Meeting Generation Schedule of Wind Farms with Battery Energy Storage Systems
A Case study of Adama I wind farm

A Thesis Submitted

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In

POWER SYSTEM AND ENERGY ENGINEERING
By

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SCHOOL OF GRADUATE STUDIES
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EXAMINERS' APPROVAL SHEET

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DECLARATION

I hereby declare that the thesis “Meeting generation schedule of wind farms with battery energy storage systems: a case study of Adama I wind farm” is my own work conducted under the guidance of Dr. Baseem Khan, Assistant professor, Department of Electrical Engineering, Hawassa University Institute of Technology, Hawassa (Sidama), Ethiopia.

I further declare that to the best of my knowledge, the thesis does not contain any part of work that has been submitted for the award of any degree either in this university or any other university without proper citation.

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ACRONYMS

η_{BESS}	Overall efficiency of BESS
η_{ch}/η_{dis}	Charging/discharging efficiency of the BESS
AC	Alternating current
B1, B2	battery1, battery2
BESS I	Battery energy storage system 1
BESS II	Battery energy storage system 2
CAES	Compressed Air Storage Systems
CGs	Committed Conventional Generators
CPF	Cumulative distribution function
DC	Direct current
DI i	Dispatch interval i
DSO	Distribution System Operators
E_{ac}	Actual Energy from wind farm
E_c	Energy charged into the BESS
E_{ch}	Expected charging energy during a dispatching interval (DI)
ECU	Energy curtailed
E_d	Energy discharged from BESS
E_{dis}	Expected discharging energy during a dispatching interval (DI)
EEP	Ethiopian Electric Power
EEPCO	Ethiopian electric power corporation
EES	Electrical Energy Storage
EEU	Ethiopian electric utility
EIED	Expected injected energy dispatch

Ent	Energy not dispatched
ENTSO − E	European Network of Transmission System Operators
E_s	Submitted Energy schedule
ESS	Energy Storage System
ETB	Ethiopian birr
F − 1(·)	Inverse function of cumulative distribution function of the versatile distribution
FACTS	Flexible Alternating Current Transmission System
FRT	Fault Ride through
GHG	Green House Gas
GoE	Government of Ethiopia
Gw, Mw	Giga watt , Mega watt
GWEC	Global Wind Energy Council
IEA	International Energy Agency
IEC	International Energy committee
IPP	Independent Power Producers
ISO	Independent system operators
Kwh	Kilo watt hour
LCO	Lithium Cobalt Oxide
LDC	Load dispatch center
LFP	Lithium Iron Phosphate
Li − ion	Lithium-ion
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate
$M_{in,}$	The index of income of the wind farm

NCA	Lithium Nickel Cobalt Aluminum Oxide
NMC	Lithium nickel manganese cobalt oxide
OBB	Operation benefits of the BESS-integrated WF
OCB	Operation Costs of the BESS
OPB	Operation profits of the BESS-integrated WF
$\mathrm{P_b}$	Charging/discharging power of the battery energy storage systems (BESSs)
$P_{bI,\ i}$	Charging/discharging power of BESS 1 at dispatch interval i
$P_{bII,i}$	Charging/discharging power of BESS 2 at dispatch interval i
$P_{chI,i}$	Charging power of BESS 1 at dispatch interval i
$P_{chII,i}$	Charging power of BESS 2 at dispatch interval i
$P_{dI,i}$	Discharging power of BESS 1 at dispatch interval i
$P_{dII,i}$	Discharging power of BESS 2 at dispatch interval i
$\mathrm{P_{div,i}}$	Power deviation between scheduled and BESS-integrated WF at a given DI i
$P_{mcI,i}$	Maximum allowable charging power provided by BESS I at DI i
$P_{mcII,i}$	Maximum allowable charging power provided by BESS II at DI i
$P_{mdI,\ i}$	Maximum allowable discharging power provided by BESS I at DI i
$P_{mdII,\ i}$	Maximum allowable discharging power provided by BESS II at DI i
PDF	Probabilistic density functions
PMGS	Value of index probabilities of meeting generating schedule
$P_{r,ch}$	Rated charging power of the BESS with unit capacity
$P_{r,dis}$	Rated discharging power of the BESS with unit capacity
$P_r\{.\}$	Probability of the event given in the brace
$P_{s,i}$	Desired injected power at DI *i* fixed by the generation schedule

P_{wc} , $P_{wc,i}$	Curtailed wind power, Curtailed wind power at DI i
P_S	Submitted power generation schedule i Index of DI
P_{W-BESS}	Power of BESS- integrated wind farm
$P_W, P_{W,i}$	Output power of the wind farm (WF), Actual wind power at dispatch interval i
$P_{W-BESS,i}$	Power of BESS- integrated wind farm at dispatch interval i
RES	Renewable energy storage
$S_{1,i-1}$	SOC of BESS I at DI i
$S_{II,i-1}$	SOC of BESS II at DI i
SOC_{min}	Minimum allowable value of battery state-of-charge (SOC)
SOC_{max}	Maximum allowable value of battery state-of-charge (SOC)
ΔP_i	Power deviation between *P*w, *i* and *P*s, *i*
SMES	Superconducting Magnetic Energy Storages
SOC	State of Charge
SOE	State-owned enterprises
T&D	Transmission and distribution
TSO	Transmission System Operators
TWh	Tera watt hour
VAR	Voltage-ampere-reactive
WECS	Wind Energy Conversion System
WFs	Wind farms
WTGs	Wind Turbine Generators
x	Stochastic variable that denotes per unit value of wind power in the versatile distribution
α, β, γ	Shape parameters of the versatile distribution
T	Length of DI

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ABSTRACT

This study is based on an idea of integrating battery energy storage systems (BESS) into wind farms (WFs) so that BESS-integrated WFs will get the ability to inject energy into power grids as pre-determined generation schedule which was set previously based on the meteorological forecast and BESS characteristics. In this study, it is proposed to integrate two independently controlled BESSs into the WFs so that it would balance stochastic power deviations between actual wind power and the scheduled power. Simulating models on operations of the BESS-integrated WF during a year have been built using conditional statements or linear optimization and solved in MATLAB. Technical performances of BESS-Integrated wind farm on meeting generation schedule along with the cost, benefits and the profit attributed to the BESSs are therefore measured by a series of indices proposed in this work. Based on simulation results, technical and economic indices of a dual battery operation under both state exchanging strategies were compared with a single battery operation. Simulation results shows that charging/ discharging state exchanging strategy of the BESS (in case of two battery integration) as well as the number of batteries integrated to the wind farm (single or dual) has significant impacts on the performance of the BESS-integrated WF. At 2MW battery, the wind farm's probability of meeting generation schedule (PMGS) was improved from 51.11% to 70.88%, 61.6% and 69.74 % by simultaneous state exchanging strategy, asynchronous state exchanging strategy and single battery operations respectively. At this battery size, the profit of wind farm was found to be 2,289,898ETB when simultaneous state exchanging strategy is adopted. For asynchronous and single battery operation, the profit was -2,369,648 and -3,574,103 ETB respectively.

Index Terms—, Meeting power generation schedule, wind power fluctuation, battery energy storage systems (BESS), Li-ion batteries, linear optimization, single-battery operation, dual battery operation, state exchanging strategy.

CHAPTER ONE

INTRODUCTION

1.1 Wind Power Development in the World

Wind power, as a renewable energy, is plentiful, widely distributed, clean, and does not release Green House Gas (GHG) during operation. Currently, it has achieved rapid development due to the fast increase of energy demand and accelerating depletion of the world fossil fuels [1].

According to the statistics from Global Wind Energy Council (GWEC), the worldwide cumulative installed wind capacities in the past ten years are shown in Fig. 1.1. The total installed capacity has reached 539,123 MW. By the end of 2015, the percentage of global electricity supplied by wind power was 3.7%. In 2018 this figure has reached 4.8%. As estimated by International Energy Agency (IEA), the total installed capacity of wind energy is expected to reach 2,182 TWh by 2030[2].

From the development perspective, more than 100 countries all over the world had been using wind power for a commercial basis by 2012. Fig. 1.2 illustrates top 10 countries with new installed wind power capacity in 2017. It shows that a greater part of new installed wind power was added outside the traditional markets of Europe and North America. The value of China was nearly half of the installations, which is 37%.

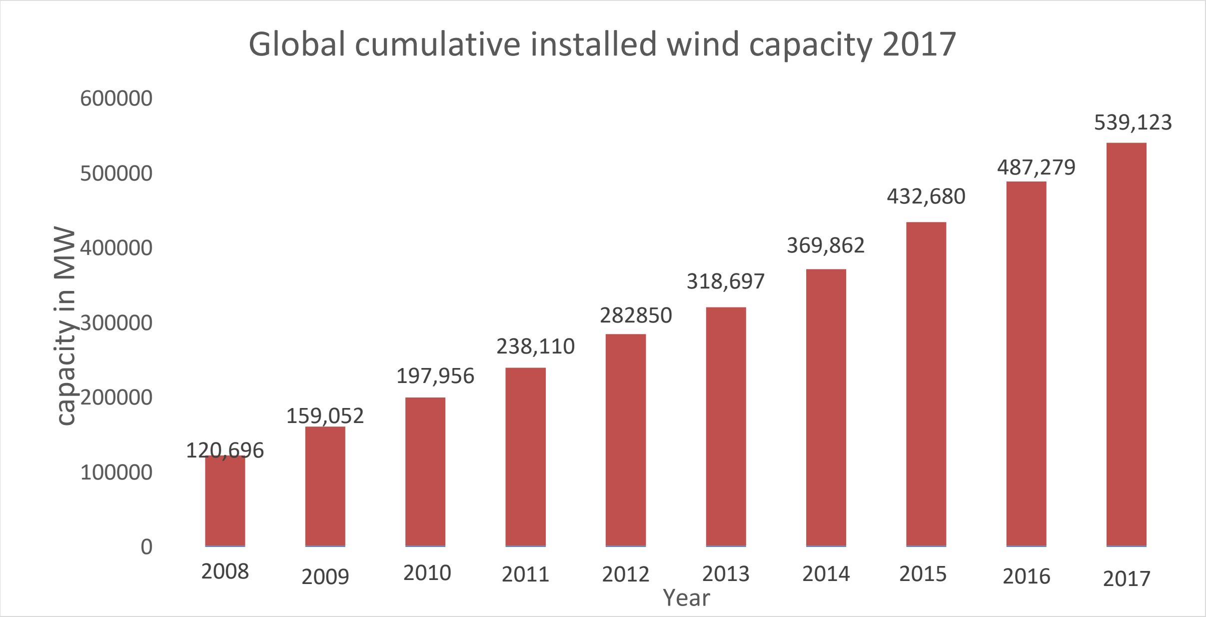

Figure 1.1 Global cumulative installed wind capacities 2008-2017[3]

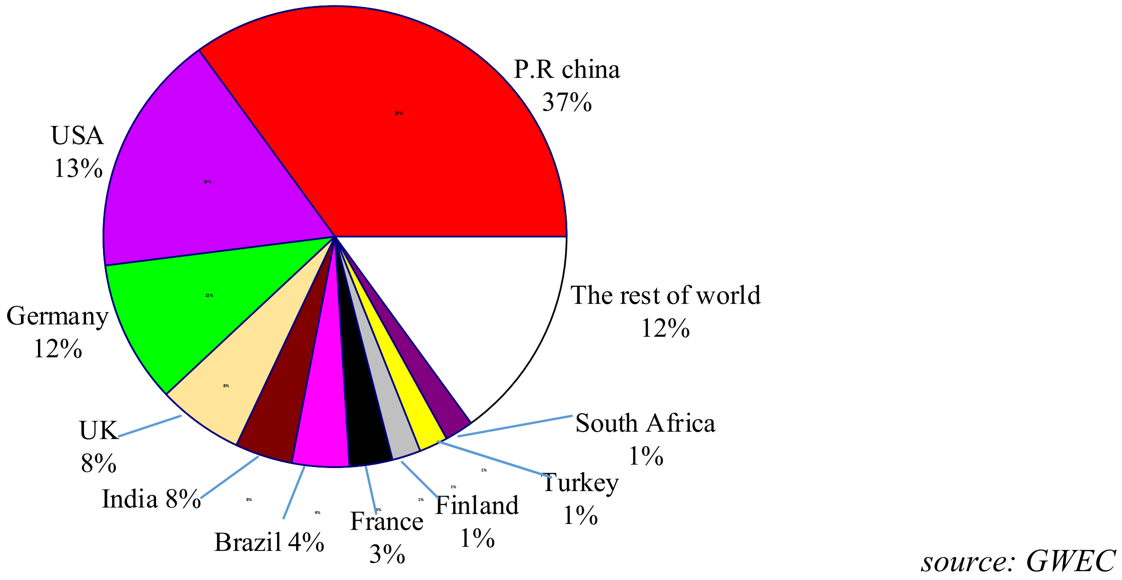

Figure 1.2 Top 10 new installed capacity Jan. Dec. 2017

Recently, relatively high levels of wind power penetration have been achieved in some countries. As illustrated in Fig. 1.3, the penetration level of Denmark has reached 48%, followed by Ireland with 30% and Portugal with 30%, according to the report of US Department of Energy. United States has planned projections of wind power capacity to be as large as 30% of total generation by 2030.

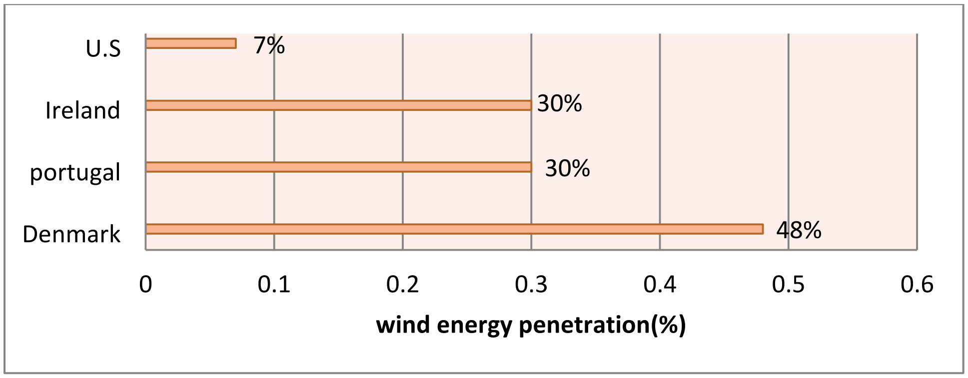

Figure 1.3 Wind power penetration in leading wind markets 2018[3]

1.2 Wind Power Development in Ethiopia

Ethiopia has vast hydro, wind, solar, and geothermal renewable energy potential. With its large hydropower potential, Ethiopia is placed as second in Africa next to Democratic Republic of Congo. The total exploitable reserves of hydro and wind energy are 45GW and 1,350GW respectively [4]. Only about 5 percent of Ethiopia's hydro resources and less than 1 percent of

Ethiopia's wind resources have been developed thus far. As of 2014, hydropower accounted for 88 percent of Ethiopia's total installed electricity capacity, while wind power contributed just 8 percent [5].

Even though, Ethiopia has historically focused largely on hydropower for electricity generation, now wishes to diversify generation from other renewable sources to increase climate safety. According to the 10 years masterplan, the planned expansion of electricity generation (2015-2025) has three main components: 7,600MW of hydro-power, 5,200 MW of wind power, 5,200 MW of solar power, and 900 MW of other power (including geothermal)[6].

The country's hydro-power, including the reservoirs that typically can store water for a full year's power generation, represents an excellent starting point for the integration of wind power. The current integration of the existing 324 MW of wind power (Adama I (51 MW), Adama II (153MW) and Ashgoda (120MW)) is working satisfactorily, but as wind and solar start to contribute significantly to overall power generation, more advanced methods need to be in place. The variable nature of wind power generation, and its increased role in overall power generation, may require the development of new procedures, e.g. in the National Electricity Transmission Control Centre. Effective operation includes state of the art wind prognoses, as well as the use of realtime information about wind and solar generation and electricity demand [6].

Most countries that are using wind farms at large-scale, have grid connection codes that specify the requirements that should be fulfilled by each wind farm which seeks to be integrated to grid. But in case of Ethiopia, Ethiopian Electric Power Corporation(EEPCO) is almost the state-monopoly that owns and controls the national power grid with all high voltage power transmission lines above 66 kV; including all involved electrical substations and almost all power plants within the national power grid [5]. Since the generation, transmission and distribution systems are not operated separately; there is no wind farm connection requirement developed yet.

