are able to provide power for short periods of time to suppress fast wind power fluctuations. The major drawback of this kind of energy storage is that they are low energy density which leads to high costs for large scale applications.

- **Flywheels**
  Flywheel energy storage are the mechanical energy storage devices which store energy in the form of kinetic energy. They store their kinetic energy in a rotor which is charged/discharged through a motor/generator.[18] Flywheels are charged by accelerate the rotor to a very high speed. It can be done during the off-peak hours by drawing energy from the grid or from the wind power plant. Flywheel energy storage(FES) has a direct relation with rotor mass and square of the speed surface. So higher the speed, more energy is stored in the system. There are two categories of flywheel:low-speed flywheel and high-speed flywheels. Flywheel energy storage(FES) devices such as high-speed FES are able to speed up to 100 000 rpm. They can be used for short duration (approx. one hour). Moreover, they require little maintenance. Flywheel can be optimised for either storage or for power capabilities making the design unsuitable. Therefore, they can't be used as the sole providers of the energy storage for the power generation applications.

- **Lithium Ion Batteries**
  Lithium ion batteries are one of the most widely used batteries. They are used commonly in the electric vehicles. The cathode of the Li-ion batteries is lithiated metal oxide while the anode is made of graphite carbon with layering structure. The electrolyte in Li-ion batteries can be solid polymer, gel or liquid. However, the majority of the batteries use liquid electrolytes which contain lithium salt such as; LiPF6, LiCIO4, LiBF4 etc. During the charging process, lithium ions migrate from cathode to anode through electrolyte where they combine with the electrons and deposited between the carbon layers as lithium atoms.Whereas the discharging process is it´s reverse.

  Lithium ion batteries are characterized as the most efficient batteries among the energy storage technologies and have high energy densities of around 150-200 Wh/kg. Lithium ion batteries have depth of discharge(DOD) at 80% and they can operate at temperatures between -30° C and 60° C. The main drawback in using the lithium ion batteries is their initial high cost due to their packaging and internal overcharge protection circuits.

  Lithium ion batteries are widely used in electric and hybrid electric vehicles. Li-ion batteries are considered most suitable solution for grid support application such as; commercial end energy management systems, frequency regulation, wind power smoothing and Solar PV power smoothing as well.

  The use of Li-ion battery technologies for grid support applications was verified in several field demonstrations. In 2017, Hornsdale power reserve was deployed by Tesla which has a capacity of 129 MWh and 100 MW. Later, it was expanded to 194 MWh at 150 MW in 2020. This energy storage plant is used to provide stability to the grid and also used to prevent blackouts.

Table 2.1: Battery Properties Comparisons [[19],[20],[21], [22]]

Technology	Discharge time	Cost in $/kWh	Cycling capability @ % DOD	Life (Years)	Energy (η%)	Self Discharge (%)	Specific Energy (Wh/Kg)	Operating Temperature in °C
Na-S	Sec-Hrs	200-600	2500 @100	10-15	75-85	N0	125-175	320
Lead-acid	Sec-Hrs	50-150	500-2000 @70	5-10	70-80	<0.2	30-50	-5 to 40
Ni-Cd	Sec-Hrs	400-2400	3500 @100	10-20	60-80	0.2-0.3	40-60	-40 to 50
Li-ion	Sec-Hrs	900-1300	1500-3500 @80	10-15	75-95	1-5	150-250	-30 to 60
VRB	Sec-10 Hrs	600	100 - 13,000 @75	10-20	70-85	No	30-50	0 to 40
Flywheel	Sec-Hrs	200 - 150,000	-	20	85-95	-	100-130	-35 to 40

2.2.1 Selection of Battery Energy Storage System(BESS):

Battery Energy Storage systems (BESS) are made up of multiple electrochemical cells connected in series or stacking them together to get the desired voltage and capacity. The different properties of batteries are discussed in table 2.1. Upon looking at the table , we can conclude that Nickle-Cadmium batteries suffer from "memory effect"[27] and these batteries are quite costly. Moreover, they pose some health risks as well. Flow batteries can be used as well in renewable applications because of their long term storage of energy. Flow batteries include Vanadium redox batteries (VRBs) and Ploysulfide bromide batteries (PSBs), which is due to their reliability and recycling capabilities. Lead-acid batteries are in the market for more then a decade now and are highly suitable for renewable integration. Reason being, their low cost and low self discharge. Lithium-ion batteries have the highest energy density , are light in weight as well and portable which enhances their flexibility and modularity. Amongst all these battery types, only lithium ion and lead-acid batteries are available commercially.

2.3 Power Market:

A consequence of increased penetration level of wind power in the electric power system is that the spot market will be more volatile and the requirement for the real-time balancing capacity will be increased. The larger demand for the balancing capacity is due to the fluctuations in the wind power generation, also because it is difficult to predict wind speed accurately for more than 24 hour. Increase volatility in spot prices is not necessarily a problem, as long as these prices reflect the true marginal cost of the system operations and the players can respond to correctly to these prices, while the errors in wind power forecast will result in less efficient usage of the system. The forecast errors in wind power production make it necessary to invest in the increased flexibility of the existing units or install new power plants. Hence it is important to reduce the wind power forecast error or if the consequences can be mitigated.

2.3.1 Nord Pool Market:

Generally in an electricity market a typical contract is that the seller injects an amount of energy in the electric power system during a certain period such as intraday or day-ahead market, and the buyer extracts the same amount of energy during the same period. In the Nordic electricity market 1h is used as a trading period.

The trading in the Nordic electricity market is mostly done ahead of the trading period. Consumers and producers can trade based on the forecasts in market places such as: day-ahead sport market, Elspot, the adjustment market Elbas and bilateral contracts. Elspot is the sealed bid auction market with sealed marginal pricing, while the spot market is the most important market because it has the largest volumes and the pricing of the spot market also have an influence on the other markets.

The Nordic system operator runs a real time balancing market during the trading period. The market is used for restoring primary control reserves, manage transmission congestion and to restore the frequency to it nominal value, these controls are considered as tertiary controls. Practically, the consumers and the producers are expected to follow the trading in the day-ahead spot markets. If there are any minor deviations in the system they will be managed by the primary control, but if the operator sees that the frequency may increase or drop outside the normal operation interval then the bids will be activated from the real-time balancing market[28]. The players are only paid for the period that are activated during the real-time balancing and the market is also voluntary. The up-regulation price is uniform for all up-regulation bids and the down-regulation price is also uniform for all down-regulated bids. The measurement of the generation and the consumption is compiled after the trading period and are compared with the real-time balancing market and the day-ahead spot market and this information is used for the imbalance settlement.

Nordic power system has a large share of hydro power plants and a considerable storage capacity in hydro reservoirs, and thermal power plants such as: nuclear power plants are used for base load or gas turbines which have a short start-up time are used for short term power production. This tells us that the ramp rates and unit commitment is rarely a constraint for Nordic power system. The main impact of the forecast errors is related to the up and down-regulation units because the system had to deviate from the planned generation, which may result inn extra costs such as: opportunity costs (change in water value), lower efficiency, and start-up and shut-down costs. All these costs are included by the player before they submit there bids in real-time balancing market[28]. Therefore, the price difference will increase between the real-time balance market and day-ahead spot market with increasing volumes of activated real-time balance market (the different in these markets is referred as regulation fees), which indicates higher costs for the players responsible in the imbalance market and also for the system operator in the real-time balancing phase. Furthermore, more units will be stopped or started more frequently and the system resources will be deployed less efficiently because more units will be operated off their best efficiency points due to forecast errors.

3

Methodology

In this paper, two different models are investigated. In Model-1, we propose a method to define the battery capacity that is required to deliver constant power for the system. During the planning and designing of the wind battery hybrid power system (WBHPS), an historical wind turbine data was acquired to make sure that the defined battery capacity can handle the wind power variation. The historical wind data acquired for this study was over a period of 1 year. The study investigates the battery capacity which is required to deliver constant power over different time periods, furthermore is it economically beneficial to have BESS if we intend to deliver constant power over longer time periods.

In Model-2 the main purpose of the simulation study was to see its impact on wind farm producers profit based on the planned and forecast-ed wind power production. In this model, the simulation studies were based on the predicted values of the wind turbine, and the deviation in this prediction, considering the electricity price, BESS consumption costs, and the working curve of the battery storage. The battery capacity was defined here which is 60 MWh.

The model used in this study controls the BESS using the forecasted value of wind turbine generation and the power delivered to the grid. The model uses the last measured value of the BESS state of energy (SOE) as an input and BESS charging /discharging power is considered as an output for each time step of the scheduling period. The BESS capacity is calculated in Watt-hour (Wh), thus instead of SOC, the term SOE is used [23]. In addition, Depth of discharge (DoD) is defined as the discharged energy from 100% SOE i.e., $DoD = 1 - SOE$ [26].

3.1 Battery Capacity:

To mitigate the wind power variation, the battery capacity must be sufficient including the power and energy ratings of the capacity. To determine the battery capacity, the dispatching strategy for the wind power should be defined primarily. In [25], several dispatching strategies are investigated and compared regarding the battery capacity and its ability to cooperate with the TSO. In several dispatching strategies the averaged method requires the smallest battery capacity to be able to cooperate with the TSO.

To calculate the size of the battery, we need the average energy requirement for the battery per day, which can be calculated from the maximum power surplus/deficit. Let $P_d(t)$ is the power difference which is calculated in (3.1), where the $P_{dis}(t) = P_{load}(t)$ is the power that is needed to be dispatched, while $P_{gen}(t)$ is the power generated by Wind Turbine over a time period Δt.

$$P_d(t) = P_{gen}(t) - P_{dis}(t) \tag{3.1}$$

Once we have the $P_d(t)$, we can calculate the E_{batt}. Here, N is depicted as the number of days.

$$E_{batt}(kWh) = max\sum_{i=1}^{N} P_d \Delta t \tag{3.2}$$

When sizing the BES, we need to take into account the DoD%, DoD of each battery is selected to ensure the efficiency and longevity of the battery. Days of autonomy are indicated as the number of days the battery is capable of handling the dispatch without the need to be charge. In standalone case application, this factor varies from 4 to 6 days though it can maybe be higher then 10 days in professional applications [24]. The battery capacity can be calculated as:

$$E_{batt(max)}(kWh) = \frac{E_{batt}(kWh)D}{DoD\%} \tag{3.3}$$

The required battery capacity E_{cap} in Ah can be calculated as:

$$E_{cap}(Ah) = \frac{E_{batt(max)}(kWh)}{V * 1000} \tag{3.4}$$

In (3.4), V is the nominal (DC) voltage of the battery, E_{cap} is in Ah which is the required battery capacity. The ratio between the battery capacity E_{cap} to Ah rating of single battery module/cell gives us the number of battery which is needed to be connected in parallel (N_p). The ratio between the system voltage and the voltage rating of single battery gives us the number of batteries needed to be connected in series (N_s) for the formulation of battery bank. There are a lot of optimization algorithms which can be used to further minimize the size of the battery bank while considering the battery capacity E_{cap}.

3.1.1 Scheduling of BES

For the proposed BES modeling, the battery energy management system operates on the charge/discharge model which is based on the Power surplus/deficit occurring in the Wind Battery Hybrid Power System (WBHPS). The constraints that are used in the BESS operations are summarized as follows.

1. Power balance Constraint:
$$P_{gen}(t) = P_b(t) + P_{dis}(t) \tag{3.5}$$
2. Battery power limitation Constraint:
$$P_{b,min} \leq P_b(t) \leq P_{b,max} \tag{3.6}$$
3. Battery SOC Constraint(s):
$$SOE_{min} \leq SOE(t) \leq SOE_{max} \tag{3.7}$$
where the SOE level is calculate by using this equation:
$$SOE(t) = SOE(t-1) + \frac{P_b(t)\Delta t}{E_b} \tag{3.8}$$
4. Battery energy limitation Constraint:
$$E_{b,min} \leq E_b(t) \leq E_{b,max} \tag{3.9}$$
Case 1: Battery is charging
$$E_b(t) = E_b(t-1) + (\Delta t P_b(t))\eta_{ch} \tag{3.10}$$
case 2: Battery is discharging
$$E_b(t) = E_b(t-1) + \frac{(\Delta t P_b(t))}{\eta_{dis}} \tag{3.11}$$

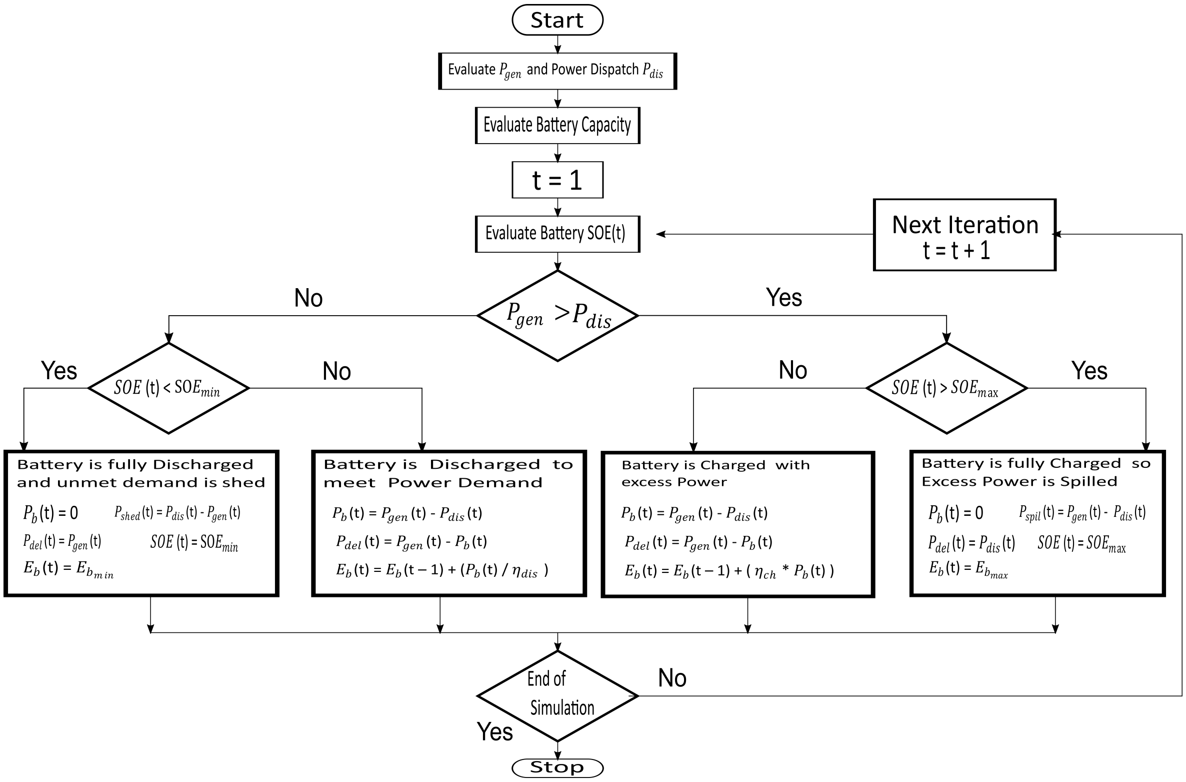

Figure 3.1: Battery Flow Chart

Where, P_b is the power exchange to and from the battery during the charge/discharge cycles. It is positive when charging and negative when discharging. E_b is the battery Size in Wh. A control block for the energy management of the batteries that take in to account the state of energy of the batteries in order to avoid the over-charge and over-discharge has been developed. In case when the battery is fully charge, the excess energy is spilled . Whereas when fully discharged , surplus demand is shed. The energy management flow chart for the system is shown in figure 3.1 above.

3.2 Wind Power Output Model based on Probability Theory

Based on central limitation theory, since their are large number of wind turbines in a wind farm, and their distribution in a larger area, it can be assumed that the prediction error of the wind farm's output obeys the standard normal deviation, with an average of zero and standard deviation of σ_w [36], [37]. Research conducted on the prediction of wind power output that the relationship between the output prediction data[[38], [39]] and the standard deviation of the wind power output prediction is linear, the mathematical description for which is:

$$\sigma_w(t) = k_w P_{gen}(t) + k_0 \tag{3.12}$$

In (3.12), P_{gen} is considered the predicted value of the wind power output, σ_w is the standard deviation of the wind power prediction deviation in time slot t and k_w, k_0 are the coefficients of the wind power output prediction. According to the probability theory and mathematical statistics from [40], the probability of prediction deviating with in range of $\pm 3\sigma$ is 99.75%. The output of the wind farm in time period t is :

$$\tilde{P}_{gen}(t) = P_{gen}(t) + \sigma_w(t) \tag{3.13}$$

where $\sigma_w(t)$ is the wind power output prediction deviation.