However; in 2018 there was Key Developments in Ethiopian Electric Power Corporation. One of these developments is the decision of the Government to sell stake in Sate Owned Enterprises i.e. The Government plans to partial privatization of the largest state-owned enterprises (SOE) which includes the Ethiopian Electric Power Corporation. Domestic and foreign investors can become minority shareholders in these firms, although how much they will own has not yet been determined. So a grid code or connection requirement will be developed.

Consequently, large-scale wind farms are going to be integrated to EEPCO's grid [7]. This will result in increased penetration of wind energy into EEPCO's grid and this increase will have significant influence on the stability of the power system unless some sort of flexibility is added to it. Now day's energy storage systems are found quite comfortable to be integrated with wind farms to add extra flexibility to the wind farm.

1.3 Statement of Problem

Wind energy is considered as one of the most promising renewable energy resources, with the use of the technology experiencing significant growth in recent years [8], [9]. Due to this, Ethiopia has planned to expand its wind power capacity to 5,200 MW by 2025. Consequently wind penetration in EEPCO will grow soon which means the grid will be introduced to many novel problems due to the fact that power from the wind cannot be commanded; it is a non-dispatchable resource.

In fact, like other generation units, wind farms (WFs) determine their short-term generation schedules in future hours and submit them to the dispatch center. It is based on this schedule that the dispatch center makes the power balance between supply and demand.

However, Different from other generation units, WFs cannot be dispatched flexibly due to the volatility of wind conditions and consequently with inherent stochastic nature. This means that when the wind suddenly picks up in this area, power generation from wind can go from nearly 0 MW up to 51 MW in a matter of hours. Since both power generation and consumption takes place in the same instant, any balanced power system must be able to match power consumption with power production, meaning that in this case up to 51 MW of generation must be reduced or increased somewhere else (usually hydro units) on the system in a short period of time, which is difficult. It, therefore, requires extra flexibility from the power system to ensure the required level of security and reliability.

In this study, Battery energy storage systems (BESSs) are proposed to be integrated into WFs for smoothing wind power fluctuation so that the WFs could meet the desired generation schedules.

1.4 Objectives

The general objective of this study is to assess ways of BESS utilizations to offset power deviations between stochastic wind power and predetermined generation schedules for enabling the BESS-integrated WF to inject energy into power grids as predetermined schedules.

- **Specific objectives**

- To determine the characteristics of a storage system that have the greatest effect on its ability to mitigate fluctuations
- To assess BESS's coordination with the load flexibility
- To compare single battery operation with a two battery operation
- To study the impact of battery size and charging/discharging strategy on system reliability and Economy
- To assess the economic value of the battery energy storage option

1.5 Scope

As the potential field of study is extremely wide it is necessary to design a reasonable frame for this study. An appropriate scope shall be defined hereafter. It will entail details on what was part of the study and what has purposefully been excluded in order to respect limitations in time and resources.

BESSs have a broad range of applications in power systems, for which a comprehensive summary is developed in Subsection 2.3. Of the many possible applications for BESSs, Battery in combination with wind farm will be studied: In fact, the fluctuation of wind power highly affects the frequency and voltage of the grid. However, in low level of power integration (less than 100 MW) its impact is considerably insignificant. Due to this reason, frequency and voltage regulations are not included in this study.

Therefore, this study will focus on simulations that combine a wind farm with a grid level energy storage source in the form of BESSs (lithium ion batteries). The energy storage source is meant to increase the dispatchability and reliability of the wind farm just like normal dispatchable generation sources. It is assumed that all technical requirements, such as power electronics for

AC/DC conversion as well as regulatory frameworks are provided by the transmission and generation system operator.

Generally, the main focus of this study is on answering the questions of what will be the Technical and economic performance of battery integrated wind farm:

- If a single battery is integrated to the wind farm,
- If two batteries are integrated to the wind farm, controlled independently and operate by simultaneous state exchanging strategy,
- If two batteries are integrated, controlled independently and operate by asynchronous state exchanging
- And finally, the physical size of the battery is evaluated and presented, after a series of simulations.

CHAPTER TWO

BACKGROUND STUDY ON WIND POWER VARIABILITY AND ENERGY STORAGE SYSTEMS (ESS)

In this section, the main findings of the literature review regarding the nature of wind power, impacts of wind power integration on main grid, Energy Storage System (ESS), the different types of batteries based on their chemistry, possible applications, modeling techniques and related studies on ESS integration to wind farms are presented.

2.1 Variability of Wind Power

One of the most critical features of wind generation is the inconsistency of wind. Wind speed variation is common with time of day, time of year, height above ground, and location on the earth's surface. This makes wind power generators into what might be called energy producers instead of power producers. That is, it is easier to predict the energy production for the next month or year than it is to forecast the power that will be produced at 4: 00 PM next Tuesday. Wind power is not dispatchable in the same way as a gas turbine [10]. A gas turbine can be programmed to be turned on at a given time and to be turned off at a later time; with full power production in between. A wind turbine is productive only when the wind is available.

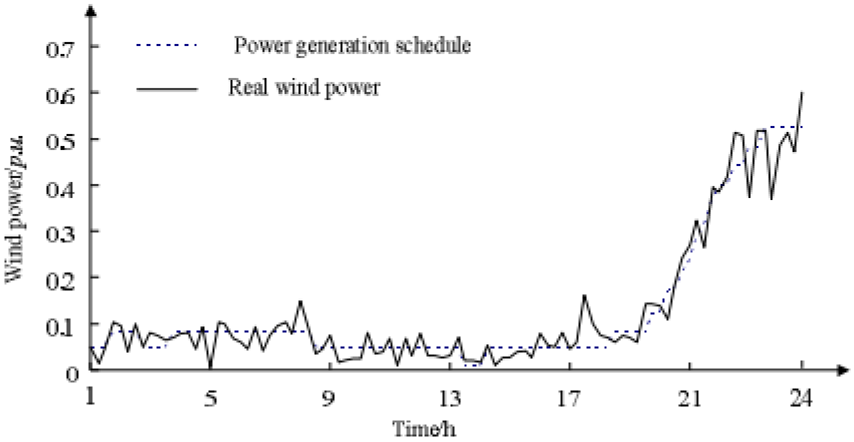

Figure 2.1 Power generation schedules and real wind power during a typical day [13]

As shown on figure 2.1, wind power always fluctuates around the forecasted values because forecasted errors exist objectively. Hence, fluctuating characters of the wind power will have dramatic impacts on determining generation schedules. Inappropriate generation schedules will increase burdens of the BESS and subsequently deteriorate the performances on tracking desired generation schedule. In literatures, Gaussian distribution [11], Beta distribution [12] or versatile distribution [13] was utilized to describe fluctuating characters of the wind power. It is known that forecasted errors increase dramatically with forecast timescales, so fluctuating characters are directly affected by the forecast timescale. Moreover, many studies have found that fluctuating characters of the wind power also vary dramatically with the levels of their output [13, 14, 17]. However, many studies highlighted the lack of generalization of Gaussian and Beta distributions for some forecast timescales and magnitudes [13]. Fortunately, the versatile distribution has three shape parameters, i.e., α, β, γ which can be adjusted to describe fluctuating characters of the wind power in various forecast timescales and magnitudes with more accuracy.

The fluctuating characters of the wind power are assumed to obey the versatile distribution proposed in [13], whose probabilistic density functions (PDF) and cumulative distribution function (CPF) can be expressed by Equations (2.1) and (2.2), respectively.

$$f(x) = \alpha\beta\exp[-\alpha(x-y)/\{1+\exp[-\alpha(x-y)]\}^{\beta+1} \tag{2.1}$$

$$F(x) = \{1+\exp[-\alpha(x-y)]\}^{-\beta} \tag{2.2}$$

Where values of parameters α, β and γ vary with forecasted values of the wind power and forecast timescales.

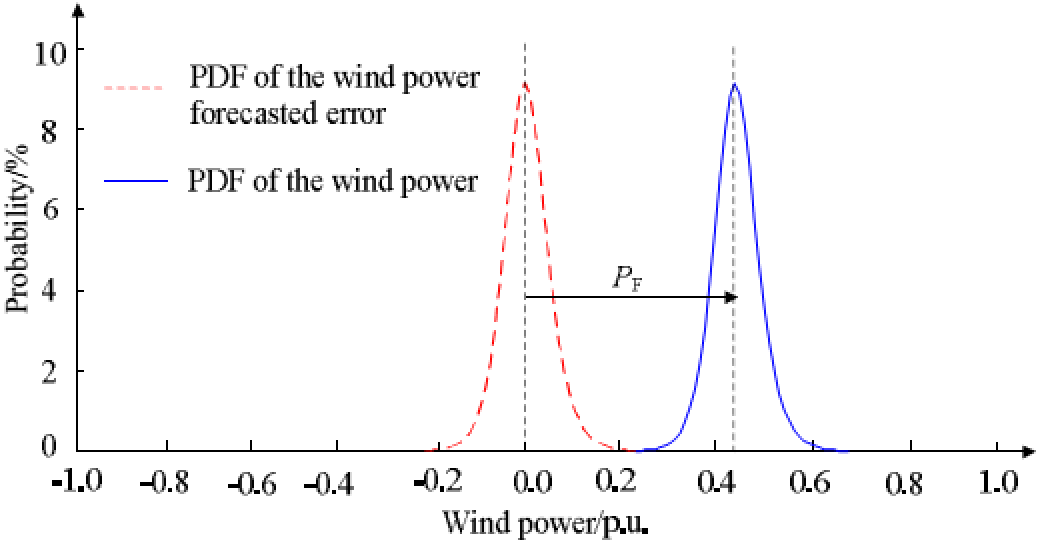

Figure 2.2 Wind power fluctuation and wind power forecasted error [13]

Figure 2.2 depicts that the PDF of the wind power can be obtained by shifting that of the wind power forecasted error to the right by a magnitude of the corresponding forecasted value PF. Since the two kind of PDFs have the same shape, they are essentially consistent each other. The only thing that differentiates the two kinds of PDFs is that they have different locations [13]. That is to say, fluctuating characters of wind power and forecasted error for the same forecasted value can be described by the same distribution.

Wind power varies within fractions of time, essentially under the influence of climatological fluctuations. The fluctuation occurs on all time scales: seconds to days, months, seasons and years. Understanding these fluctuations and their predictability plays of great importance for the integration and optimal utilization of wind in the power system. Even though, Electric power systems are inherently variable at both demand and supply levels, they are designed to effectively cope up with these fluctuations through their configuration, control systems and interconnection.

2.1.1 Short-term variability

The studies of the data obtained from functioning wind farms and meteorological measurements at typical wind farm locations allows us to quantify the variability of net output of wind power that is expected for a given period of time (within the minute or hour, or during the entire course hours). The distinction between these specific time scales is made since such kind of information corresponds to several types of power plants for balancing. The results of the studies show that the power system can effectively handle this short-term variability. System operators only need to focus on the net output of large groups of wind farms, and the wind power variability is viewed based on the level and variation in power demand [10].

- Variations within the Minute: The fast variations (seconds to minute) of aggregated wind power output (as a result of turbulence or transient events) are very small, due to the aggregation of wind turbines and wind farms, and its impact the system can be neglected.
- Variations within the Hour: The variation of wind power within an hour is much more important for the system. But it should always be considered in relation to the variations of the consumption. Local fluctuations are mostly equal to geographical diversity, and will generally remain within ±5 per cent of installed wind power capacity at the regional level. The most influential variations are always due to the passage of storm fronts, when wind turbine reaches its storm limit (cut-out wind speed) and shut down rapidly from full to zero power. However, because of the averaging effect across a wind farm, the net power output will take several minutes to drop to zero. And in general, this is only

substantial in relatively in a very small geographical areas, since in larger areas it takes hours for the wind power capacity to terminate during a storm. For example, one of the biggest storms of decades takes place in Denmark – a small geographical area - on 8 January 2005. During the time in the West Denmark area, six hours were needed to drop the installed wind power from 2000 MW to 200 MW (5 MW/ minute). Currently, it is possible to predict the passage of a storm front and technical solutions are available to reduce the steep gradient, such as the provision of wind turbines with storm control. Thus, power system reserves should be more concerned with intra-hour variations in order to set balancing, when wind power penetration reaches the point at which variations in production are equal to variations in c (when 5-10 per cent of annual electricity demand is produced by wind power).

- Variations from Hour to Hour: The variations between the prediction and actual wind power production several hours ahead affect the scheduling of the power system. Errors in demand forecast should always be considered to find uncertainty of wind power forecasts. There are much work being conducted in these areas and it is clear that solutions are available.

Generally the variability of wind power highly affects the grid stability and load balance. So some measures should be taken by wind farms to improve unpredictable fluctuation of actual wind power output.

2.1.2 Methods of controlling wind power variability

Several studies have proposed different methods to control the variability of actual generated wind power. Among those, Fast ramping gas generators, electricity storage and wind curtailment are most commonly used methods to compensate this variability.

Curtailment technique allows generators to smooth the peaks in generation when available power is greater than the expected but cannot compensate for troughs resulted from sudden drops in power production which means it cannot fill the needed gap when the power generated is less than the scheduled**.** Since there is no means of any storage, the curtailed power is completely wasted and represents lost generation profit for the wind turbine [10].

Gas generators can start and fill the needed gap when the wind power is deficient; however, they cannot follow a wind profile exactly because of their ramping constraints and lead times for startup. They can fill the gap in case of negative deviation; if the wind power is less than schedule. If excess power is generated there is no option other than curtailing. Additionally, gas generators suffer efficiency penalties when they operate close to their minimum without forgetting a rapidly rising price of fuel and Maintenance and service cost.

Electricity storage systems have the ability to absorb energy in peaks and supply energy in troughs. The fact that they can be used to fix both positive and negative deviations together with rapid progresses in battery technologies provided a promising opportunity of coping with stochastic wind power [14]. Here are the aspects that Energy storage system is better than gas generators

System Startup: The main advantage of battery backup power is its capability to start up within milliseconds. This means that it is even faster than computers or other electronic equipment can shut down or reset. So the grid will not experience any dips or ups due to wind power variation. By contrast, even a gas generator with more advanced technology and automatic startup can take 10 to 20 seconds to get things running again.

Storage and Operation: In addition to its ability to store extra energy, battery backup power system is better than gas generators because of its silent, emission- free operation. Gas generators of all types are not suitable due to their toxic exhaust and they can be quite noisy -- particularly portable units. Moreover, gas generators need a reserve fuel supply, which needs periodic replacement of the fuel and conditioning additives to prevent the gas from going bad while it sits.

Running Time: Batteries can supply power sufficiently until it gets to its minimum charge level (SOC_{min}). As a result, they're mostly suitable for short-term backup (anywhere from a few hours to couple of days, depending on the type of the system and your usage). However, gas generators can run for needed length of time as long as we keep filling them with gas, and barring any mechanical breakdowns. Most Portable gas generators need refills within short duration, but larger stationary generators can operate for days on huge propane or diesel tanks or a natural gas hookup. Since a wind power fluctuates back and forth around scheduled value with in short time interval, it is difficult to shut down and restart the generator with in each variation. So batteries can suitably fit this variation.

2.2 Challenges with Wind Power Integration

Due to its variable and uncertain nature, wind power integration into the grid causes problems on different aspects of power system, such as reliability, power quality, stability and planning. The impact is largely dependent on the penetration level [15].

2.2.1 Impact on system reliability

Wind power generation is often faced with difficulties regarding the reliability in terms of the generation, planning and scheduling of the power supply. Although no power system is 100% reliable, the intermittent wind generation will increase the level of uncertainty as well as the capacity of operating reserve which in turn increases the generation costs. At the low penetration level, the additional wind power fluctuation is comparable to existing load fluctuations. The committed Conventional Generators (CGs), like hydro or thermal units, have satisfactory load tracking ability without additional operating reserve. However, it becomes challenging at a high penetration level. The response time of CGs should be fast enough during sudden and huge change of wind power resulted from random failures or gust of wind. Besides, more operating reserve is required. An extra reserve of 3-6% of the rated capacity of the wind plant is required for 10% wind integration and approximately 4-8% for 20% wind integration.

2.2.2 Impact on power quality

The power quality transmitted to the grid is evaluated by the deviation of the waveform from the normal sinusoids of voltage and current waveforms in a power system network.

Power quality components of a power system mainly include flickers, harmonic distortions and etc. Harmonics can be injected both at the generation and the consumer sides. At the consumer side, harmonics are resulted from nonlinear loads. At the generation side, harmonics can be caused by the Flexible Alternating Current Transmission System (FACTS) such as power electronics devices and reactive power compensators. The power electronic converters used by variable speed Wind Energy Conversion System (WECS) are also considered as sources of harmonics.

Flickers are the periodic voltage frequency variations typically between 0.5Hz to 25 Hz. In power system Flickers could be caused by the oscillatory output power produced by wind turbine generators and the variation due to turbulence effect in wind and the shadow of tower. IEC 61400-21 defines the measurement steps to determine the flicker effect of wind turbines.

2.2.3 Impact on system stability

Power system transient stability can be defined as the ability to continue in synchronism when it is exposed to a major disturbance, such as falling of transmission lines, reduction in generation capacity (failure of generating unit) and short circuits.

The conventional power system mainly consists of synchronous generators for electricity production whose inertia plays an important part in preserving the stability of power system experiencing a transient condition. The inertia dictates how much would be the changes in frequency because of sudden changes in power production and consumption balance. It has an impact on the_eigenvalues and vectors which has a direct impact on determining the shape of transient response and system stability. This kind of response by traditional synchronous generators is named inertia response [16]. The contributions to the system inertia by Wind Turbine Generators (WTGs) are dependent on the WTG type. Due to the direct connection the power system, fixed-speed induction generators can provide inertia response. The modern variable-speed wind turbines, whose rotation speed is normally decoupled from grid frequency by power electronic converters, may decrease the system inertia [17]. With high level penetration of wind power, this decrease aggravates the grid frequency stability.

Many faults in power system are detected and removed by the relay protection of the transmission system either by a complete disconnection or by disconnection followed by immediate re closure. There exists a short period with voltage drop beyond a specified threshold, followed by a period when the voltage returns. It is called voltage dip. In early days, the number of wind turbines integrated to the grid was very small. As the voltage dip occurred, the measure taken was disconnecting the wind turbine from the grid and then reconnecting it when the fault is cleared and the voltage returned to normal. Thus actions didn’t cause any significant impacts on power system stability. However, as wind energy penetration level increase, the power contribution of the power plant to the grid will get more significant. If the whole wind power plant is suddenly detached (the full generation goes zero), the system will lose further production capability [16].

It can further lead to a large frequency and voltage drop and possibly complete loss of power. It is very necessary to keep the turbines connected under disturbances in the network. Therefore, the new generation of WTGs is required to have the Fault Ride through (FRT) ability specified by grid codes.

2.2.4 Impact on system planning

As wind resources are mostly located in remote locations, far from the load centers, it is critical to develop sufficient transmission to transport wind power to the load centers [18].

Accordingly, transmission planning processes are highly varying and tend to be influenced by regional politics. It may happen that energy production is in one country or state, and consumed in another. The generation capacity, transmission location and load size are different from locations. These disparities made the development of wind power transmission contentious and complex. Besides, in to carry the variable, partially unpredictable wind power, new technical requirements arise regarding the transmission technology to be used.

Based on the distribution of wind resources, an alternative vision of the future grid which is called micro- grid is provided, where energy is generated and consumed locally. It can reduce the cost of line losses and the high capital cost of transmission lines. In such scheme, the electricity grid could be considered as a collection of independent micro grids with significantly reduced long-distance energy transmission requirements.

2.3 Energy Storage Systems (ESS)

As explained in the introduction, ESS will have a significant role in energy system, with different deployment opportunities in the value chain ranging from end-consumer to distributor and producer [19].

In the past, two major limitations have hindered the diffusion of ESS across the energy market: high installation costs and low energy density [20]. However, Energy storage systems have shown an increase of interest in several aspects. Due to its flexibility and balancing ability, ESS can supply to the power grid and according to the report of International Energy Agency [21] it will be greatly important in the upcoming development of electricity system. There are different forms of storage, each with unique characteristics and depending on area of use one ESS will be more suitable than another. The most developed technologies are usually divided into four main categories, according to their principles of operation [22]:

- mechanical systems
- electric systems
- electrochemical systems and
- hydrogen storage

Regarding mechanical systems, the commercially available technologies are Compressed Air Storage Systems (CAES), flywheel energy storage and the oldest storage technology, Pump Hydro Storage (PHS).

Among the electric systems technologies, we find super capacitors and Superconducting Magnetic Energy Storages (SMES) and the most developed one Electrochemical systems are represented by flow batteries, lead-acid and lithium-ion batteries.

Besides their principles of operation, electrical storage systems differentiate also in some fundamental parameters, which are important especially whether possible applications are considered. Specific power, specific energy, maximum power rating, efficiency, discharge time, lifetime and power and energy cost are some of the most relevant parameters usually taken into consideration [22].

2.3.1 ESS applications

As shown on Table 2.1, the wide range of specific power, specific energy and discharge times together with their scalability make ESS (Li-ion batteries) suitable for many different applications in the entire energy system. Before studying which are the most suitable and interesting services from the perspective of a large-scale power generator, an overall study of the most relevant applications in the energy system has been conducted. The findings presented after are mainly based on reports by Miller et al. [23] and Eyer and Corey [24], which group battery applications in five main categories.

1. Electric supply applications. In this category services such as electricity time-shifting and generation capacity are found.

2. Ancillary services, which are needed to preserve grid stability and security and are usually offered by generators and contracted by Transmission System Operators, TSOs.
3. Grid system applications. These are services that can support or benefit the transmission and distribution grid and are usually under the responsibility of the TSOs or Distribution System Operators, DSOs.
4. End-user or utility customer applications. This category groups services like time-of-use energy cost management, demand charge management, electric service reliability and power quality.
5. RES integration applications, which help improve the power generated by these sources in terms of dispatching moment and quality.

In the following section, various applications under each category are going to be presented and briefly explained.

2.3.1.1 Electric supply applications

The two main electric supply applications batteries can provide are electricity time-shifting and generation capacity. The first consists on charging the battery when electricity prices are low so that the stored energy can be dispatched later when prices are high. The minimum assumed storage discharge duration for this application is two hours, whereas the maximum or upper boundary is probably the average duration of a daily peak demand period [34]. Besides, generation capacity refers to the possibility of replacing peak demand generation capacity with BESS. This way, batteries could be used to defer and/or to reduce the investment in new capacity [23].

2.3.1.2 Ancillary services

As defined by the European Network of Transmission System Operators (ENTSO-E) [26], ancillary services refer to a range of functions contracted by TSOs for the purpose of ensuring system security and include all the services described next. Frequency regulation or frequency response is used to guarantee real time generation-load balance within a control area and thus maintain system frequency [23].

Generating units, in order to provide the service, they must be committed with some amount of generating capacity and be able to provide an automatic or very fast response. This way the power supply can be either increased or decreased when grid frequency needs to be adjusted. The battery would be charged during down-regulation moments, while it would be discharged during up-regulation and this way improve the grid frequency by delivering power. Furthermore, reserve capacity can provide additional energy when needed and comprise spinning reserves, supplemental reserves and backup supply. Spinning reserve is provided by unloaded and online generation capacity which can respond within 10 minutes when it is needed to compensate for outages in generation or transmission. Like frequency regulation, spinning reserves also hold from power supply within the time period they are committed. Supplemental reserve is used after all available spinning reserves are activated and is provided by generation capacity that may be offline, which does not have a synchronous frequency. Finally, backup supply is provided by generation available within an hour and used for backing up reserves or for commercial transactions [23, 25].

Another ancillary service is reactive power supply and voltage control, which refers to the generation or absorption of reactive power from generators to maintain transmission system voltages within specified ranges [26]. However, batteries would generally need to be coupled with VAR compensation systems to provide this service. Finally, black start capability is the ability of the system to restart a grid immediately after a blackout [25].

2.3.1.3 Grid system applications

Grid system applications are related to the transmission and distribution network and can provide support to the grid, reduce grid congestion or delay the need for upgrading the grid, among others. BESS can provide support to grid and improve the T&D system performance by compensating for electrical anomalies and disturbances such as voltage sag, unstable voltage and sub-synchronous resonance [24, 25]. In same way, transmission congestion reduction can be achieved by storing energy when there is no transmission congestion and discharging it during peak demand periods. This reduces the transmission capacity need and avoids congestion-related issues such as costs [23].

Another potential effect of the installation of BESS is the T&D upgrade deferral, which refers to the delay and sometimes even avoidance of investment in transmission and/or distribution grid upgrading [25]. Substation on-site power, which can be provided from installed battery, supplies power to switching components and to the control equipment of the substation when the grid is not energized [23].

2.3.1.4 End-user applications

From the end-user point of view, batteries can have several different applications too. They can help matching generation and consumption, reducing costs and improving power quality, for instance one of the most interesting BESS applications for end-users is time-of-use energy cost management, an electricity time-shifting operation which allows customers to minimize their overall cost of electricity [23, 25]. Similarly to the previous one, demand charge management is the reduction of power demand during peak demand periods and consequently reduction of charges from demand [23].

Another possible application is electric service reliability. This one refers to the provision of energy to ride through outages of extended duration [25] Moreover, power quality can be improved by using battery storage to protect on-site load from short-duration events that highly affects the quality of the power supplied to the load. Finally, in load following applications the battery operation aims to meet hour-to-hour and daily load variations. The power output would change in order to adjust to the changes in electricity supply and demand within the operation region or area [23].

2.3.1.5 RES integration

Energy storage systems can also help in the integration of RES, as they can store energy for later periods and this way decrease the fluctuation and unpredictability of output power from these generation sources. RES energy time-shift can be done by charging the battery from renewable generation during off-peak or low demand periods and discharging it during peak or high demand periods [23, 24 and 25]. The power output of RES can be smoothed by using storage to compensate deviations or rapid fluctuations in renewable energy generation so that the combined power output of battery and the power generation source is somehow smooth [23, 24]. Batteries provide peak shaving possibility too. This service considers the possibility of connecting to a maximum transmission power lower than the peak power of the RES plant. The battery could store the energy exceeding the power to which the plant is subscribed and discharge it during periods when generation is under that connection capacity [23].

From all the different applications for Li-ion batteries, those of interest for a power utility from the large-scale RES power generation and physical trading point of view have been selected, which are:

1. load following;
2. RES energy time-shift, or power arbitrage;
3. Frequency regulation;
4. reactive power and voltage control;
5. power output smoothing;
6. Peak shaving.

Looking into the technical characteristics of Li-ion batteries, the ratio of Power-to Energy of batteries is the key factor determining the most suitable applications for each system. In general, most of Li-ion batteries work better in high power and low energy applications, which require a shorter duty cycle. A larger share of RES (mainly wind and solar power) raises the need for frequency regulation services. Moreover, the amount of thermal- and hydro plants online and ready to provide frequency regulation may decrease. All these factors highlight the potential of BESS for frequency regulation applications [23]. Furthermore, batteries are also used to decrease grid variability, which can be done by compensating sudden drops in power output caused by rapid changes in wind or clouds or by smoothing the ramp rates power output, among others.

ESS also seem very interesting to cover deviations in the production schedules due to uncertainty and errors in wind power forecast or shift some of the production to peak demand periods[23]. Nevertheless, some types of batteries, like the NCA, are most suitable for energy applications which may require batteries to be able to store energy for some hours. This makes some Li-ion batteries as a suitable option for longer term applications too, such as load following and RES energy time-shift.

Table 2.1 ESS applications summary

Electric supply applications	Electricity time-shifting Peak demand generation capacity replacement
Ancillary services	Frequency regulation, Reserve capacity, Reactive power supply and voltage control ,Black start capability
Grid system applications	Grid support, Grid congestion reduction, Grid update deferral and Substation on-site power
End-user applications	Time-of-use energy cost management Demand charge management, Electric service reliability Power quality improvement, Load following
RES integration applications	RES time-shifting, Power output smoothing, Peak shaving

2.3.2 ESS Characteristics

BESS have six key parameters to consider for optimization: energy capacity, power rating, round trip efficiency, ramp rate, depth of discharge and degradation. Energy capacity is the total energy in Wh that a given battery can store. Power rating is the maximum power that can be charged or discharged in one hour and is described with the C-rate. 1C means that it takes one hour to charge the battery while 0.5C equals to two hours etc. Li-ion batteries have high theoretical C-rates compared to other types of batteries. However, overheating caused by the large flow of current high C-rates brings, limits the potential of utilizing high C-rates. The round-trip efficiency is derived from all losses across the entire battery. Ramp rate is how fast the battery can change from input to output and for Li-ion batteries it is a matter of seconds. Depth of discharge specifies how much energy of the maximum capacity that can be discharged. Commonly, 80% of the capacity is utilized leaving 20% in reserve. The reason behind this is to avoid the point in which the voltage drops rapidly. It increases both the lifetime of the battery and the security of power supply. The lifetime is also reflected by the number of charging cycles performed and to avoid very high degradation the daily number of cycles should be less than two [27]. One charging cycle is defined as when the battery has processed the amount of energy equal to one full charge and one full discharge [28]. Therefore, the number of charging cycles indicate how much the BESS interacts with the grid and thusly how it acts on the power market.

Energy capacity: Energy capacity for each battery is determined by selecting a Li-ion battery that matches the scope of each case i.e. it will be different for a very low scale residential PV-BESS and wind-battery installation.

Power rating*:* Power rating (C-rate) was assumed to be evenly distributed within one hour. The Crate reaches its maximum value at 1C since the BESS operates at an hourly resolution. Lower C-rates will affect the operating strategy of the battery by limiting the number of cycles that can be performed within a day. One cycle is defined as one full charge and discharge and with 1C the battery can perform 12 cycles within a day. In order to determine the magnitude of impact the C-rate has on the BESS to grid interaction, different C-rates were simulated in the sensitivity analysis.

Ramp rate: For every hour the battery can switch its operating mode from charging to discharging or stand by, but it cannot charge and discharge at the same time. Changes in power flow direction take time and are described as the ramp rate. Since the battery operates on a market with an hourly resolution and the ramp rate for Li-ion batteries is a matter of seconds it was neglected.

Round-trip efficiency: Regarding round-trip efficiency, it is important to distinguish between battery energy storage system and battery cells. A full BESS usually includes two or more battery cells in combination with power electronics, thermal management, control and monitoring components. For single battery cells factors like these are not considered. In the literature there is no consensus regarding the choice of round-trip efficiency. Many studies who analysed PV-BESS potential used values ranging between 85-95%, but they only consider a single battery cell and not the entire BES system [29]. One study in specific took a holistic approach towards BESS to investigate the overall efficiency [30]. A system efficiency of 70-80% was found. The authors also calculated a single battery cell conversion round-trip efficiency which was between 85-97%. In this study either a round-trip efficiency from commercially available system was chosen or if nothing could be found a value of 90% was assumed. However, to understand the impact round trip efficiency has on the results, different efficiencies, from 70-100%, were simulated.

Depth of discharge*:* The depth of discharge only puts a limit for how much energy can be utilized in relation to the maximum capacity. This is not in any way influencing this model as 0 to 100% discharge in the model could be seen as discharge between minimum and maximum boundary for depth of discharge in a real battery. In this sense it would only alter the battery size which in turn only changes the absolute amount of energy traded and not the operating strategy. Therefore, the depth of discharged in the model was simplified to be in the range from 100% to 0%.

The most common storage technologies are illustrated in Table 2.1. Representing BESS, lithium ion batteries were compared with other types of energy storage systems. As shown in Table 2.1, lithium ion batteries on the behalf of battery energy storage systems in comparison to other storage technologies have the following advantages;

- Faster ramp rate and higher energy density allowing more flexible installations.
- Lithium-ion batteries cover a major range of specific power, energy and discharge times and reach the maximum efficiency values for Electrical Energy Storage (EES) [31].
- Lithium-ion (Li-ion) batteries have over the last years experienced a strong growth of interest because of the fast power output for a relatively long period in combination with the reliability of its high performance.

The disadvantage of a high capital cost of investment has evidently decreased and in coming years Li-ion batteries are expected to be a cost-efficient solution. Especially in electric vehicles and decentralized energy systems such as solar PV-BESS and wind to BESS.

The opportunities of deployment for Li-ion batteries are wide and many reports suggest that they will have a strong influence on the future power market [32, 33, 34].

This together with their possibilities of being scaled to theoretically infinite power ratings and energy capacities [23], make them really versatile storage technologies, therefore suitable for a various applications.