3.2.1 Wind - Battery Profit Model

The aim of this model is to see the increase in the economic profit by temporarily shifting the wind power output using the battery system. The battery system is able to quickly respond to the deviation in the wind power output, thus reducing the cost associated with this deviation. The wind farm predicts the output of the following day and implements the output plan for the following day, in conjunction with the BES to maximize economic profit. The function is expressed mathematically as:

$$C_{total} = \sum_{t=1}^{N} [C_{plan}(t) - C_{punish}(t)] - c^B - c^{om} \tag{3.14}$$

In (3.14), C_{total} is the total economic profit of the wind and battery system, C_{plan} is the planned output profit of the wind and battery system, C_{punish} is the punishment resulting from the deviation and failure to deliver power to the grid, c^B is the daily battery cost life loss due to cycle aging and c^{om} is the daily maintenance and operations costs of the battery.

The wind farm owner provides the output plan of the day based on the wind output prediction, the electricity price and the battery capacity. The economic profit for the wind-battery system can be calculated as:

$$C_{plan}(t) = c_{spot}(t)(\tilde{P}_{gen}(t) + P_b(t))\Delta t \tag{3.15}$$

In (3.15), C_{plan} is the planned economic profit of the whole system, while $c_{spot}(t)$ is the electricity price at time t, $\tilde{P}_{gen}(t)$ is the wind power output prediction value at time t and $P_b(t)$ is the power delivered by the battery at time t.

Wind power can only be predicted in certain limit because of that, in some cases the actual output power to the grid is not consistent with the predicted power. In this case, the battery storage has to respond and deliver this unbalanced power. This power deviation can be calculated as:

$$P_{dev}(t) = |\tilde{P}_{gen}(t) - P_{gen}(t) + P_b(t)| \tag{3.16}$$

In (3.16), $P_{dev}(t)$ is the deviation of the wind-battery output from the wind prediction output from time t and $P_b(t)$ is the power delivered by the battery to balance the deviation of the wind power prediction at time t.

However, due to the limitation of the battery capacity, it is difficult to balance all the deviation form the wind power prediction, because of this unbalanced power wind farms can't deliver the committed power the grid, making it difficult for the central control of the market. Thus making it necessary to punish the wind farm owner. which is expressed as:

$$C_{punish} = w * c_{spot}(t)P_{dev}(t)\Delta t \tag{3.17}$$

In (3.17), w is the penalty co-efficient of output deviation, C_{punish} is cost punishment for deviation and $c_{spot}(t)$ is the on grid price at time t.

3.2.2 Cost of Battery life loss and Maintenance:

Since the operating environment of the battery is complex and undergoes a series of irregular charging and discharging processes, which results in loss of available battery capacity and is non-linearly linked to many factors depending on the chemistry [41], [42].Battery cycle aging can increase due to high operating temperature,high C-rates, operation in very low/high storage voltages and frequent cycling with high DOD. while calendar aging is more severe at high SoC levels and high temperatures [43].

The model presented in [44], [26] is used to model the dependency of cycle aging on collective throughput:

$$q = B_1 e^{B_2 I_c} \sum_{t=1}^{N} P_b(t)\Delta t \tag{3.18}$$

In (3.18), q represents the battery capacity loss in %, while B_1 and B_2 are pre-exponential and exponential factors which can be obtained from empirical fitting of experimental data. I_c is the average daily C-rate, which is entered as a parameter, thus (3.18) becomes linear. The Battery cost used in (3.14) is calculate as:

$$c^B = \frac{C^{B,0} q}{100\% - \eta} \tag{3.19}$$

In (3.19), η is the end of life retained capacity percentage of the battery and $C^{B,0}$ is the installation cost of the Battery.

3.3 Study Approach:

In this paper, both models follow the rule-based control method for charging/discharging the battery. The system consists of 8 wind turbines and BESS connected to the grid. The wind turbine data used in this study is collected from project Röbergsfjället, which is located in Dalarna County east of Torsby, Sweden [31], the specifications of the wind turbine are listed in the table 3.1. Tesla Power-pack is considered in the study for BES [35]. The approach adopted in the simulation studies and the demonstration of the BES dispatch depicted in the flow diagram is shown in Fig.3.1.

Table 3.1: Wind Turbine Specifications[[33],[34]]

S.Number	Specification	Value	S.Number	Specification	Value
1	Rated Power	$2000kW/2200kW$	5	Blade Length	$44m$
2	Cut-in Speed	$4m/s$	6	Frequency	50/60 Hz
3	Cut-out Speed	$25m/s$	7	Blade Length	$44m$
4	Rotor Diameter	$90m$	8	Swept Area	$6362m^2$

Nord Pool market price [32] data was used in this study, while $\eta_{ch} = 0.83$, $\eta_{dis} = 0.85$ and $\%DoD = 0.8$ are considered the same for both models. In Model-2 the maximum charging and discharging power of the battery system is 10 MW, while the capacity constraint is 0 $\backsim$ 60 MWh. The Li-ion cycle aging parameters used were taken from [44], where $B_1 = 0.0013$ and $B_2 = 0.3534$, while for parameter I_c in (3.18), which is considered Model-2, the daily average C-rate is considered 0.5 for charging/ discharging of the battery. The BES installation cost is considered 3300 SEK/kWh ($398), while the maintenance cost is considered 0.036 SEK/kWh.

During the simulation studies wind turbine generation, electricity price data was used from 2018 to run the BES scheduling simulations, where $\Delta t = 1$ Hour. Originally the data collected from the wind turbine site was for every second for one year. The initial and end levels of SOE at each simulation period are set to be 50%. Moreover, SOE is limited to 10-90% in this study.

4

Results And Discussion

4.1 Simulation results:

The simulation studies conducted on Model-1, few cases are considered to see how much constant power the wind farm owner can deliver under different time periods with BESS and wind turbine together. The time periods considered for Model-1 case studies are 1 Day, 1 Week, 1 Month, 6 Months, and 1 Year. Moreover, the battery SOE is limited between 10-90 %.

- **Case 1 :**
  As Shown in Fig 4.1 of simulation, we commit the WBHPS to supply constant power to the grid over a period of one day. Wind turbines generated 253.54 MWh energy and average power at time Δt was 10.56 MW, during this period, excess energy spilled during this period is 29 MWh, while no excess energy was shed during this period. Power delivered to the grid/TSO was 9.4 MW to ensure that WBHPS can deliver constant power committed. The BES size calculated to deliver this power was 35 MWh and maximum power BES can deliver at time Δt is 19 MW/h, battery was charge till $E_{b_{max}}$ = 31 MWh and discharged till $E_{b_{min}}$ = 3.5 MWh.

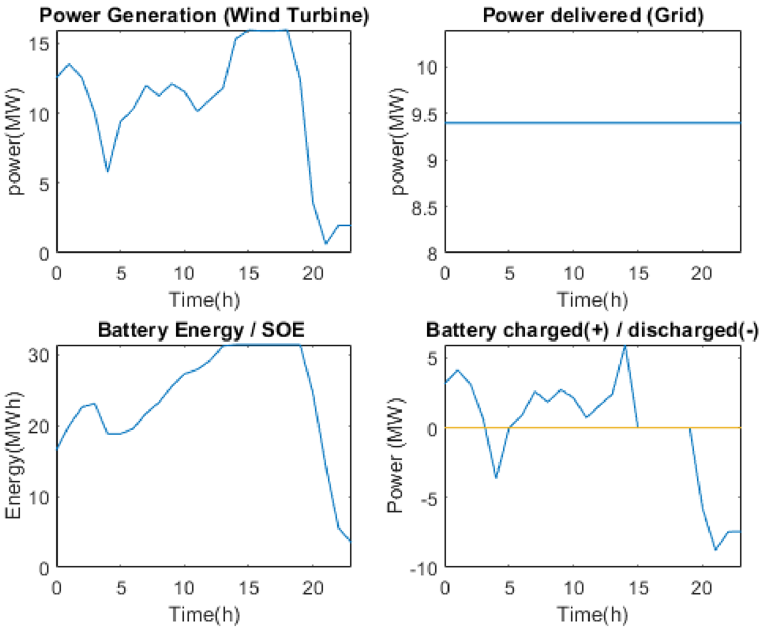

Figure 4.1: Power Commitment(1 day)

- **Case 2 :**
  In Fig 4.2 of simulation, we commit the WBHPS to supply constant power to the grid over a period of 1 week. Wind turbines generated 1.061 GWh energy and average Power at time Δt was 6.32 MW over a period of 1 week. No excess energy was shed during this period, while excess energy spilled during this period was 272 MWh. Power delivered to the grid/TSO was 4.32 MW to ensure that WBHPS can deliver the constant power committed. The BES size calculated to deliver this power was 249 MWh, moreover battery was charge till $E_{b_{max}} = 224$ MWh while discharged $E_{b_{min}} = 24.9$ MWh.