Table 2.2 Comparison of energy storage technologies [27]

	Pumped Hydro Storage	Compressed Air	Power to Gas	Flywheel	Flow Batteries	Li-Ion Batteries
Power [MW]	100-5000	10-100	0,1-1000	0,001-1	0,1-100	0,1-20
Life Time	30-60 years	25-40 years	7-10 years	20 years	10000-20000 cycles	10000-20000 Cycles
Self-Discharge [%/Day]	0,5	0-10	0	--	0,2	0,1-0,3
Ramp Rate	s-min	s-min	s-min	ms –s	ms-s	ms-s
Energy Density [Wh/l]	0,2-2	2-6	700	20-80	20-70	200-400
Efficiency [%]	70-85	40-70	45-55	70-95	60-85	85-95

2.3.3 Li-ion batteries

The Li-ion composition is the most commonly used battery types as storage and dominates the market for household applications. It has beyond a 50% share of utility-scale installations worldwide. The predicted installed power and market share of Li-ion batteries is shown in Figure 2.3. Li-ion batteries components include [35];

- A carbon (usually graphite) negative electrode;
- A metal-oxide positive electrode;
- An organic electrolyte (ether) with dissolved lithium ions; and
- A micro-porous polymer separator

Since Li-ion batteries are increasingly often used technology, there has been a major reduction of cost in recent years, see Figure 2.4 [19]. It is expected that the cost reduction will continue until it stabilizes around 70-100 $/kWh by 2030 [36]. Since one of the major disadvantages of BESS is the high capital cost, lower future prices would make it financially more attractive.

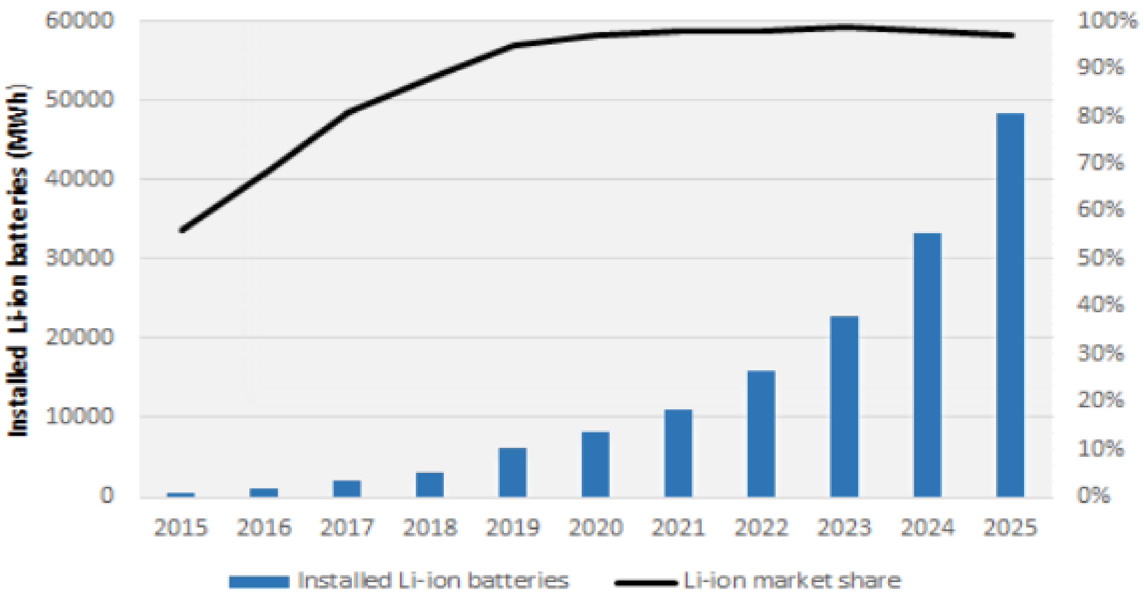

Figure 2.3 Projections for Li-ion battery [33]

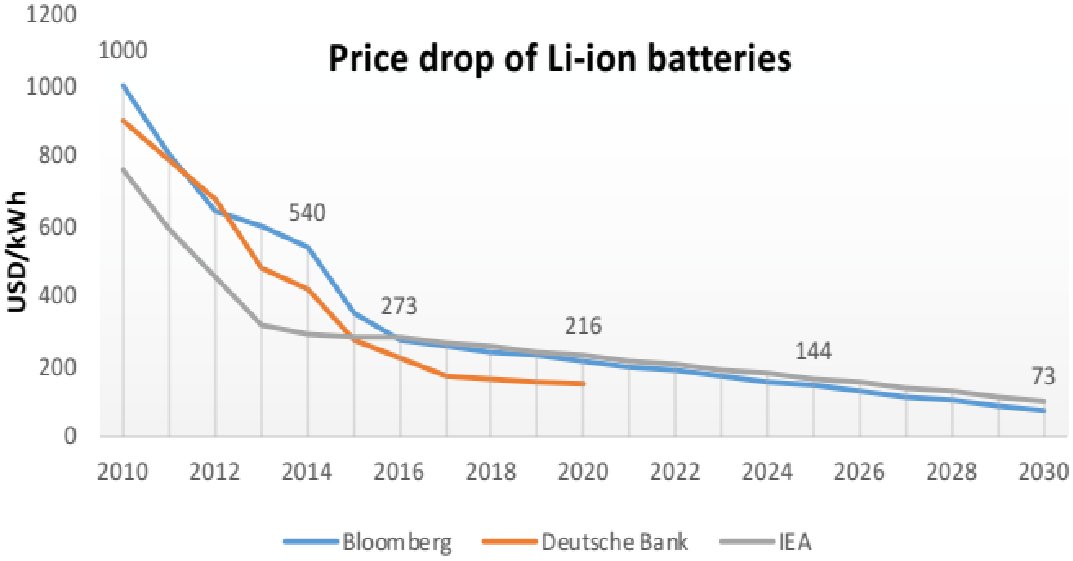

Figure 2.4 Li-ion battery costs [33; 36]

The major driving force of this reduction is the development in the electric vehicle industry which sales are expected to grow from 2 million cars in 2014 to 16 million in 2025 [33] Furthermore, battery producing companies have improved the technology and are expected to deliver a new generation of batteries that will reduce costs even more. Initial capital expenditure has been the major barrier for batteries so far [34].

2.3.3.1 Characteristics of li-ion

When the battery is charging, ions flow from the positive metal oxide electrode to the negative graphite electrode, while the reverse flow of ions takes place when the battery is discharging [37]. The technical characteristics of these batteries are dependent on the electrodes and electrolyte materials, but some generalizations can be made. First, since they have high energy density, most Li-ion cells have a nominal voltage of 3.7 V. This value is much higher than the nominal voltage of many other battery cell chemistries, which means fewer Li-ion cells are needed to produce the same power output. Second, like other battery types, they have response times on the order of 20 milliseconds. Third, Li-ion batteries have relatively high round trip efficiency, usually ranging between 85 to 95 %. Finally, Li-ion batteries have expected cycle lives of 6,000 to 8,000 cycles [38].

An important parameter used to characterize this technology is the C rating. It represents the continuous current draw the cell would support. As consequence, it is often used to represent the ratio between the maximum power output and the capacity of the cell if represented in coherent measurement units. For example, a 3MWh cell with a 1 C rating would provide a maximum output of 3 MW, whereas a maximum power output of 6 MW would be provided with a 2 C rating, and so on.

Cycle life is the number of charging and discharging cycles that the battery can do depending on its Depth of Discharge (DoD) and the charging rate. The DoD represents the minimum amount of energy available in the battery after it is completely discharged, thus the level to which the battery is discharged [39]. So, one can define a cycle as full charge/discharge of a battery. The number of cycles in a determined period *T*, *NT*, can therefore be calculated with the following formula:

$$N_T = \frac{\sum_{t=O}^{T} E_{c,t} + E_{d,t}}{2 * E_{b,max}} \tag{2.3}$$

Where;

- $E_{c,t}$= energy input to the battery (charged) in the time frame *t*;
- $E_{d,t}$= energy output from the battery (discharged) in the time frame *t*; and
- $E_{b,max}x$ = battery maximum capacity.

The State of Charge (SOC) is the indicator of how much energy content there is in the battery for each instance, usually given as a percentage of the battery's capacity. However, Li-ion batteries have disadvantages as well. First, the expected lifetime is related to the cycling DoD. So, it should be avoided to fully discharge Li-ion batteries. Second, the metal oxide electrode can become thermally unstable due to over discharge or charge and be subject to thermal runaway1 if left unchecked. Finally, Li-ion batteries still face significant cost barriers [37].

2.3.3.2 Li-ion battery types according to their chemistry

Apart from the general features of Li-ion batteries, the chemistry of the batteries can affect some of their characteristics, of which specific power and energy, safety, temperature range, cycle life and possibility of fast charge are the most noticeable ones [40]. Figure 2.5 illustrates the performance of some Li-ion electrode materials [41]. Based on the chemistry, six main types of Li-ion batteries can be identified as relevant in literature [42], which has the following main characteristics.

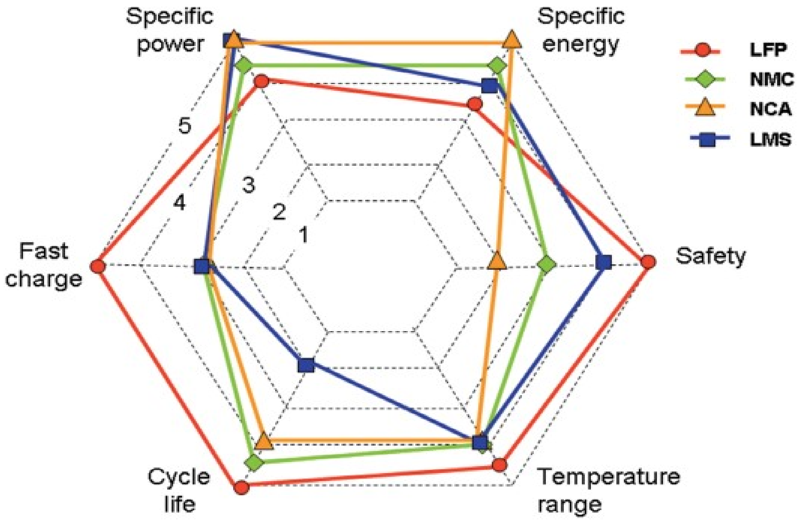

Figure 2.5 Li-ion batteries performance with respect to several characteristics, ranked from 1 (worst) to 5 (best) [41].

- Lithium Manganese Oxide, LMO. These batteries are suitable from medium to large-scale applications. Poor cycle life is their main drawback.
- Lithium Nickel Cobalt Aluminum Oxide, NCA. They have a long lifetime, around 20 years with 6 000 cycles at 60% DoD, and they have high energy capacity.

- Lithium Iron Phosphate, LFP. LFP batteries can have an even longer lifetime than NCA type batteries. They can last over 20 years with more than 7 000 cycles at more than 95% DoD. Moreover, they have a very constant charge/discharge voltage and high power, making them very suitable for fast applications. Their dis advantage is that they present a quite high self-discharge rate.
- Lithium Titanate, LTO. These types of batteries have high power rating and low energy capacity, with less than one hour discharge duration. This makes them best suited for power applications.
- Lithium Cobalt Oxide, LCO. LCO batteries are not suitable to be installed in combination with RES plants, as they are not the safest type of technology. In fact, they have been replaced by LFP type Li-ion batteries.
- Lithium nickel manganese cobalt oxide, NMC. They can have quite high energy capacities, with more than 2h duration. Thus, these types of batteries are used for day to night load-shifting applications.

2.4. Literature Review on Related Studies

In this section, papers based on: types of storages integrated to the wind farm, type of control strategy, number of batteries to be integrated and benefits are presented. Different simulation approaches and profitability assessments can be found in literature, regarding to both battery storage in stand-alone applications and in combination with renewable sources. A review of relevant studies is hereafter presented.

Braff et al. [41] have compared different storage technologies and set cost improvement targets. As first, the operation of a fixed range of sizes of hybrid wind and solar plants combined with storage in different locations is optimised with a linear solution technique. Then, optimal storage sizes are obtained to maximise the value of the systems for arbitrage purposes. In this second phase, the annual revenue divided by the annualised costs is used as indicator of profitability. Storage technologies are shown to add value to solar and wind energy as of now, but cost decrease is needed to reach profitability.

The operation of different storage technologies considering different markets has been simulated by Berrada et al. [42]. Using a linear programming model, the maximum daily profit generated by offering different energy products has been identified. The simulation of ancillary services has been approached using an average dispatched to contracted energy ratio. Results of the work from Berrada et al. [42] show high potential revenues and profitability for PHS and CAES in different US markets. On the other hand, a strong influence of the previously mentioned contract ratio is proven. The difference between dispatched energy and bidden capacity represents a challenge when offering ancillary services with ESS. First of all, the uncertainty of the availability of the battery during the bidden hours, due to a potential maximum SOC when charge is needed and vice versa, could lead to high penalties for the service not provided. Besides, the remuneration based on the activation could increase the income variability.

Optimal sizing of a lead-acid BESS for primary frequency control in European markets has been performed by Oudalov et al. [43], identifying it as the most valuable service for the owner of the storage system. The simulation has been run on historical data linking the battery operation to the grid frequency, considering a payment linked to the capacity made available according to the market framework. The developed model is a control algorithm which aims to maximise the Net Present Value (NPV) taking into account a series of technical constraints among which dynamic maximum and minimum SOC and grid code requirements are noticeable.

A similar approach has been adopted by Schweer et al. [44], where the operation of the M5BAT hybrid battery storage has been optimised to offer frequency containment reserve. In this simulation, a weekly and a daily spot auction for the service have been considered together, in order to have the possibility to reschedule the production. This way, it would be possible to face the uncertainty of the activation of the service and ensure the operation during a time frame of at least 30 minutes, as required by the regulator in the case of Germany.

A piece-wise approximation has been used to make the developed model linear. The importance of balancing the discrepancies between the scheduled and actual wind power production has been analysed by Korpaas et al. [45], performing a three steps simulation: firstly the wind production is forecast. As second, based on this forecast, the bids on the power exchange are scheduled. As last, the operation of the storage in real time to balance the deviation of the wind power generation from the scheduled one is simulated. The model has been solved using a dynamic programming algorithm and the battery efficiency has been identified as a relevant factor. Moreover, it has been demonstrated that the value of the storage is dependent on the difference between spot and regulating power prices. Applications of battery storage for compensation of forecast errors for wind power have been analysed by Cai et al. [46] and their economic benefit has been demonstrated for the German electricity market. Regarding energy arbitrage purposes, several simulations are available in literature [48, 47, and 42] and the profitability has always been shown to be strongly dependent on the market volatility and the battery storage cost. Energy storage systems with arbitrage purposes have been simulated following two main approaches. A first one is to set price triggers which, when reached, allow the system to charge or discharge. These prices can be static and obtained from historical time series, or dynamically changed during the battery operation using moving averages, as described in [49, 48]. A second option is to assume a price forecast and to optimise the bidding strategy, for example the Day Ahead bid, maximizing the possible revenue with a linear or mixed-integer linear program, as suggested by Sioshansi et al. [50] and Graves et al. [51].