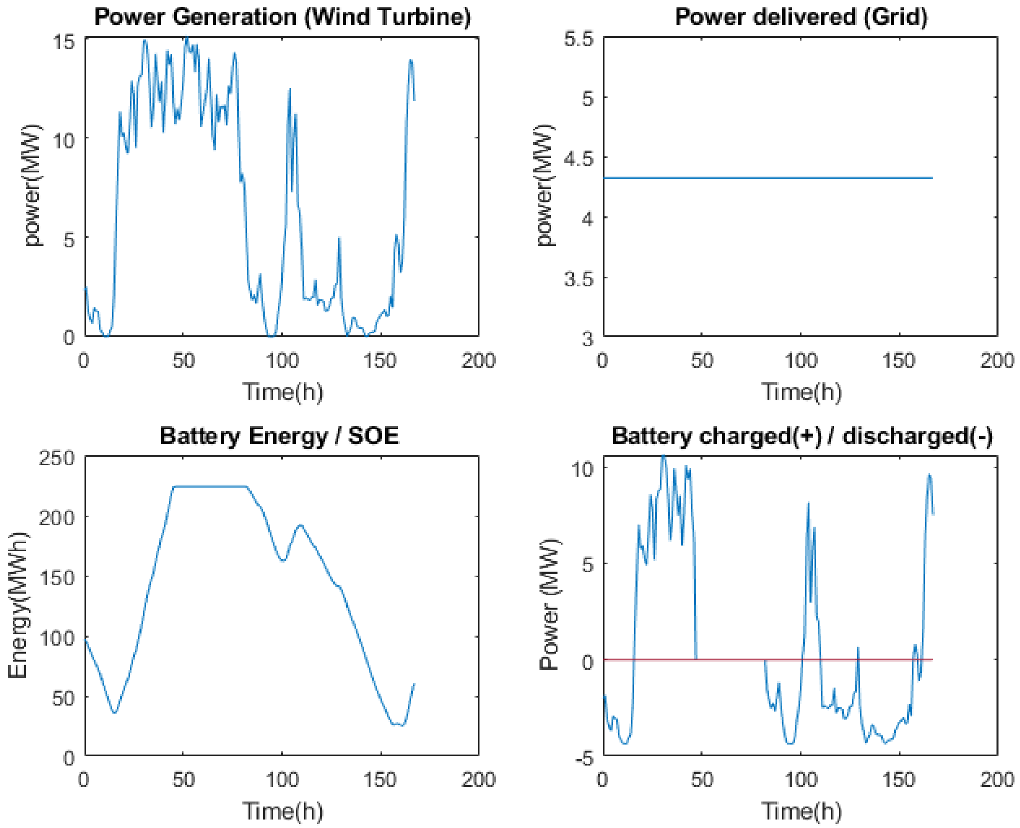

Figure 4.2: Power Commitment(1 Week)

- **Case 3:**
  In Fig 4.3 of simulation, we commit the WBHPS to supply power to the grid over a period of 1 month. Average power generated by wind turbine at time Δt was 4.47 MW, while total energy generated over this period was 2.898 GWh. Excess energy spilled during this period was 1.2 GWh, while no excess energy was shed during this period. Power delivered to the grid/TSO was 1.97 MW to ensure that WBHPS can deliver constant power committed. The BES size calculated for this period was 374 MWh, moreover battery was charge till $E_{b_{max}} = 336$ MWh while discharged till $E_{b_{min}} = 37.4$ MWh.

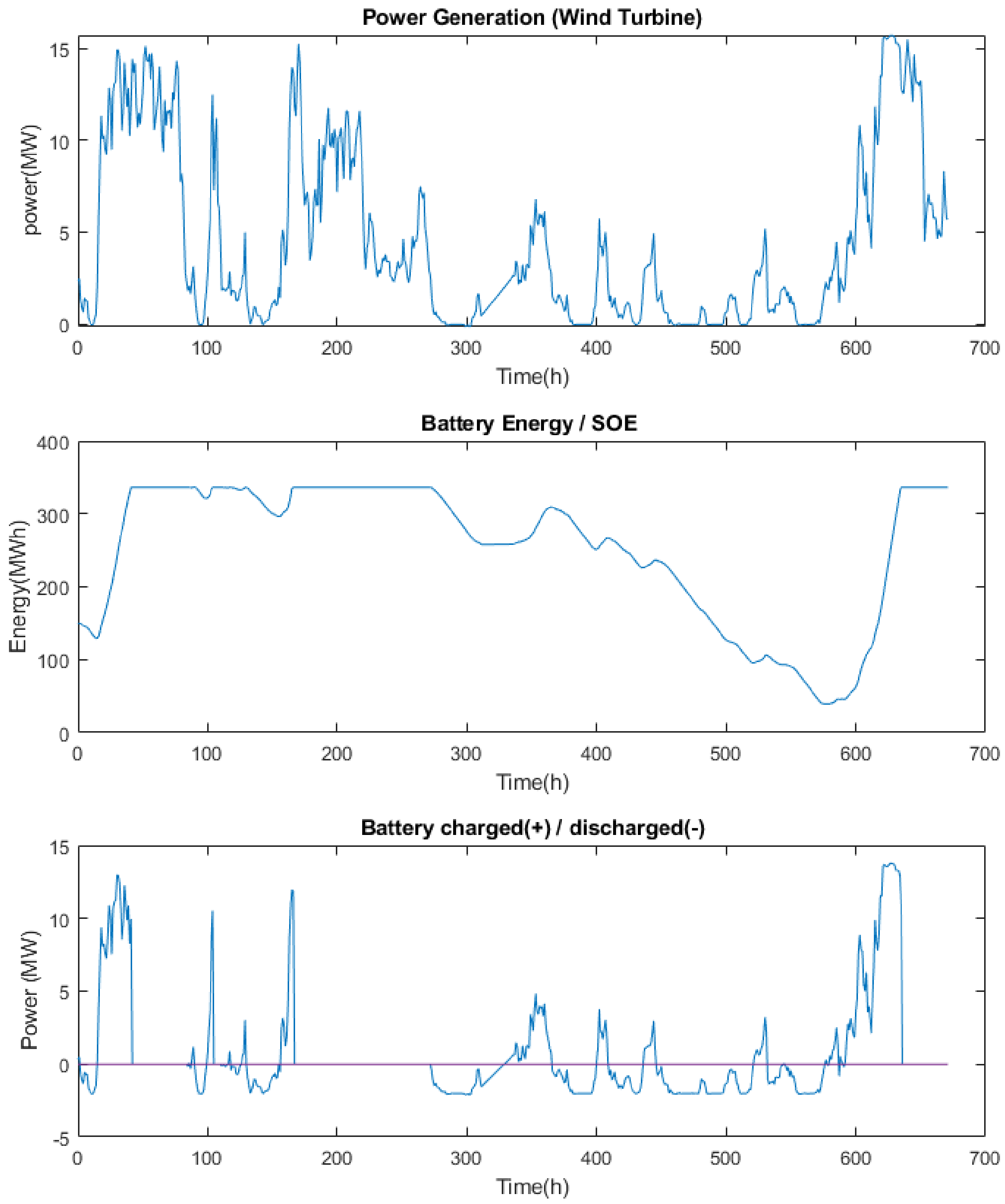

Figure 4.3: Power Commitment(1 Month)

- **Case 4:**
  In Fig 4.4 of simulation, we commit the WBHPS to supply power to the grid over a period of 6 month. Average power generated by wind turbine at time Δt was 3.97 MW, while total energy generated over this period was 14.194 GWh. Excess energy spilled during this period was 7.26 GWh, while no excess energy was shed during this period. Power delivered to the grid/TSO was 1.66 MW. The BES size calculated during this period was 382 MWh, moreover, the battery was charge till $E_{b_{max}} = 345$ MWh and discharged till $E_{b_{min}} = 38.3$ MWh.