S. Teleke et al. [52], the predicted wind power in next hour was selected as a power schedule, and a conventional feedback-based control strategy was proposed to control the BESS for enabling the BESS-integrated WF to generate electricity following the predetermined generation schedule. A year later [53], an open-loop optimal control strategy was proposed by M. E. Baran et al. to replace the feedback-based control strategy proposed by S. Tekele et al. for achieving better performances on meeting the generation schedule. Control strategies proposed in both papers are[52,53] effective, but may lead to frequent switch of the BESS states between charging and discharging states and consequently shorten the lifetime of the BESS dramatically. A new operation strategy was designed by Q. Li et al [54], for maximizing the lifetime of BESS by completing a fully charging cycle followed by a discharging cycle. The short-term power generation schedule in [54] was determined by the battery state-of-charge (SOC), battery charging/discharging states and forecast errors on wind power. However, this strategy was rather complex and the generation schedule needs to be revised frequently according to the actual WF power output. In D. L. Yao et al [55, 56], the BESS was divided into two parts, named as in-service BESS and stand-by BESS respectively. These two parts of the BESS are controlled separately, i.e., the in-service BESS is charged by wind power, and the stand-by BESS discharges to utility grids following the predetermined generation schedule. It is clear that the strategies proposed in these papers [55, 56], can achieve excellent performance on meeting the desired generation schedule because they achieve a thorough decoupling between the stochastic wind power outputs and the desired power schedules. However, the BESS capacity requirement is relatively high, as all energy injected to power grids are from the in-service BESS and all energy generated by wind turbine generators are stored in the stand-by BESS in advance. In Y. Yuan et al [57], in order to reduce BESS capacity requirement, BESSs were utilized to offset power deviations between the wind power outputs and the power generation schedules. In those two literatures [55-57], the charging/discharging states will be exchanged immediately if any part of the BESS arrives at full charging/discharging states in order to avoid over charging/discharging. However, impacts of the state exchanging strategy of other parts of the BESS on the performance of meeting the power generation schedule are not discussed in these papers. The limitation of all previous literatures [52-57] is that the economic aspects, such as benefits, costs and profits attributed to the BESS are not included. In fact, battery is still so expensive that considerations of the BESS economic characters are of great importance. In this paper, BESSs are assumed to be integrated in WFs to meet the desired generation schedules. The short-term generation schedules are determined based on metrological forecast. To extend BESS lifetime, the BESS is divided into two parts, which are utilized to respectively compensate positive and negative power deviations between the wind power and the predetermined power schedule and its performance is compared with single battery operation. If any part of the BESS reaches its full charging/discharging state, the charging/discharging state will be exchanged immediately in order to avoid over charging/discharging. As for state exchanging of the other part of the BESS, there are two strategies, named simultaneous state exchanging strategy and asynchronous state exchanging strategy, respectively. The impacts of these two strategies on generation schedule tracking are considered. Linear optimization or conditional statement are utilized to simulate operations of the BESS-integrated WF, and the technical performances on meeting the desired generation schedule together with the BESS benefits, costs and profits are subsequently quantified by a series of indices.

CHAPTER THREE

METHODOLOGY AND MODELING OF BATTERY INTEGRATED WIND FARM

The methodology of the thesis report shows the technical approach of the study. The study was conducted according to the lines of the flowchart presented in Figure 3.1. Scope and objective have been defined in chapter one. Next to that, there was a review on existing literature relevant to the field of studies. The information obtained from the literature used to get a better understanding of the broader background and figure out the best approach to the actual task. Initially, a thorough literature study on Li-ion batteries, technical characteristics, types based on their chemistry and applications is performed. After a detailed analysis, the most interesting type of BESS i.e Li-ion battery is selected and thus chosen to be modeled.

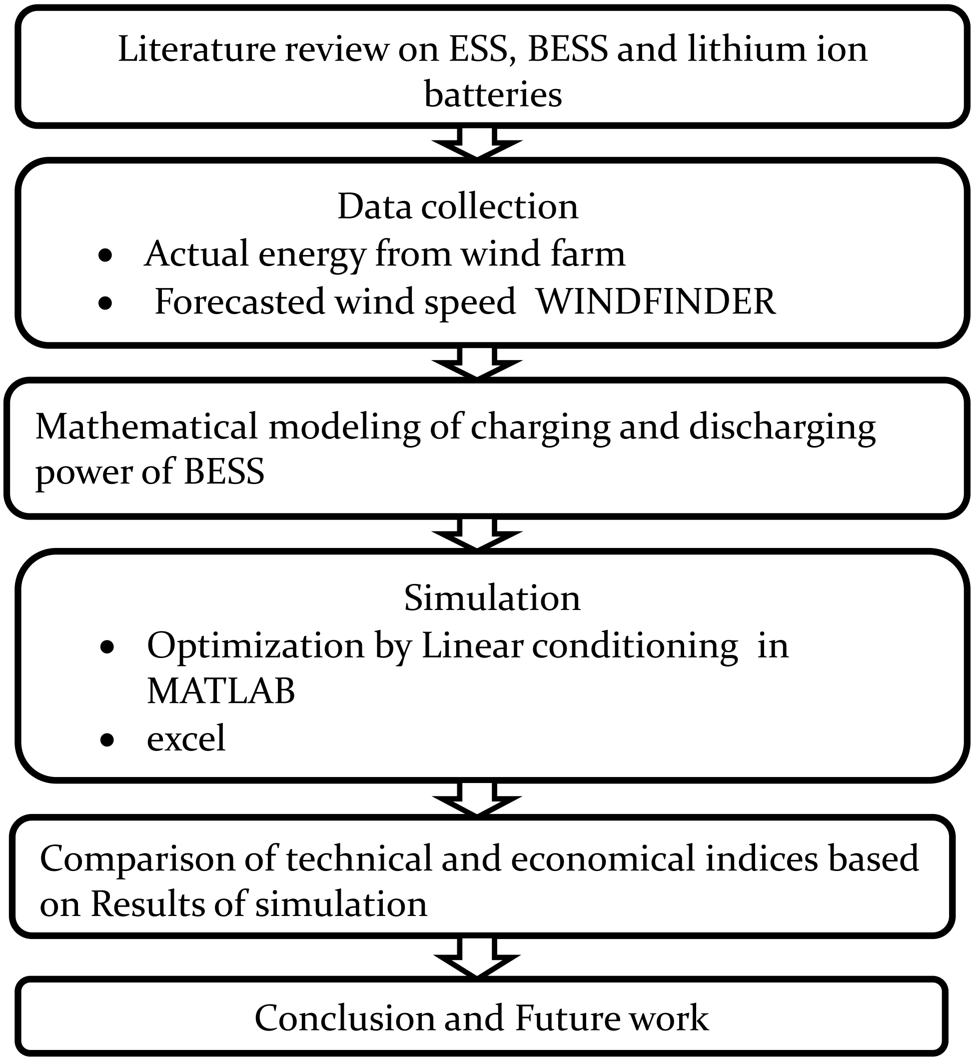

Figure 3.1 Flow chart of the methedology

The next step was collecting wind speed forecast Data from WINDFINDER app within 3 hours ahead of an actual wind power generation. It is possible to take a forecast even one day a head. But if the forecasted span increase forecasting errors increase which affects the performance of wind farm. Then the actual wind power record for corresponding time span was taken from the wind farm. Following that, linear optimization or the control algorithm mathematical models are developed to simulate the operation of the battery and calculate the potential revenues for various battery sizes. These models are built and solved using Microsoft Excel and MATLAB. After obtaining the operation of the battery for the service, the revenue streams, number of cycles and battery size are calculated. Using these results, together with BESS investment costs and some technical characteristics such as the cycle lives as inputs, an economic assessment is performed. The economic assessment is then followed by a technical analysis, whose aim is to give some insight in the most relevant parameters affecting the profitability of BESS and breakeven costs for services which are not profitable yet.

3.1 Existing System Description

Figure 3.1 Adama I wind farm [58]

Adama I Wind Park is located in the middle of Ethiopia, about 95km from Addis Ababa and 3km from Nazret, with altitude elevation of 1824-1976m. The central geographical position of the wind park is 39°13'48"E, 8°32'41"N. the wind farm has 34 turbines with a combined capacity of 51MW. The 34 wind turbines are grouped into 3: the first group with 10 turbines and the remaining two groups contain 24 wind turbine generators (12 each). The electricity generated by the 34 Wind turbine generators is transmitted through three cables to two 33 KV transmission lines (1.95 Km + 1.97 Km) then to the substation where the voltage will be boosted from 33Kv to 132 KV and then transmitted to Adama substation through a 132KV transmission line, then connected to the National Grid[59]. The generated power is directly injected into grid wheather it is the same as scheduled amount or not.

The power curve of the scheduled and the corresponding actual generated power on a particular day are shown in the figure 3.3. As shown on figure 3.3, an actual power always fluctuates around the forecasted value. It is this unpredictable fluctuating nature of actual power that causes power mismatch between generation and demand as explained in literature. So the wind farm should add some flexibility to its generation system so that actual power will match pre-determined schedule. To do this, three possible options were mentioned in literature, namely; gas generators, curtailment and energy storage systems. As discussed on previous section; BESS were found to be a best match to fill the missing element of wind farms i.e flexibility.

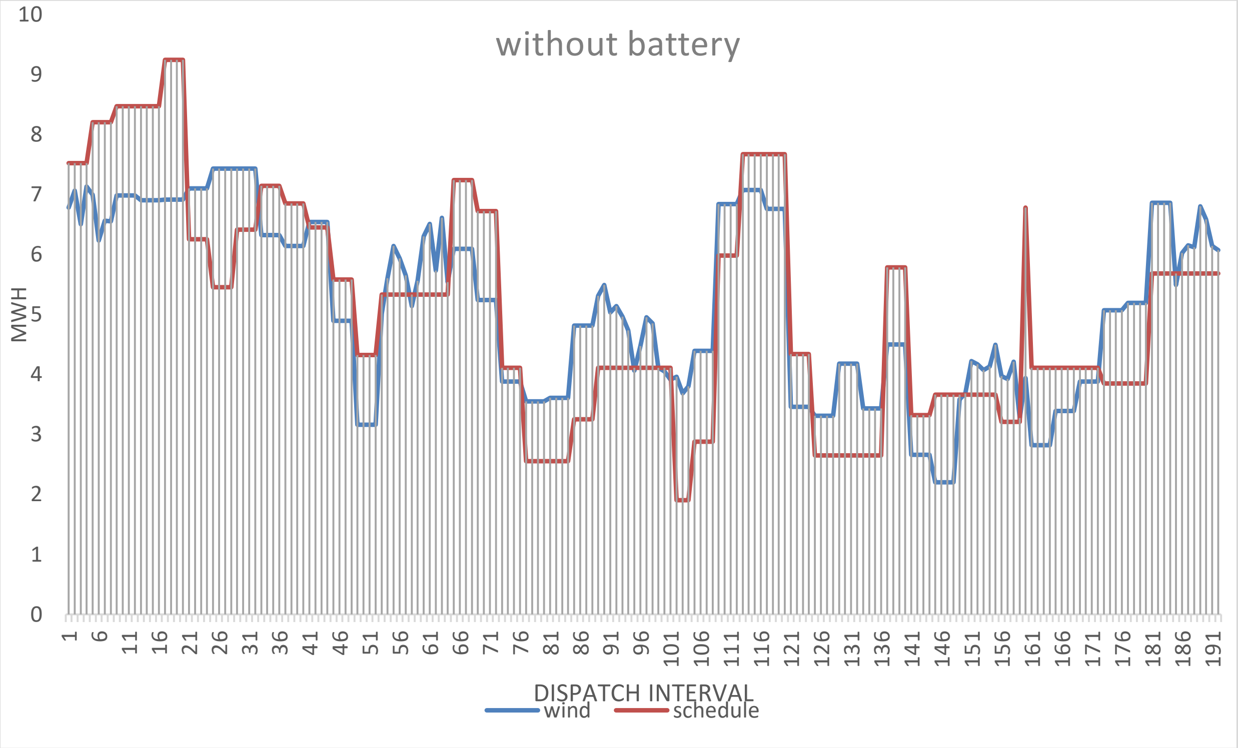

Figure 3.2 output and schedule of the wind farm on a particular day

3.2 Proposed System Model

3 .2.1 Model of BESS integrated wind farm

In this section, the model which is developed in this study shall be described. To establish the optimal operating strategy for wind power in combination with battery storage a simplified model of the system is employed. Figure below shows a scheme of the underlying system: Wind turbines and battery storage system are connected to each other and to the grid through a common bus bar. As shown in the figure, the BESS is divided into two parts namely; BESS I and BESS II and it is integrated with the help of a DC/AC power converter.

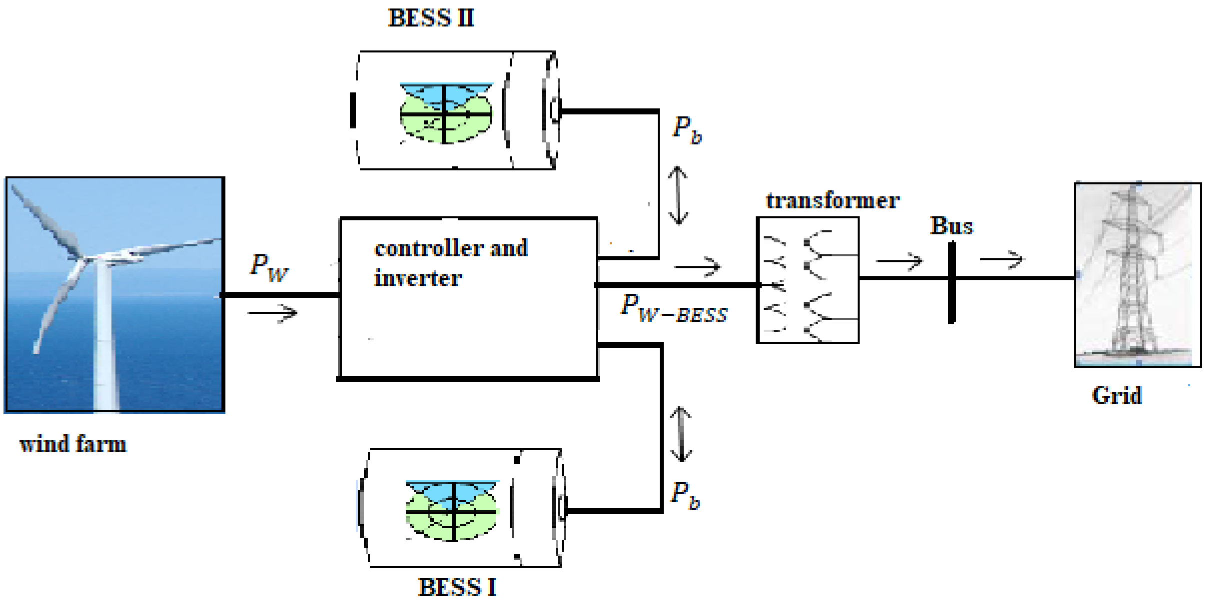

Figure 3.3 BESS-integrated WF schematic diagram

Figure 3.4 shows power flow of BESS integrated WF where, P_W is the power output of the WF, P_b is the charging/discharging power of the BESS, which is controlled by power controller according to a certain control strategy as discussed in section 3.2.2. P_{W-BESS} is the output power of the BESS-integrated WF, and can be expressed by Equation (3.1).

$$P_{W-BESS} = P_W + P_b \tag{3.1}$$

The reference directions of electric power flow are shown by the arrows. If the BESS discharges, the value of P_b is positive, and it is negative when the BESS is being charged. The BESS's integration increases WF's ability to control power thus enable operators to control charging/discharging power of the BESS in order to offset stochastic power deviations between the actual wind power and the pre-determined schedule of the generation system. This will in turn enable the BESS integrated WF to generate electricity following the pre-determined generation schedules to some extent. Up to this point, the BESS integrated WF is considered to have the ability of meeting the generation schedules.

3.2.2 BESS control scheme

Fig. 3.4 illustrates the role of BESS is to compensate for the irregularly varying power output of the wind farm. The two batteries are connected to the wind farm's output at the point of common coupling and net power is injected to the system. Thus, the goal of the controller is to achieve the objective of equating the net power supplied to the grid (P_{w-BESS}) with predetermined schedule (P_S)over a given time period. Taking P_S, $P_W$and SOC as input, and keeping the constraints in mind, the controller compares the $P_W$with reference P_S and makes the decisions of which battery will charge or discharge at a time and what amount of power to be charged or discharged in each battery in order to supply the grid as per schedule. The algorithms for such decision making process of the controller is discussed in the sections 3.4 along with their perspective state exchanging strategies.

3.2.3 Objective function

Optimization aims at maximizing profit and minimizing the difference between schedule and injected energy by managing the overall power output of the system. This output management includes direct output of the wind turbines to the grid as well as charging the battery with wind power and discharging it into the grid. The objective function and constraints along with parameters and decision variables will be explained below.

The objective function is derived from the optimization statement above and is formulated in the following equations

$$\mathrm{P_{div,i}} = |\mathrm{P_{s,i}} - \mathrm{P_{w-BESS,\ i}}| \tag{3.2}$$

$$\mathrm{M_{in,}} = \rho_1 \mathrm{P_{w-BESS,}}\ \mathrm{T} - \text{price of battery} \tag{3.3}$$

Where, $\mathrm{P_{div,i}}$ $-$ difference between scheduled power and BESS-integrated WF power, $\mathrm{M_{in,}}$ is income of BESS integrated wind farm, ρ_1 $-$ Tariff and T- Duration in hour.