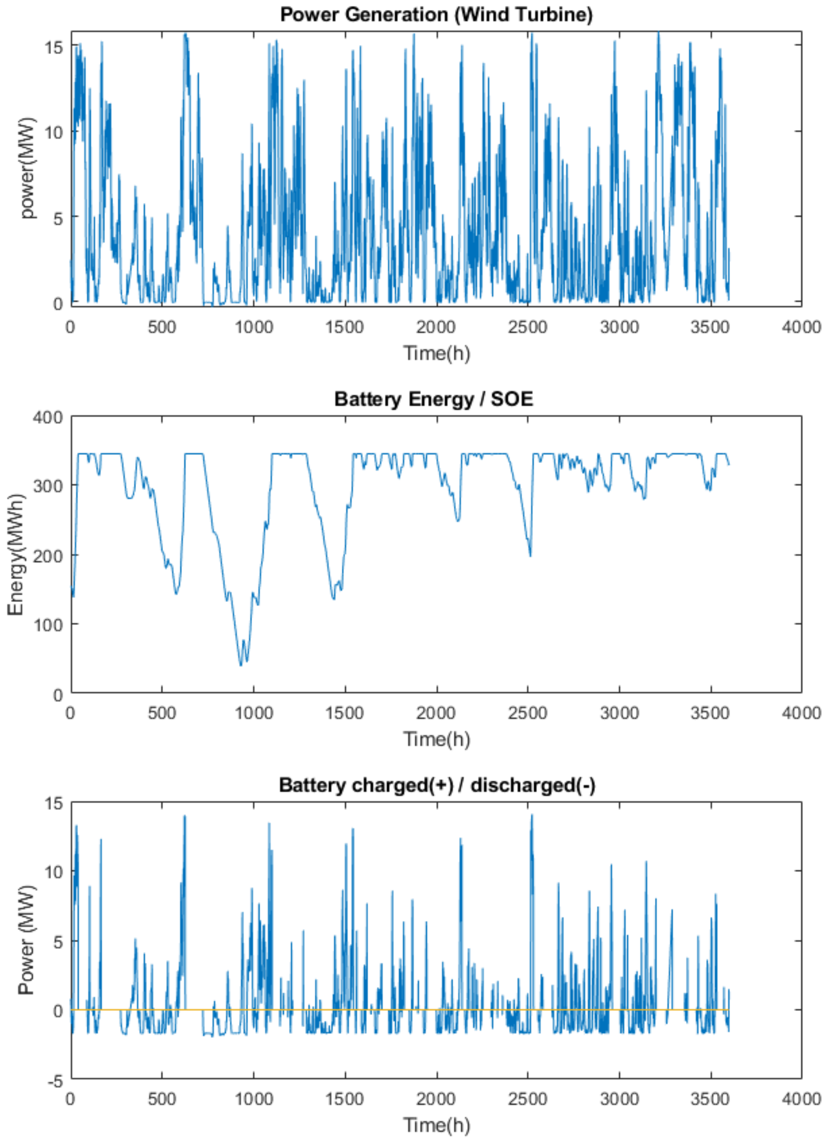

Figure 4.4: Power Commitment(6 Months)

When we doubled the size of BES as shown in Fig 4.5 to see its impact on the power delivery commitment. By increasing the size of BES, excess energy spilled during this period was reduced to 3 GWh and power delivered to the grid/TSO was increased to 2.63 MW. BES size calculated for this period was 708 MWh, moreover, the battery was charge till $E_{b_{max}} = 637$ MWh, while discharged till $E_{b_{min}} = 70.76$ MWh.

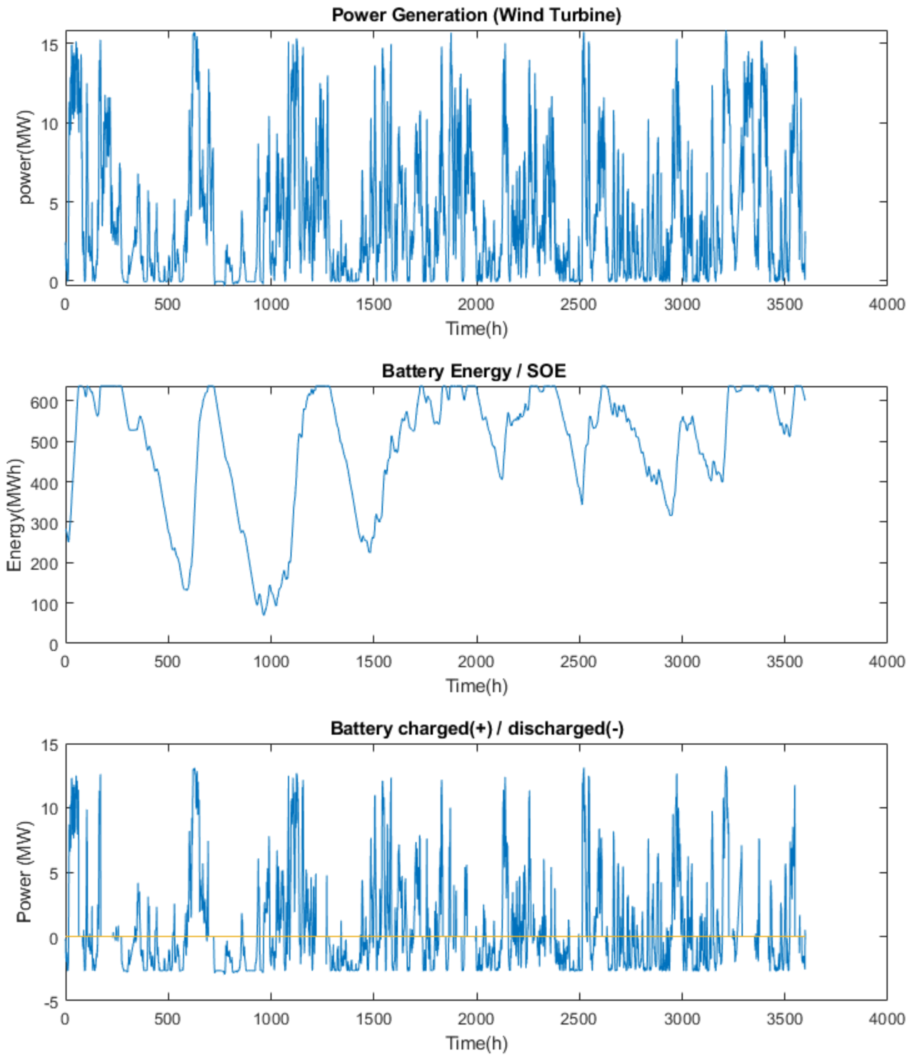

Figure 4.5: Power Commitment(6 Month "BES size doubled")

- **Case 5:**
  In Fig 4.6 of simulation, we commit the WBHPS to supply power to the grid over a period of 1 year. Average power generated by wind turbine at time Δt was 4.8 MW, while total energy generated over this period was 37.319 GWh. Excess energy spilled during this period was 26.34 GWh, while no excess energy was shed during this period. Power delivered to the grid/TSO was 1.24 MW. The BES size calculated during this period was 396 MWh, moreover, the battery was charge till $E_{b_{max}}$ = 356 MWh and discharged till $E_{b_{min}}$ = 29.5 MWh.