The objective of the overall work is to minimize the power deviation from the schedule so the grid will get as per schedule and to maximize the benefit as much as possible.

3.2.4 Constraints

Constraints are used to maintain a physically possible power flow. The operation of BESS is subjected to the following constraints:

I. Battery capacity

Suppose, At DI (dispatchinterval) i, actual wind power($P_{W,i}$) is larger than the desired power generation schedule submitted to dispatch center($P_{s,i}$), i.e., the power deviation between $P_{W,i}$and$P_{s,i}$, is larger than zero. Under this condition, to ensure the BESS-integrated WF to generate electricity as the desired power generation schedule, the surplus energy must be charged into BESS I which is supposed to be in charging state, if not, this part of energy should be curtailed. At this case, the maximum allowable charging power provided by BESS I can be determined by Equation (3.4).

$$P_{mcI,i} = -\max\{0.5P_{r,ch}E_c, [0.5(S_{max} - S_{1,i-1})E_c]/[T\eta_{ch}]\} \tag{3.4}$$

Where the capacity of BESS I is 0.5*E_c, i.e., half capacity of the BESS, $\eta_{ch}$is utilized to approximately express internal power losses in batteries and converters when the BESS is charging.

Assume actual wind power $P_{W,i}$, is less than the desired power generation schedule submitted to dispatch center($P_{s,i}$), in this case, BESS II which was assumed to be at discharging state should be discharged to compensate the power deficiency; otherwise the BESS-integrated WF cannot generate the same amount of electricity as the desired power generation schedule. The maximum allowable discharging power provided by BESS II can be determined by Equation (3.5).

$$P_{mdII,\ i} = \max\{0.5P_{r,dis}E_c,\ [0.5(S_{II,i-1} - S_{min})\eta_{dis}E_c]/T\ \} \tag{3.5}$$

Where, η_{dis} is utilized to express internal power losses in batteries and converters approximately when the BESS discharges.

II. Battery's state of charge

$$S_{min} < SOC < S_{max} \tag{3.6}$$

Even though it is not decided by the controller, the profit of WF should be also considered as constraint since it limits us from using the large battery capacity

3.2.5 Determination of short-term generation schedules

The WF is assumed to take a short term wind speed prediction from WINDFINDER apps, which offers wind forecasts for over 45000 places all over the world, 3 hours to 7 days ahead. On the basis of short-term forecasted wind power, WF can determine their short-term generation schedules in future hours and submit them to load dispatch center(LDC).

In a liberalized electricity market, if WFs cannot meet the submitted generation schedules, they will be penalized by the ISO according to the power deviations between their submitted generation schedules and the real output power [60]. However, Ethiopian electric power corporation is state monopoly, i.e all generation, transmission and distribution systems are owned by the state. Hence, the wind farm will not be penalized even if there is power deviation from submitted schedule. But the power deviation will cause mismatch between the load and generation which will reduce distribution system reliability and maximize customer dissatisfaction

For the BESS-integrated WF explained in Figure 3.4, the essence of meeting generation schedule is to utilize the BESS to minimize the power deviations between the desired power schedules and the wind power. When the wind power is larger than the submitted power generation schedule, the BESS in Figure 3.4 will be charged to absorb surplus wind energy; otherwise certain part of wind energy will be curtailed. Under this condition, the expected charging energy during a dispatching interval, can be expressed using Equation(3.7).

$$E_{ch} = \int_{P_s}^{1} f(x)(x - P_s)T dx \qquad (3.7)$$

If the wind power is less than the submitted power generation schedule, the BESS will be discharged to compensate the power deficiency. At this moment, the expected discharging energy during a DI can be calculated using Equation (3.8).

$$E_{dis} = \int_{0}^{P_s} f(x)(P - x_s)T dx \qquad (3.8)$$

Typical value of the variable T is set to be 15 minutes.

In a charging-discharging cycle of the BESS, the energy discharged from the BESS is always less than that charged into the BESS due to power losses in both batteries and converters. The ratio between discharging and charging energy can be quantified by a battery efficiency parameter. To achieve a balance between charging and discharging, the desired generation schedule of the BESS-integrated WF can be calculated by Equation (3.9).

$$g(P_s) = E_{dis} - \eta_{BESS} E_{ch} = 0 \tag{3.9}$$

3.2.6 Operation strategies of the BESS

Figure 3.3 shows, the desired power generation schedule and the wind power of certain WF during a typical day over 48 hours. As shown on the power curve, the real wind power always fluctuates randomly around the power generation schedule. The power deviation at DI i between the real wind power and the power generation schedule can be calculated by Equation (3.10).

$$\Delta P_i = P_{W,i} - P_{s,i} \tag{3.10}$$

If the BESS is controlled as a whole, random fluctuations of the wind power will lead to frequent changes between charging and discharging states and may consequently shorten the lifetime of the BESS dramatically. To prolong the lifetime of battery, the BESS is divided into two parts with equal capacity, i.e., BESS I and BESS II respectively, and is controlled independently for respectively offsetting the positive and negative power deviations illustrated in Figure 3.3. If any part of the BESS reaches its full charging/discharging state (i.e., the SOC of this part of the BESS reaches its maximum/minimum allowable value predetermined by battery characters), its charging/discharging state must be exchanged immediately for avoiding over charging/discharging otherwise the life time of the BESS will be notably shortened [61].

To manage those two batteries, two entirely different state exchanging strategies are proposed, named asynchronous and simultaneously state exchanging strategies, as illustrated in Figures 3.5 and 3.6, respectively.

In Figures 3.5, it is assumed that BESS I arrives its fully discharged state at DI i, i.e., the SOC of this part of the BESS reaches its minimum allowable value (SOC_{min}). BESS I must switch immediately from discharging state to charging state otherwise it will be over discharged. However, at this moment BESS II has not arrived its fully charged state, i.e., its SOC is still less than the maximum allowable value, so that it will continue to charge until it reaches the maximum limit. If BESS II is not exchanged from charging state to discharging state at the same time, two parts of the BESS are both in charging state in several following DIs, i.e., from DI i to DI j as indicated in Figure 3.5. During these DIs, possible power deficiencies cannot be compensated as both parts of the BESS are in the charging state and may result in a decreased performance on meeting desired generation schedule. The state exchanging strategy of the BESS illustrated in 3.5 is named as the *asynchronous state exchanging strategy.*

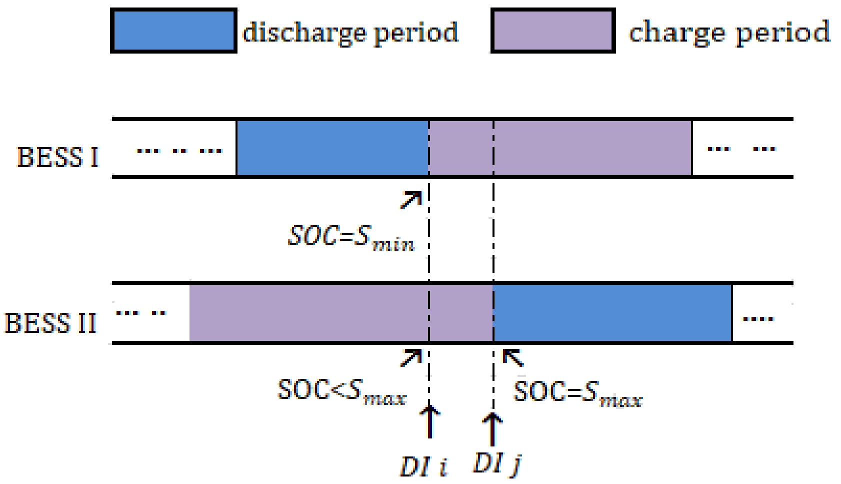

Figure 3.4 Asynchronous state exchange strategy of the BESS

On the other hand; for the same case, if BESS II is exchanged from charging state to discharging state in pace with BESS I regardless of the SOC of BESS II(whether it is fully charged or not), the two parts of BESS are always at opposite states at any time. Due to this, not only positive power deviations but also negative power deviations can be compensated by charging and discharging power of the BESS to some extent. Thus, the performance on meeting the generation schedule can be improved dramatically. Unfortunately, simultaneous state exchanging strategy may not fully utilize BESS II (in this case) due to an incomplete discharging process and subsequently increase operation cost of the BESS. The state exchange strategy of the BESS illustrated in Figure 5 is named as the *simultaneous* state exchanging strategy.

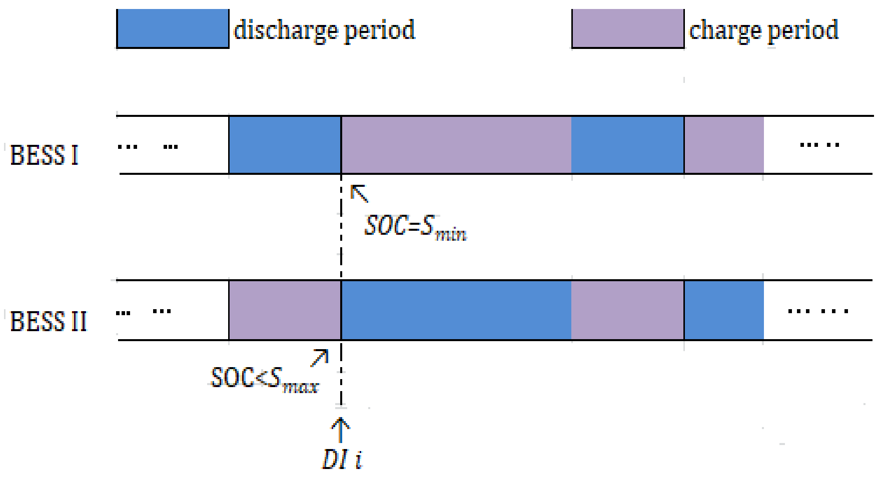

Figure 3.5 Simultaneous state exchange strategy of the BESS

In the above assumption, BESS II is the one that switches its state passively in order to keep in pace with the state exchange of another part of the BESS, as illustrated in figure 3.6. However, the BESS that switches its state passively might be changed from BESS II to BESS I due to random power deviations between the wind power and the power generation schedules. As a result, the numbers of charge-discharge cycles of two parts of the BESS during certain time horizon will be increased dramatically due to simultaneous state exchange of the BESS.

3.2.6.1 Determination of charging/discharging power

State exchanging strategies of the BESS (simultaneous or asynchronous) as described above will affect charging and discharging states of BESS I and BESS II. Therefore, charging/discharging power of the BESS varies when different strategies are adopted.

I. Simultaneous state exchanging strategy

When the simultaneous state exchanging strategy is adopted, BESS I and BESS II are always in opposite states. In other words, if BESS I is in discharging state at DI i, BESS II will be automatically in charging state at the same DI or vice versa.

At DI i, it is assumed that real wind power $P_{W,i}$, is larger than the desired power generation schedule submitted to the dispatch center $P_{s,i}$, Then, the charging power of BESS I at DI i can be calculated by Equation (3.11).

$$P_{bI,i} = \begin{cases} \Delta p_i & \mid \Delta p_i \mid \; \leq \; \mid \Delta p_{mcI,i} \mid \\ p_{mcI,i} & \mid \Delta p_i \mid \; > \; \mid \Delta p_{mcI,i} \mid \end{cases} \tag{3.11}$$

From Equation (3.11) it is clear that BESS I cannot fully absorb surplus wind energy if the power deviation is larger than the maximum allowable charging power provided by BESS I. in this situation, a portion of wind energy must be curtailed to keep the committed power schedule rigidly. So the curtailed wind power can be stated by Equation (3.12).

$$P_{wc} = \begin{cases} 0 & \mid \Delta p_i \mid \; \leq \; \mid \Delta p_{mcI,i} \mid \\ \Delta p_i - p_{mcI,i} & \mid \Delta p_i \mid \; > \; \mid \Delta p_{mcI,i} \mid \end{cases} \tag{3.12}$$

BESS II's charging power is set to be zero even if BESS I cannot fully absorb excess wind energy. Otherwise, a life circle of BESS II will be shortened. At this DI, the injected power of the BESS-integrated WF can be expressed by Equation (3.13).

$$P_{W-BESS,i} = P_{W,i} + P_{bI,i} + P_{bII,i} - P_{wc,i} \tag{3.13}$$

On the other hand, assumed the value of $P_{W,i}$ is smaller than the value of $P_{s,i}$, i.e., the power deviation Δp_i at this DI is negative. So BESS II which was assumed to be at discharging state should be discharged to fill the power gap between the two; otherwise the Battery-integrated WF cannot generate the same amount of electricity as the desired power generation schedule.

Then, the discharging power of BESS II at DI i can be calculated by Equation (3.14).

$$P_{bII,i} = \begin{cases} \Delta p_i & \mid \Delta p_i \mid \, \leq \, \mid \Delta p_{mdII,\ i} \mid \\ p_{mdII,i} & \mid \Delta p_i \mid \, > \, \mid \Delta p_{mdII,\ i} \mid \end{cases} \tag{3.14}$$

$$\text{EIED} = \begin{cases} 0 & if\ both\ batteries\ are\ at\ minimum\ SOC \\ (\Delta p_i - p_{mdII,i})T & \mid \Delta p_i \mid \, > \, \mid \Delta p_{mdII,\ i} \mid \end{cases} \tag{3.15}$$

If the power deviation is less than the maximum allowable discharging power provided by BESS II, the discharging power of BESS II can compensate the power deficiency entirely, i.e., the BESS-integrated WF can strictly satisfy the desired generation schedule. On the other hand, if power deviation is greater, the power output of the BESS-integrated wind farm (the combined power of battery and wind) will be less than the desired generation schedule, which means there will be lack of power on distribution side.

At this moment, BESS I's discharging power is set to be zero at this DI, even if BESS II cannot compensate the power deviation completely. Otherwise, a life circle of BESS I will be shortened. Assuming that the discharging and charging energies are positive and negative respectively; at this DI, the power injected by the WF can be calculated by Equation (3.16).

$$P_{W-BESS,\ i} = P_{W,i} + P_{bI,\ i} + P_{bII,i} \tag{3.16}$$

Where, $P_{bI,\ i} = P_{dI,i} - P_{chI,i}$ and $P_{bII,i} = P_{dII,i} - P_{chII,i}$

In this thesis work, η_{ch} and η_{dis} are assumed to be constant and equal in values. The correlations among these two parameters and efficiency parameter η_{BESS} can be expressed by Equation (3.17).

$$\eta_{BESS} = \eta_{ch} \times \eta_{dis} \tag{3.17}$$

Figure 3.7 shows the algorithm of the controller to determines the battery to be used at a time and amount of energy to be charged and discharged.