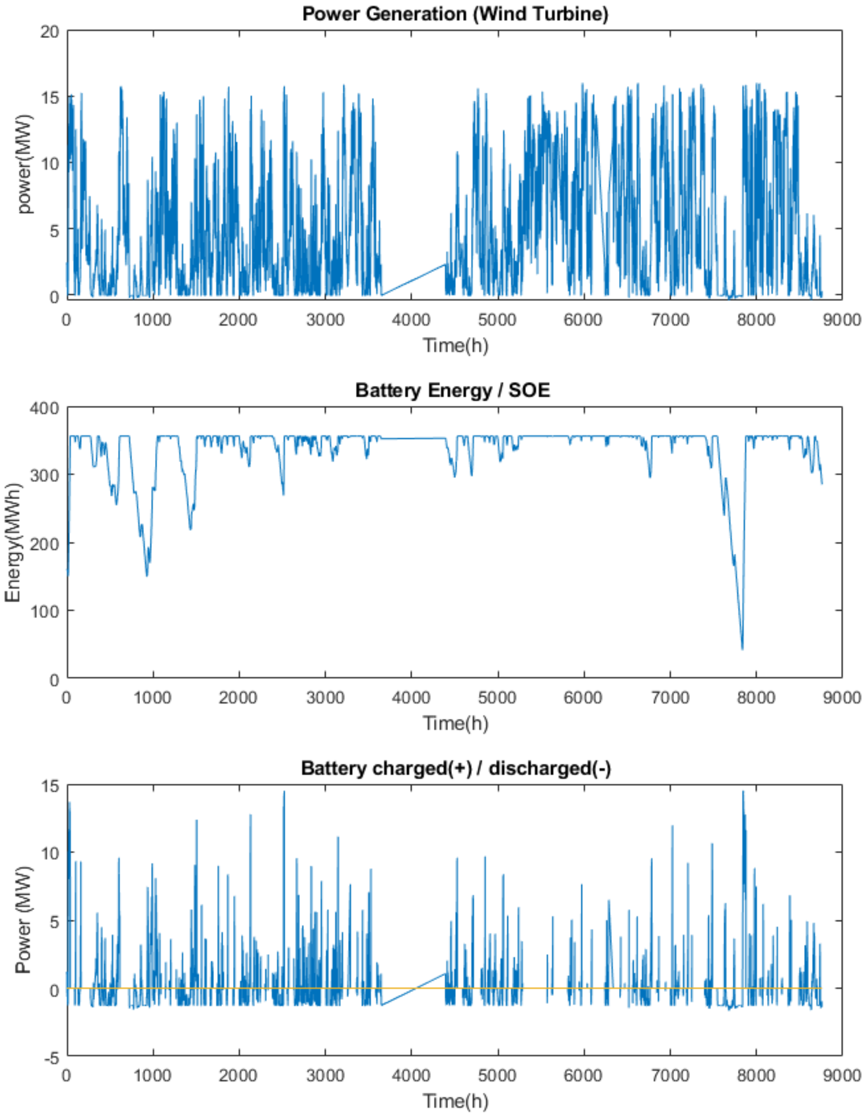

Figure 4.6: Power Commitment(1 year)
**Slope seen in the figure is because of missing data from July 2018

In Fig 4.7 by doubling the BES size, power delivered to the grid/TSO was increased to 2.07 MW, while the excess energy spilled during this period was reduced to 19.02 GWh. The BES size calculated was 741 MWh, moreover, the battery was charged till $E_{b_{max}} = 667$ MWh and discharged till $E_{b_{min}} = 74$ MWh.

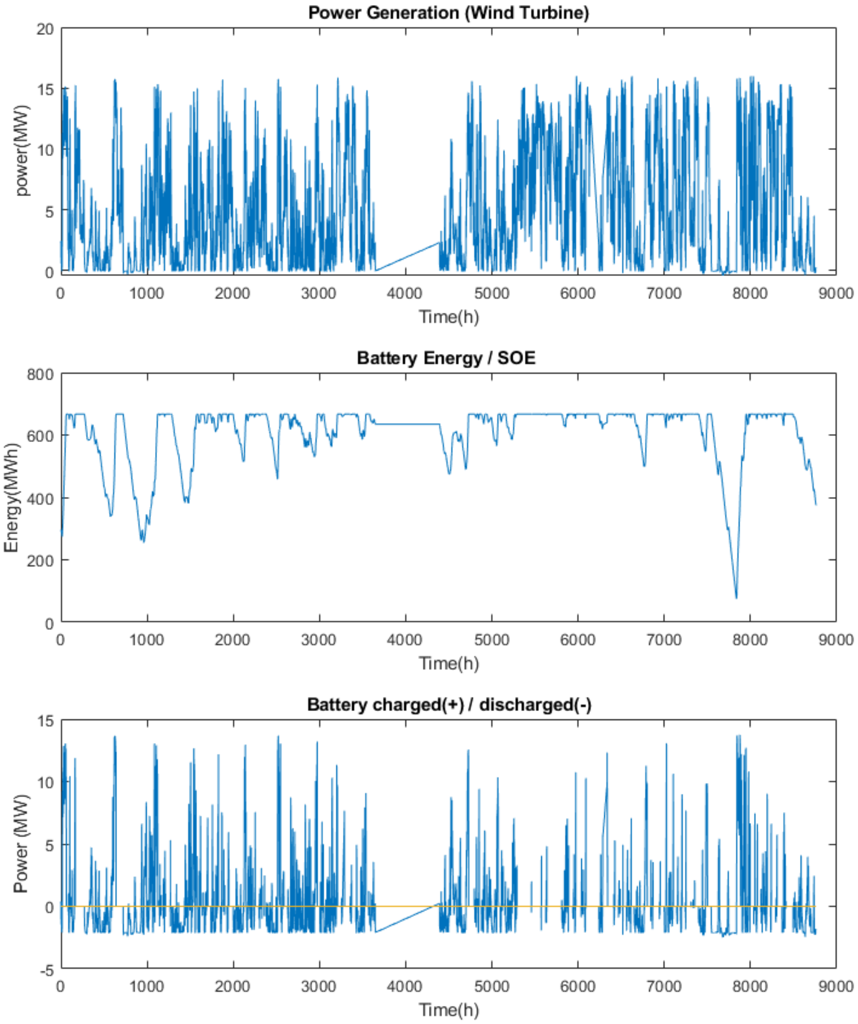

Figure 4.7: Power Commitment(1 year "BES size doubled")
**Slope seen in the figure is because of missing data from July 2018

When the size of BES increase by 4 times as shown in Fig 4.8 to see its impact on power delivery commitment. By increasing the size of BES, excess energy spilled during this period was reduced to 7.992 GWh and power delivered to the grid/TSO was increased to 3.29 MW. BES size calculated was 1.336 GWh, moreover, the battery was charged till $E_{b_{max}} = 1.203$ GWh while discharged till $E_{b_{min}} = 134$ MWh.

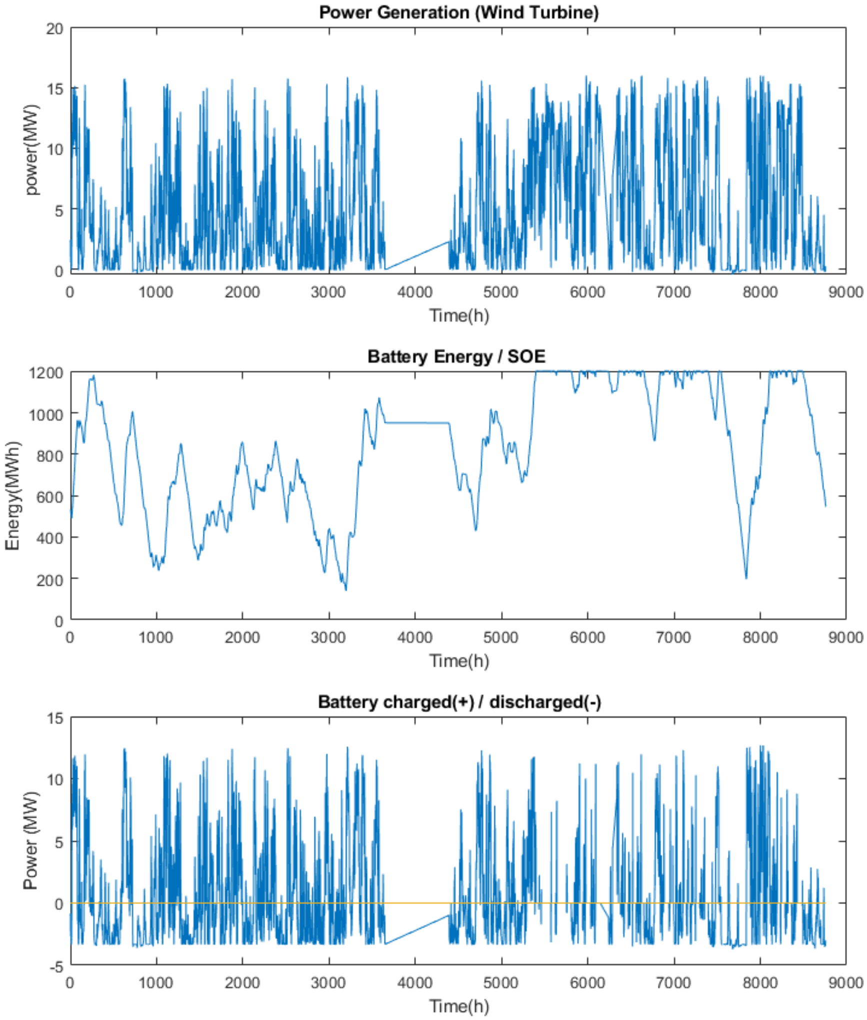

Figure 4.8: Power Commitment(1 year "BES size increased by 4 time")
**Slope seen in the figure is because of missing data from july 2018

In simulation study conducted in Model-2, the simulation was run for one day to see its economic profit for the wind farm without the BESS working mode and with the wind-battery working mode. The punishment coefficient w is applied to reduce the deviation between the planned and the forecasted output of the wind turbine. In case of any output deviation, the system should provide or store energy capacity, greater the output deviation is, the greater the energy which is needed or stored. The punishment coefficient is always greater then 1, while, it is considered as 1.25 in this paper, and the load is considered constant. The BESS capacity was considered as 60 MWh to run this simulation example.

Table 4.1: Economic benefits of wind farm with different levels of forecast.

K_w	K_o	Wind Farm Economic Profit (SEK)	Wind-BES System Economic Profit (SEK)
0.1	0.01	44,618	58,556
0.2	0.02	37,225	56,029
0.3	0.03	29,778	53,679
0.4	0.04	22,331	51,329
0.5	0.05	14.883	48,980

The predicted economic profit for the wind farm producers with BES and without BES is shown in table 4.1. When the wind prediction coefficient K_o and K_w are considered 0.01 and 0.1, the profit margin for the wind-battery system is 23% greater as compared to wind farm working alone. Similarly, when the wind prediction error K_o and K_w are 0.02 and 0.2, the profit margin between wind-battery and wind farm alone is increased by 33%. When the wind prediction error K_o and K_w are 0.05 and 0.5, the profit margin is increased by 68% as compared to wind farm working alone. As shown in table 4.1, the profit margin for the wind farm producers continue to decline, when the forecast error increases.

Table 4.2: Economic benefits of wind farm with different values of Penalty co-efficient.

w	Wind Farm Economic Profit (SEK)	Wind-BES System Economic Profit (SEK)
0.50	49,236	63,721
0.75	47,697	62,000
1.00	46,158	60,278
1.25	44,618	58,556
1.50	43,079	56,835
1.75	41,540	55,113
2.00	40,000	53,391

In table 4.2, the profit generated for wind farm producers from different values of penalty coefficient for the wind farm with the BESS working mode and the wind farm without the BESS working mode, and K_w and K_o are 0.1 and 0.01. when the penalty coefficient of deviation w is 0.5, the profit margin for the wind producers 22.7% for the wind- battery system as compared to the wind farm alone. When the penalty coefficient w is increased to 1.00, the profit margin increases to 24%. Similarly, when the penalty coefficient w is increased to 2.00 , the profit margin increases to 25%. As shown in table, with the increase in penalty coefficient, even though the profits for the wind farm producers continue decline, the profit margin for the wind-battery system continues to increase as compared to wind farm alone.

4.2 Simulation Discussion:

In Model-1, After evaluating different scenarios under the battery dispatch model there are few things to be considered:

- **BESS Size:**
  while looking at the results from all these case it becomes evident that BESS size is directly related to the average power delivered over a period of time because of the excess power spilled. In case 1, the 11% of excess power was spilled in case 2 25%, case 3 41%. In case of case 4, initially, excess power spilled out of total power generated was 51%, but by doubling the size of BES extra power spilled was reduced to 21% and power delivered the grid was increased 58%. In case 5,initially 70% of the power generated by wind turbines was being spilled, by doubling the BES size power spillage was reduced to 50% and the power delivered to the grid was increased 67%. Similarly, by increasing the BES size by 4 times, power spillage was reduced to 21% and constant power delivery was almost doubled.

  Though in all the cases studied power delivered to the grid could be increase by increasing the BES size one important factor which needs to be considered is the stochastic nature of the wind as well as it is evident in case 3 if we look in Fig 4.3 power generation was high in the first half while it was quite low in the second half which resulted in the power delivery to be lowest in this case.

- **Trade-off:**
  There is a trade-off between the battery capacity and the power spillage which was considered as well if we want to store all the power produced by the wind turbine, the battery capacity for the system will be too big. Consequently, it will increase the battery investment for the wind farm owner and it is not economically beneficial.

- **SOE Limits:**
  In all these case the SOE was limited between 10% - 90% which resulted in more power to be spilled, we could be less strict with SOE limits to conserve more power in to the battery. While considering the optimal SOE limits we need to consider the degradation cost of the battery. If the revenue generated can compensate the degradation cost larger SOE limits could be used.

- **Revenue:**
  In Model-1, the main focus of the study was on balancing services as a revenue stream. As seen from the results, a lot of excess power was spilled due to BES size and that excess power can be sold in the intra-day market and real-time balancing services as a second source of revenue.

- **Battery Cost:**
  As seen from table 4.3, initially the constant power delivered to over longer periods of time was too small and a lot of excess power was spilled due to smaller battery capacity. To increase the power dispatched to the grid the the battery capacity was increased, by increasing the battery capacity by 4 times in case of 1 year, the power dispatched to the grid was only doubled. which is not an economically beneficial and not beneficial for the investors as well.

In Model-2, analysis conducted on predicted economic profit with the wind turbine alone and the wind-battery working mode based on the forecast error. In table 4.1, even though the profit margin for the wind farm producer continues to decline in both the wind farm alone and with wind-battery working mode, but the profit percentage is clearly increased via use of the battery system. The greater the forecast error is, the greater is the profit that can be generated using the wind-battery system. Which indicates that the battery can play an important role in decreasing the forecast error.

Table 4.3: BESS Capacity Installation Cost.

Cases	Power Delivered (MW)			Excess Energy Spilled(MWh)			Battery Installation Cost(SEK)		
	BESS	2*BESS	4*BESS	BESS	2*BESS	4*BESS	BESS	2*BESS	4*BESS
1 Day	9.4	0	0	29	0	0	0.12 mil	0	0
1 Week	4.32	0	0	272	0	0	0.74 mil	0	0
1 Month	1.97	0	0	1,200	0	0	1.23 mil	0	0
6 Months	1.66	2.63	0	7,260	3,000	0	1.26 mil	2.34 mil	0
1 Year	1.24	2.07	3.29	26,340	19,020	7,992	1.31 mil	2.46 mil	4.41 mil

Similarly, in table 4.2, even though the profit margins continue to decline, when the penalty co-efficient increases, the profit for the wind-battery system increases as compared to wind farm working alone. When the penalty co-efficient w increases, by reducing the output deviation the wind-battery system can increase the profit. Penalty co-efficient has an impact on the profit margins of the wind producers, so it is necessary that the operators set a reasonable penalty co-efficient. The penalty co-efficient should not be either too high or too low, to prevent wind farm producers to be too optimistic or cautious when they are reporting their output plans. Penalty co-efficient set for this study is 1.25.

5

Conclusion

This article represent two different models which uses BES as a resource. In Model-1, BES is used with the wind farm to deliver constant power to the grid for different time periods. The conclusion obtained from the study performed at Model-1 shows:

- If we intend to deliver constant power over a longer time periods i.e: 6 month, 1 year, it will require an enormously large battery capacity which is an unrealistic approach. It is realistic to have a BESS capacity for 1 day or at most to 3 days, so we can assure the power we can deliver the power we promised to the grid/TSO. For that purpose the BESS capacity of 100 MWh is good enough.

- when we look at longer periods a lot of power produced by the wind turbines was spilled because of small BES size and constant power delivered to the grid was not so much either. By increasing the size of BES the system was able to store a lot more energy and the power delivered to the grid was increased as well.

- Even when, the system was able to deliver more power if we look into case 5, where by doubling the BES size Power delivered was increased by 67% and by increasing it 4 times the power delivered to the grid was almost doubled. It is not an economically beneficial solutions because the profit margin doesn't increases as much as the cost.

- Instead of increasing the BES size the excess power spilled can be sold in intra-day market real-time balancing market as a second source of revenue. Excess power can also be used for ancillary services or frequency regulation purposes.

Based on the analysis conducted on Model-2, it can be concluded that, by having battery system with the wind farm, it can have a significant influence on the wind farm's economic profit. Based of the forecast error of wind power, and the ability of the battery system to adjust based on forecast error deviation, an analysis of the economic profit due to HESS was investigated. The conclusion obtained from the study performed on Model-2 from WBHPS (16 MW WF, 60 MWh Battery) shows:

- The forecast error in the wind power output decreases the economic profit of the wind farm. As the forecast error increases, the economic benefit of the WBHPS decreases from 58,556 SEK to 48,980 SEK.

- The battery system reduced the negative effect of the forecast error and enhances the economic profit of the wind farms (WFs). As the forecast error increases, the economic benefit of the WBHPS increased by 68% as compared to the wind farm working alone.

Bibliography

[1] Kundur P. Power system stability and control. Mc Grau-Hill Inc.; 1993.