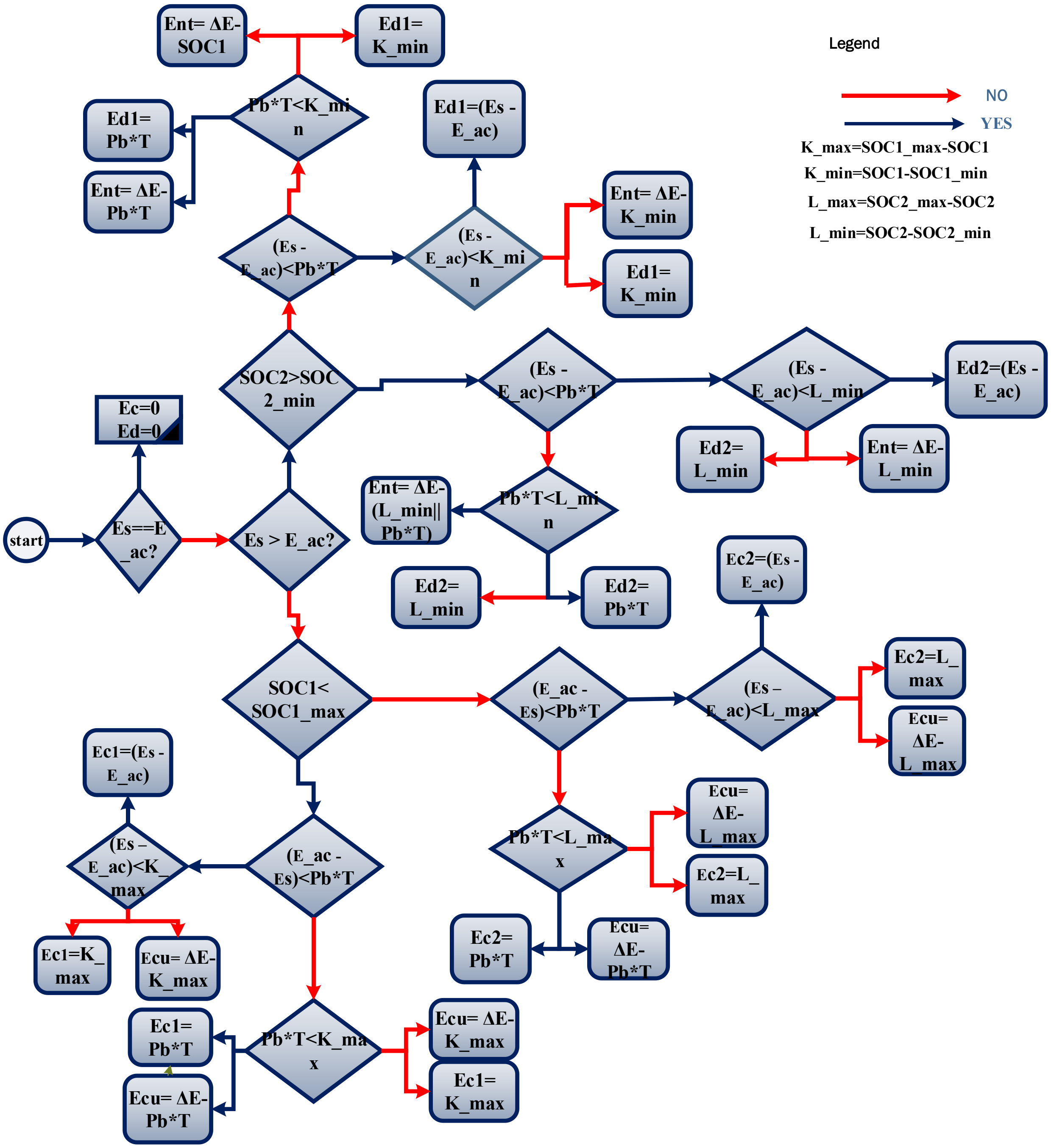

Figure 3.6 Control algorithm of simultaneous state exchanging strategy

I. Asynchronous state exchanging strategy

If the adopted state exchanging strategy is asynchronous, two parts of the BESS might be at the same charging or discharging state during same periods of time. In these periods, the determination of charging /discharging power of the BESS will be different from simultaneous state exchanging strategy. In other periods during which two parts of the BESS are in opposite states, the charging/discharging power of the BESS can be determined according to methodology proposed previously.

It is assumed that the wind power at DI i exceeds the desired power schedule, i.e., the power deviation $\mathit{\Delta} P_i$ at this DI is positive. At this moment, in order to reduce wind power curtailments surplus wind energy will be stored in the BESS. If both parts of the BESS are in the discharging state, they cannot be switched to charging mode to store the surplus wind energy unless they are fully discharged. Otherwise, a battery life cycle will be shortened. Under this condition, all surplus wind energy must be curtailed for enabling the BESS-integrated WF to meet the desired generating schedule and the curtailed wind power can be expressed using Equation (3.18).

$$P_{wc,i} = P_{w,i} - P_{s,i} = \mathit{\Delta} P_i \tag{3.18}$$

On the other hand, if BESS I and BESS II both are in charging state, they both have abilities of storing the surplus wind energy. The maximum allowable charging power provided by them can be by Equation (3.4). It is assumed that the value of $S_{1,i-1}$ is larger than that of $S_{2,i-1}$ i.e., BESS I is closer to its full charging state than BESS II. So, BESSI has priority of storing the surplus energy, so that it can reach to fully charged state as soon as possible and immediately exchanged from current charging state to discharging state. In this way the WF will get the ability to cope with possible power deficiencies. If this excess energy is greater than the capacity of BESS I i.e BESSI failed to absorb the surplus wind energy completely, the surplus energy will be stored into BESS II. If the surplus wind energy is too large to be thoroughly absorbed by both BESS I and BESS II, the remaining wind energy must be curtailed. In this case; at DI i, charging power and curtailed wind power can be respectively expressed by Equations (3.19), (3.20) and (3.21). And the injected power of the BESS-integrated WF can be expressed by Equation (3.16).

$$P_{bI,i} = \begin{cases} \Delta p_i & |\Delta p_i| \le |\Delta p_{mcI,i}| \\ p_{mcI,i} & |\Delta p_i| > |\Delta p_{mcI,i}| \end{cases} \tag{3.19}$$

$$P_{bII,i} = \begin{cases} 0 & |\Delta p_i| \le |p_{mcI,i}| \\ -\Delta p_i - p_{mcI,i} & |p_{mcI,i}| < |\Delta p_i| \le |p_{mcI,i} + p_{mcII,i}| \\ p_{mcII,i} & |\Delta p_i| > |p_{mcI,i} + p_{mcII,i}| \end{cases} \tag{3.20}$$

$$P_{wc,i} = \begin{cases} 0 & |\Delta p_i| \le |p_{mcI,i} + p_{mcII,i}| \\ \Delta p_i + p_{mcI,i} + p_{mcII,i} & |\Delta p_i| > |p_{mcI,i} + p_{mcII,i}| \end{cases} \tag{3.21}$$

When the WF cannot generate sufficient energy to cope with the desired generating schedule, i.e., the power deviation Δp_i at this DI is negative, the energy stored in the BESS should be discharged to compensate the deficiency of that power. At the time, there are three possible options for the state BESSs.

- If the batteries are in opposite state i.e one is on charging state and the other is on discharging state, the BESS which is on discharging state will fill the power deficiency.
- If both parts of the BESS are unfortunately in charging states, they will fail to fill the needed gap; otherwise, a battery life cycle will be consumed. Under this situation, the BESS-integrated WF cannot generate the amount of electricity as the desired generating schedule, and the injected power is only equal to real wind power.
- If both parts of the BESS are fortunately in discharging states, the energy stored in them can be discharged to reduce the power deficiencies or even to cover them completely. At this point, the maximum allowable discharging power provided by them can be expressed by Equation (3.5). Like it was described in charging case, the priority of discharging for the two parts of the BESS depends on its state of charge. For convenience of description, it is assumed that BESS I is closer to its full discharging state than its counterpart. So, BESSI will have the priority to discharge the stored energy, so that it can arrive to its fully discharged state as soon as possible. Then, if BESS I reaches full discharged state, it will be immediately exchanged from current discharging state to charging state in case of the need to store possible surplus wind energy. If BESS I fail to fill the needed power deficiencies thoroughly, BESS II will also discharge for the purpose of meeting power generation schedule. If the deficiency of power at this DI is too large to be entirely compensated by the BESS, WF operators have no choice than leaving as it. In this case, discharging power of BESS I and BESS II can be expressed by Equations (3.22) and (3.23) and the injected power of the BESS-integrated WF can be obtained by Equation (3.16).

$$P_{bI,i} = \begin{cases} -\Delta p_i & |\Delta p_i| \leq |\Delta p_{mdI,i}| \\ p_{mdI,i} & |\Delta p_i| > |\Delta p_{mdI,i}| \end{cases} \tag{3.22}$$

$$P_{bII,i} = \begin{cases} 0 & |\Delta p_i| \leq |p_{mdI,i}| \\ -\Delta p_i - p_{mdI,i} & |p_{mdI,i}| < |\Delta p_i| \leq |p_{mdI,i} + p_{mdII,i}| \\ p_{mdII,i} & |\Delta p_i| > |p_{mdI,i} + p_{mdII,i}| \end{cases} \tag{3.23}$$

$$EIED=\begin{cases} \Delta p_i T & both\ batteries\ are\ on\ charging\ state \\ 0 & \Delta p_i < p_{mdI,i} + p_{mdII,i} \\ (\Delta p_i - (p_{mdI,i} + p_{mdII,i}))T & \Delta p_i > p_{mdI,i} + p_{mdII,i} \end{cases} \quad (3.24)$$

Generally; scheduled energy can be obtained by combination of the wind turbines output and the batteries i.e if the actual output is greater than the schedule, excess energy will be stored in to batteries and if it is deficient, energy will be discharged from batteries. The algorithm of the controller to determines the battery to be used at a time and amount of energy to be charged and discharged is shown in fig 3.6

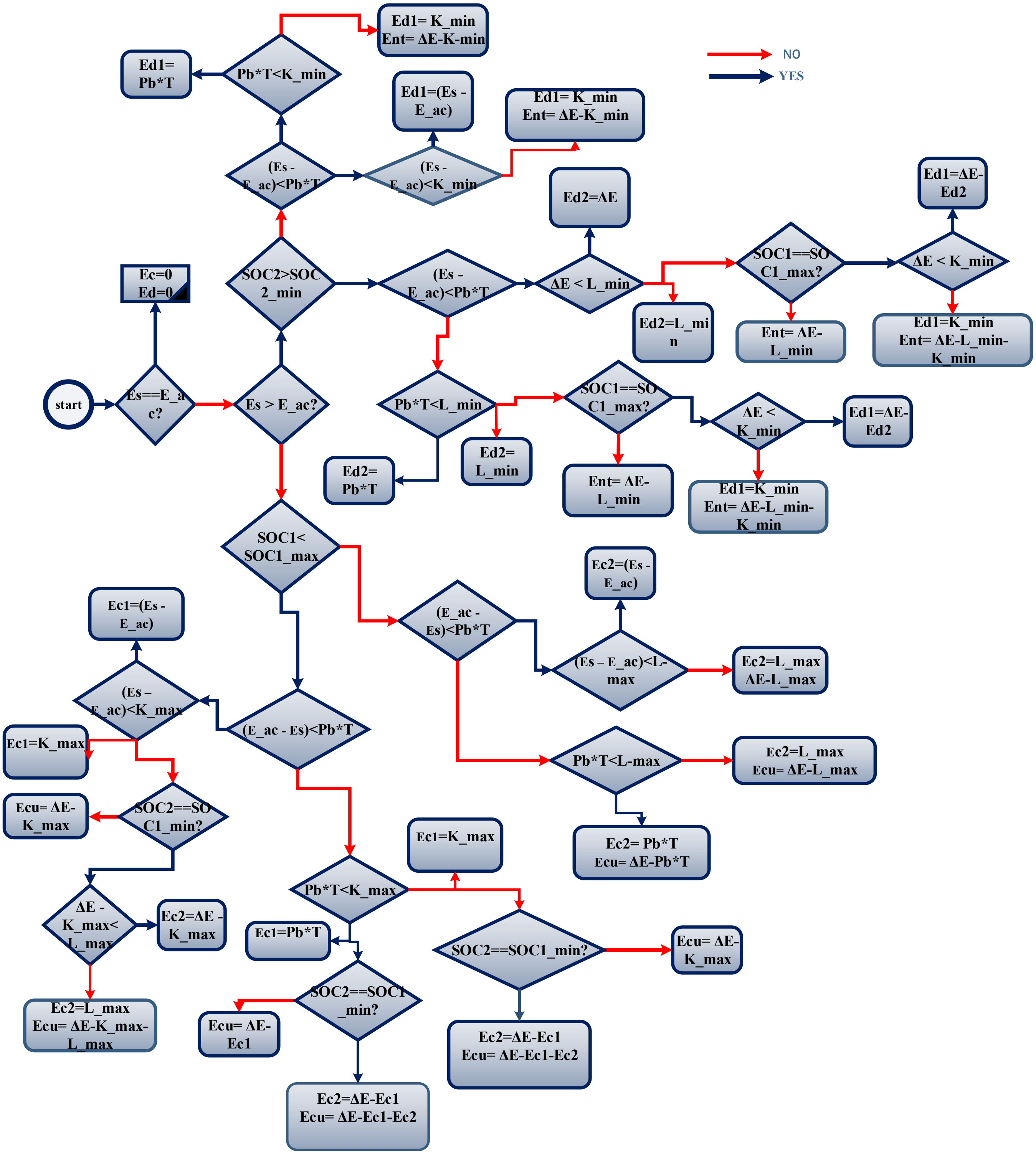

Figure 3.7 control algorithm of asynchronous state exchanging strategy

3.2.7 Battery selection

The battery which is used in this study is lithium ion battery (Li-ion), because of its compatibility as compared to other types of BESS technologies when it is integrated to the wind power farm. High efficiency (85-95%), high energy capacity, better response times on the order of 20 milliseconds and long life span at 100% depth of discharge (DOD) up to 10000 cycles are some of its remarkable features as described in chapter two [27].

Unlike battery type selection, the size of the battery was determined based on series of simulations. So, in order determine the size of the battery, the performance of the wind farm was tested in various battery capacities in all cases of operating strategies (single, simultaneous and asynchronous). In all cases, Technical indices (PMGS, EIED and ECU) appeared improving with increase in battery capacity. Contrarily, the profit of battery integrated wind farm showed an increment with increase in battery capacity for small battery sizes in simultaneous state exchanging strategy and it showed negative increment for other cases as described in the result section. So the BESS capacity with maximum profit was chosen.

3.2.8 Economic structure

The two broad categories of Ethiopian electric power corporation; Ethiopian Electric Power (EEP) and Ethiopian electric utility (EEU) owns and controls the entire power system of the country. The first one administers the national power grid with all high voltage power transmission lines above 66 kV as well as all involved electrical substations and nearly all power plants within the national power grid (except some co-generation power plants which belongs to the Ethiopian Sugar Corporation which is also state owned). The other one controls electric power distribution and the operation of power transmission lines of ≤66 kV within the national power grid [4].

Since both are state owned, one is responsible for generation and transmission whereas the other is responsible for distribution i.e for selling the generated energy. So, the energy generated by the wind farm is assumed to be sold by EEU and the income is for EEPCO. The Load Dispatch Center (LDC) is a medium between those two state owned companies in which it runs the consumption forecasts, controls the generation accordingly and the electricity flow from one energy generating area to a consumption area (including when exporting electricity to neighboring countries) and if needed decide of the areas where rolling blackouts will happen. So, all generating units submit its schedule to the load LDC.

It is assumed that the power generated by each generating units is distributed for each demand sectors according to its percentage of composition. An internal Demand composition of EEPCO's distribution system as per report of 2017 and average electricity price according to a newly enhanced tariff is shown on the table 5[61].

Table 3.1 an internal demand composition and average price

Demand Sector	Composition (%)	average price ETB/kwh
Domestic	38	1.880
Commercial	24	2.1240
Industrial	36	1.531
Street	2	2.1240

So, it is assumed that the power generated by the wind farm is distributed for each demand sector according to its percentage and the income for EEU due to the energy of wind farm is assumed as the income of the windfarm.

Based on table 3.1, the economic attributes of EEU due to BESS-integrated wind farm i.e OBB, OCB and OPB can be calculated by tequations 3.28 and 3.29

3.2.9 Technical indices

Parameters which show the performance of battery integrated wind farm on meeting generatingschedule. During a certain studied time horizon

PMGS _ Probability of meeting generation schedule

$$\text{PMGS} = P_r\{P_{W-BESS,i} = P_{s,i}\} \quad i = 1,2,3,\ldots\ldots,n \tag{3.25}$$

Where P_r is probability

EIED_ Expected energy not dispatched (expected injected energy dispatch)

$$\text{EIED} = \sum_{i=1}^{n}(P_{s,i} - P_{W-BESS,i})\text{T} \tag{3.26}$$

ECU _ Energy curtailed

$$\text{ECU}=\sum_{i=1}^{n}(P_{w,i} - P_{s,i} - P_{ch,i})\text{T} \tag{3.27}$$

OBB_ Operation benefits of battery integrated wind farm

$$\text{OBB}= \sum_{i=1}^{n} P_{W-BESS,i}\text{T} \times \rho \tag{3.28}$$

Where $\rho=(0.38 \times 1.88 + 0.24 \times 2.14 + 0.36 \times 1.98 + 0.02 \times 2.14)$

OPB_operation profit of battery

$$\text{OPB} =(\sum_{i=1}^{n} (P_{W-BESS,i} - P_{W,i})\text{T}) \times \rho - \text{OCB} \tag{3.29}$$

OCB_ operation cost of batteries

$$\text{OCB} = \text{price of batteries} \tag{3.30}$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Technical Performances of WF with Various BESS Capacities

It is assumed that the battery energy storage system is integrated into the wind farm according to the technical scheme indicated in Figure 3.4. For the battery integrated wind farm, the technical performances on the meeting generation schedule always improve with the increase in BESS capacity no matter which state exchanging strategy is adopted or how many batteries are used, as indicated in Figures 4.1, 4.2 and 4.3.