[2] ENTSO-E. Operational handbook; policies; load-frequency control and performance. <https://www.entsoe.eu/>; 2009 [access date 26.04.13].

[3] Lin, J., Sun, Y.Z., Sorensen, P., et al.: ‘Method for assessing grid frequency deviation due to wind power fluctuation based on time-frequency transformation’, IEEE Trans. Sustain., 2012, 3, (1), pp. 65–73

[4] Abrantes, A.: ‘Overview of power quality aspects in wind generation’. Proc. North American Power Symp. (NAPS), September 2012, pp. 1–6

[5] Abedini, A., Mandic, G., Nasiri, A.: ‘Wind power smoothing using rotor inertia aimed at reducing grid susceptibility’, Int. J. Power Electron., 2008, 1, (2), pp. 227–247

[6] Howlader, A.M., Urasaki, N., Yona, A., et al.: ‘A review of output power smoothing methods for wind energy conversion systems’, Renew. Sustain. Energy Rev., 2013, 26, (8), pp. 135–146

[7] Yoshimoto, K., Nanahara, T., Koshimizu, G.: ‘New control method for regulating state-of-charge of a battery in hybrid wind power/battery energy storage system’. Proc. IEEE 2006 Power Systems Conf. Expo., November 2006, pp. 1244–1251

[8] Teleke, S., Baran, M.E., Bhattacharya, S., et al.: ‘Optimal control of battery energy storage for wind farm dispatching’, IEEE Trans. Energy Convers., 2010, 25, (3), pp. 787–794

[9] Hauer, I.; Balischewski, S.; Ziegler, C. Design and operation strategy for multi-use application of battery energy storage in wind farms. J. Energy Storage 2020, 31, 101572.

[10] Zhang, F.; Meng, K.; Dong, Z.; Zhang, L.; Liang, J. Battery ESS Planning for Wind Smoothing via Variable-Interval Reference Modulation and Self-Adaptive SOC Control. Strategy. IEEE Trans. Sustain. Energy 2017, 8, 695–707.

[11] Shi, J.; Zhang, G.; Liu, X. Generation Scheduling Optimization of Wind-Energy Storag Generation System Based on Feature Extraction and MPC. Energy Procedia 2019, 158, 6672–6678.

[12] “Directive 2009/28/ec of the european parliament and of the council of 23 april 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing directives 2001/77/ec and 2003/30/ec (text with eea relevance).” http://eur-lex.europa.eu.

[13] Ackermann, T. (2005). Wind power in power systems.

[14] Freris, L.L.(ed), Wind Energy Conversion Systems, Prentice Hall International(UK) Ltd, 1990,3889.

[15] Turbowinds. (1999). Active Stall Control. Retrieved 2009-10-29 from Turbowinds: http://www.turbowinds.com/activestall.html

[16] C. N. Rasmussen, “Energy storage for improvement of wind power characteristics,” 2011 IEEE PowerTech Trodheim, Norway, pp. 1 – 8, June 19 - 23, 2011.

[17] P. Braun, M. Swierczynski, R. Diosi, D. Stroe, and R. Teodorescu, “Optimizing a hybrid energy storage system for a virtual power plant for improved wind power generation: A case study for denmark,” 6th International Renewable Energy Storage Conference and Exhibition (IRES 2011), Berlin, Germany, November 2011.

[18] https://www.sciencedirect.com/topics/engineering/flywheel-energy-storage

[19] Fathima, Amjed Hina and Kaliannan Palanisamy. “Battery energy storage applications in wind integrated systems — A review.” 2014 International Conference on Smart Electric Grid (ISEG) (2014): 1-8.

[20] Francisco Díaz-González, Andreas Sumper, Oriol Gomis-Bellmunt, Roberto Villafáfila-Robles, A review of energy storage technologies for wind power applications, Renewable and Sustainable Energy Reviews,Volume 16, Issue 4,Pages 2154-2171,May 2012

[21] Aisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, Yulong Ding, Progress in electrical energy storage system: A critical review, Progress in Natural Science,Volume 19, Issue 3,Pages 291-312,March 2009

[22] https://www.adb.org/sites/default/files/publication/479891/handbook-battery-energy-storage-system.pdf

[23] H. Pandžić and V. Bobanac, "An Accurate Charging Model of Battery Energy Storage," in IEEE Transactions on Power Systems, vol. 34, no. 2, pp. 1416-1426, March 2019

[24] Ángel A. Bayod-Rújula, Marta E. Haro-Larrodé, Amaya Martínez-Gracia, Sizing criteria of hybrid photovoltaic–wind systems with battery storage and self-consumption considering interaction with the grid, Solar Energy,Volume 98, Part C,Pages 582-591, December 2013

[25] Nguyen, C.L., Lee, H.H.: ‘A comparative analysis among power dispatching control strategies for hybrid wind and energy storage system’. Proc. 20th Int. Conf. Electric Engineering, Korea, June 2014, pp. 489–494

[26] K. Antoniadou-Plytaria, D. Steen, L. A. Tuan, O. Carlson and M. A. Fotouhi Ghazvini, "Market-Based Energy Management Model of a Building Microgrid Considering Battery Degradation," in IEEE Transactions on Smart Grid, vol. 12, no. 2, pp. 1794-1804, March 2021

[27] https://www.electronics-notes.com/articles/electronic-components/battery-technology/nicad-nicd-nickel-cadmium-memory-effect.php

[28] “The Electricity Market in Sweden and the Role of Svenska Kraftnät”, May 2011

[29] Angeliki Loukatou, Paul Johnson, Sydney Howell, Peter Duck, Optimal valuation of wind energy projects co-located with battery storage, Applied Energy, Volume 283,116247, February 2021

[30] F. Bouffard and F. D. Galiana, "Stochastic security for operations planning with significant wind power generation," 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008, pp. 1-11

[31] https://vbk.lansstyrelsen.se/en

[32] Nord Pool. Accessed: May 7, 2020. [Online]. Available: https://www. nordpoolgroup.com

[33] https://www.vestas.com/en/products/2-mw-platform/V90-2-0-MW

[34] https://nozebra.ipapercms.dk/Vestas/Communication/2mw-platform-brochure/?page=8

[35] https://www.tesla.com/powerpack

[36] Angeliki Loukatou, Paul Johnson, Sydney Howell, Peter Duck, Optimal valuation of wind energy projects co-located with battery storage, Applied Energy, Volume 283, 116247, February 2021

[37] Bouffard, F.; Galiana, F.D. Stochastic security for operations planning with significant wind power generation. In Proceedings of the 2008 IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008; pp. 1–11.

[38] Ulrich Focken, Matthias Lange, Kai Mönnich, Hans-Peter Waldl, Hans Georg Beyer, Armin Luig, Short-term prediction of the aggregated power output of wind farms—a statistical analysis of the reduction of the prediction error by spatial smoothing effects, Journal of Wind Engineering and Industrial Aerodynamics, Volume 90, Issue 3, Pages 231-246, March 2002

[39] A. Fabbri, T. G. S. Roman, J. R. Abbad and V. H. M. Quezada, "Assessment of the cost associated with wind generation prediction errors in a liberalized electricity market," in IEEE Transactions on Power Systems, vol. 20, no. 3, pp. 1440-1446, Aug. 2005

[40] Miao, M.; Lou, S.; Zhang, Y.; Chen, X. Research on the Optimized Operation of Hybrid Wind and Battery Energy Storage System Based on Peak-Valley Electricity Price. Energies 2021

[41] M. Koller, T. Borsche, A. Ulbig and G. Andersson, "Defining a degradation cost function for optimal control of a battery energy storage system," 2013 IEEE Grenoble Conference, 2013, pp. 1-6

[42] J. Schmalstieg, S. Käbitz, M. Ecker and D. U. Sauer, "From accelerated aging tests to a lifetime prediction model: Analyzing lithium-ion batteries," 2013 World Electric Vehicle Symposium and Exhibition (EVS27), 2013, pp. 1-12

[43] Wikner, Evelina and Torbjörn Thiringer. “Extending Battery Lifetime by Avoiding High SOC.” Applied Sciences (2018)

[44] John Wang, Justin Purewal, Ping Liu, Jocelyn Hicks-Garner, Souren Soukazian, Elena Sherman, Adam Sorenson, Luan Vu, Harshad Tataria, Mark W. Verbrugge, Degradation of lithium ion batteries employing graphite negatives and nickel–cobalt–manganese oxide + spinel manganese

oxide positives: Part 1, aging mechanisms and life estimation, Journal of Power Sources, Volume 269, December 2014,Pages 937-948

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