The values of the index EIED and ECU always decrease as the BESS capacity increase, while the values of the index PMGS raises monotonically with increasing BESS capacity. From Figures 4.1, 4.2 and 4.3, it is also found that the increase in the amplitude of the technical performances of the BESS-integrated WF became rather small when the BESS capacity has reached a certain value. It can consequently be inferred that if the BESS-integrated WF is demanded to totally meet the desired generation schedule, the required BESS capacity might be too large to be accepted.

Figures 4.1, 4.2 and 4.3 also depict that state exchanging strategy is an important factor to determine the technical performance of the BESS-integrated WF. When the asynchronous state exchanging strategy is adopted, both parts of the BESS might be in the same charging/discharging state during some DIs. If both parts of the BESS are in charging states, they cannot compensate for the power deficiencies. As a result, the BESS-integrated WF cannot track the desired power schedules in this situation. In contrast, if both parts of the BESS are in discharging states, available discharging power is consequently increased and technical performances on meeting the desired generation schedules will be improved but there is no space for surplus energy which will increase index ECU. These two opposite factors, i.e., a positive factor and a negative factor affects the technical performances BESS on meeting the desired generation schedules when the asynchronous state exchanging strategy is adopted. As a result, the simultaneous state exchanging strategy can result in better technical performances on satisfying the desired generation schedules in most values of the BESS capacity, as illustrated in Figures 4.1, 4.2 and 4.3. That is to say, the simultaneous state exchanging strategy can bring a higher value of the index PMGS and a lower value of the index EIED and ECU in most values of the BESS capacity.

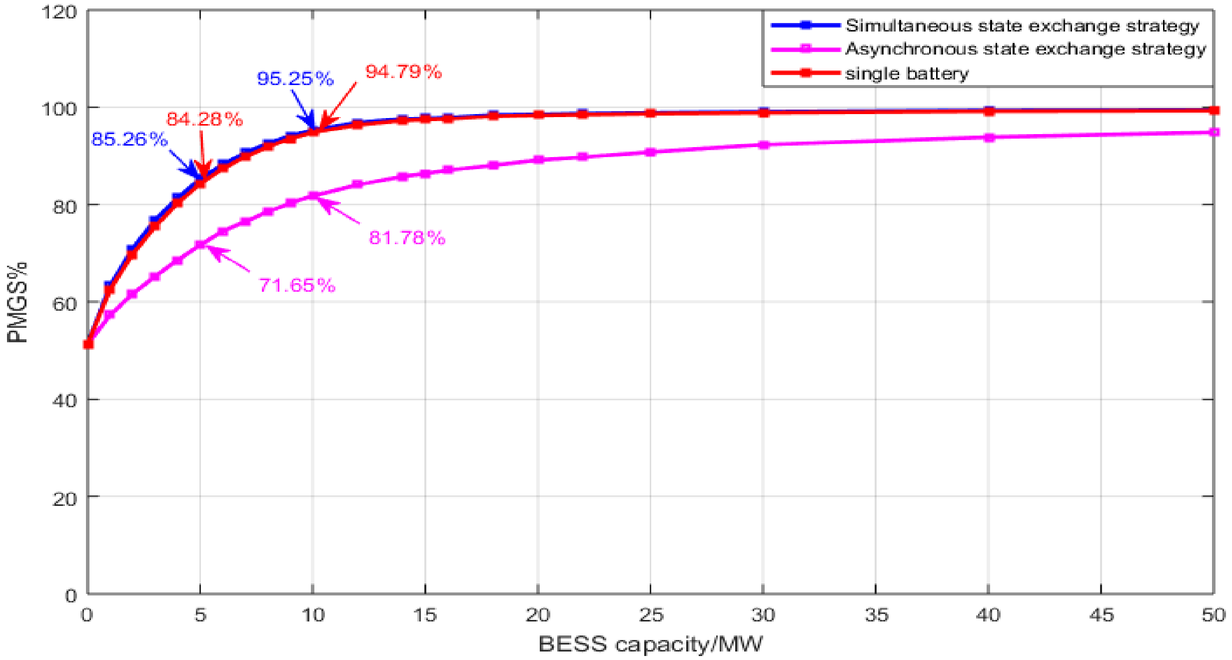

Figure 4.1 probabilities of meeting generation schedule with various BESS capacities

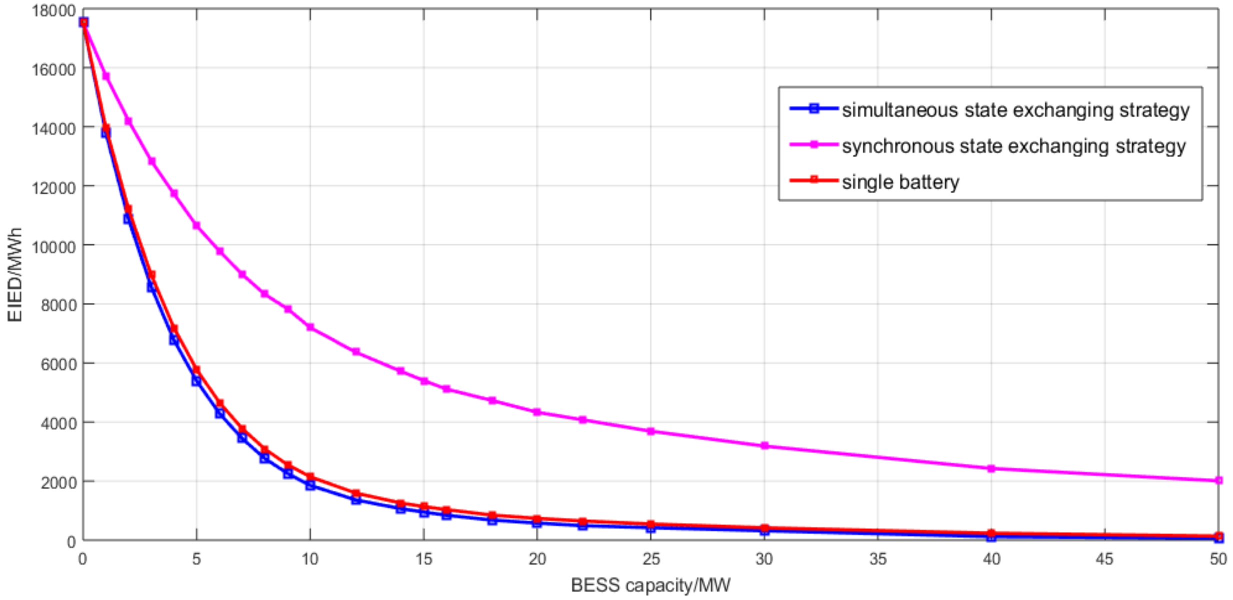

Figure 4.2 Expected injected energy deviation in various BESS capacities

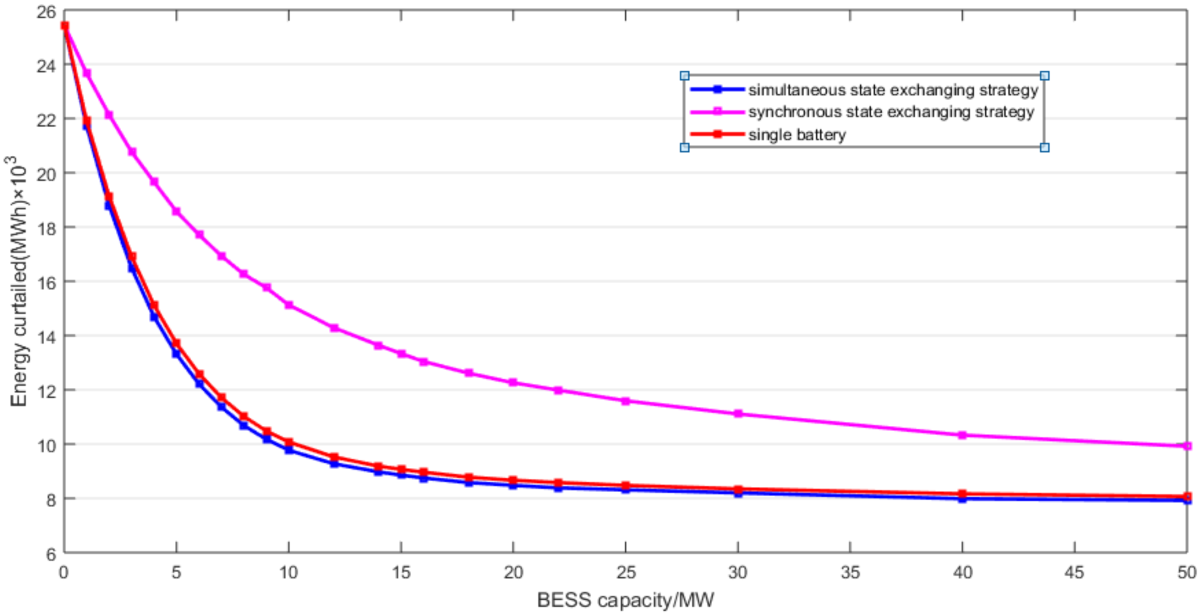

Figure 4.3 Energy curtailed with various BESS capacities

In fact, both batteries are in the same state at the same dispatch interval doesn't mean it always reduces the technical performance of WF. If both parts of the BESS are in discharging states during the same dispatch interval where more energy is needed from BESS, the available discharging power of these DI is consequently increased. Therefore, the power deficiency which cannot be satisfied by one battery would be compensated by the two, which means technical performances of these DIs tend to be improved.

4.2 Economic Characters Of The BESS-Integrated WF

Currently, the cost of batteries is very high so that the economic factor is of great importance when designing a BESS-integrated WF. The values of indices OBB, OCB and OPB in different state exchanging strategies are respectively illustrated in tables 4.1, 4.2 and 4.3. From table 4.4, it can be found that the benefits resulted from the BESS which is calculated based on equation (3.23, 3.24 and 3.25), increase with an increase in the battery capacity regardless of which state exchanging strategy is used. It can be seen that OBB of the wind farm is better if a simultaneous state exchanging strategy is adopted than asynchronous state exchanging strategy or single battery operation.

Table 4.1 operation benefit of BESS integrated wind farm (ETB) with various BESS capacities in different operating strategies

Size (Mw)	Simultaneous Operation	Asynchronous Operation	Single Battery
1	7989898	5005956	7,675,799.2
2	13997046	9030352	13,525,897
3	18728165	12485443	18,178,491
4	22438462	15174918	21888788
5	25304617	17903654	24774574
6	27464049	19964930	26992900
7	29132701	21535426	28700814
8	30389098	23047029	30035736
9	31351026	24008958	31017296
10	32077381	25245723	31743650
12	32960785	26659170	32646686

However, operation costs of the BESS have been increased prominently with increasing size when a single battery operation is adopted than a two battery operation (simultaneous or asynchronous state exchanging strategy). The main reason for this cost difference between those operating strategies is the total number of batteries used per year.

As explained in the literature, it was found that the number of charge/discharge cycles the BESSs have undertaken over the studied time horizon have direct impacts on operation costs of the BESS as they determine the number of batteries used the time. The total number of charge-discharge cycles undertaken in each operating strategies is shown in table 4.2. In the case of single battery operation the total number of charge/discharge cycles is approximately 3×10^4. Whereas for simultaneous operation, the number of cycles are nearly 10^4 for each batteries and for asynchronous operation, one of the battery has undertaken nearly 10000 cycles while for the other one, thus figures are less than 7000 cycles for all battery sizes. Therefore; based on the fact that an approximate life cycle of lithium-ion batteries is 10^4 charge/discharge cycles [27], three batteries' life was totally consumed within studied time horizon if single battery operation is adopted whereas two batteries were sufficient if asynchronous or simultaneous state exchanging strategy is adopted. So, integrating a single battery to the wind farm was found costlier than integrating two batteries regardless of its state exchanging strategy. From table 4.2, it can be observed that charge-discharge cycles of the BESS were smaller when the asynchronous state exchanging strategy is adopted. Hence, two batteries were more than enough for the studied time duration. The reason for this small number of cycles is that unlike simultaneous state exchanging strategy and single battery operation, asynchronous state exchanging strategy can guarantee complete charge-discharge cycles of the BESS .i.e batteries will be changed from charging state to discharging state if only it is fully charged and it will be changed from discharging state to charging if it is completely discharged. The following table shows the number of total charge-discharge cycles in each operating strategy.

Table 4.2 the number of charge/discharge cycles for each battery under different operating strategy

Size (MW)	Simultaneous Operation		Asynchronous Operation		Single Battery
	No. cycles (B1)	No. cycles (B2)	No cycles (B1)	No cycles (B2)	No. cycles
0	0	0	0	0	0
1	10656	10182	11380	4945	28860
2	11076	10254	11529	4931	28904
3	10909	10283	11380	5052	28917
4	10637	10298	11331	5095	28969
5	10223	10379	10967	5491	28988
6	9773	10505	10915	5525	29007
7	9739	10266	10525	5900	29030
8	9493	10313	10267	6165	29050
9	9228	10434	10221	6223	29075
10	9106	10464	10008	6394	29066
12	8997	10423	9677	6703	29088

Figure 4.2 depicts that the state exchanging strategy has dramatic impacts on the economic characters of the BESS-integrated WF, particularly on the index OCB. Operation profits of the BESS are virtually that benefits minus costs, so huge differences between costs will lead to significant gaps between values of the index OPB among the operating strategies, as shown in table 4.3. Specifically, at the battery capacity of 1, 2 and 3MW, values of the index OPB in the simultaneous state exchanging strategy are remarkably better than others which are larger than zero. However, the OPB of the BESS–integrated wind farm is negative in both single battery operation and a dual battery operation under asynchronous state exchanging strategy.

So from table 4.3, it can be seen that the wind farm will experience an economic loss if two batteries are operated under asynchronous state exchanging strategy or a single battery is integrated. It also depicts that for simultaneous state exchanging strategy, the index OPB is showing an increasing trend when the BESS capacity is increasing from 1MW to 2MW and then show decrement from 2MW to 3 MW. That is to say, the index OPB reaches its maximum value when the BESS capacity is 2MW, and the corresponding maximum value is 2,597,046 ETB and its probability of meeting generation schedule is 70.88%. When the capacity exceeds 3MW, OPB of the BESS integrated was found to be negative.

Table 4.3 operation benefits of BESS integrated WF (OPB) with various battery capacities

Size Mw	Simultaneous Operation	Asynchronous Operation	Single Battery
1	2289898	-694044	-874201
2	2597046	-2369648	-3574103
3	1628165	-4614557	-7471509
4	-361538	-7625082	-1.2E+07
5	-3195383	-1.1E+07	-1.8E+07
6	-6735951	-1.4E+07	-2.4E+07
7	-1.1E+07	-1.8E+07	-3.1E+07
8	-1.5E+07	-2.3E+07	-3.8E+07
9	-2E+07	-2.7E+07	-4.6E+07
10	-2.5E+07	-3.2E+07	-5.4E+07
12	-3.5E+07	-4.2E+07	-7E+07

Table 4.4 illustrates the profit and the corresponding probabilities of meeting the desired generation schedule with different battery capacities when simultaneous state exchanging strategy is adopted

Table 4.4 operation profits (OPB) and probabilities of meeting the generation schedule of the wind farm with various BESS capacities by simultaneous state exchanging strategy

Size (mw)	Profit (ETB)	PMGS (%)
1	2,289,898	63.33
2	2,597,046	70.88
3	1,628,165	76.81
4	-361,538	81.39
5	-3,195,383	85.26
6	-6,735,951	88.24

Figures 4.1, 4.2 and 4.3 show probabilities of the BESS integrated WF to meet the generation schedule, the total amount of energy saved from being curtailed, the total amount of energy not delivered at different sizes of BESS over the year after 35040 dispatch intervals. To show the effectiveness of BESS clearly, the power curve of delivered power under different circumstances

(single battery, simultaneous and asynchronous) along with the power curve of scheduled power is presented in figure 4.4 and 4.5. The performance of the wind farm under each operating condition is summarized on tables 4.5 and 4.6. Since it is difficult to draw the power curve of the whole year, a typical 48 hours simulation was chosen and simulated with a battery size of 2MW and 3MW. On both battery sizes, power curve of simultaneous operation was found closer to the schedule than the others.

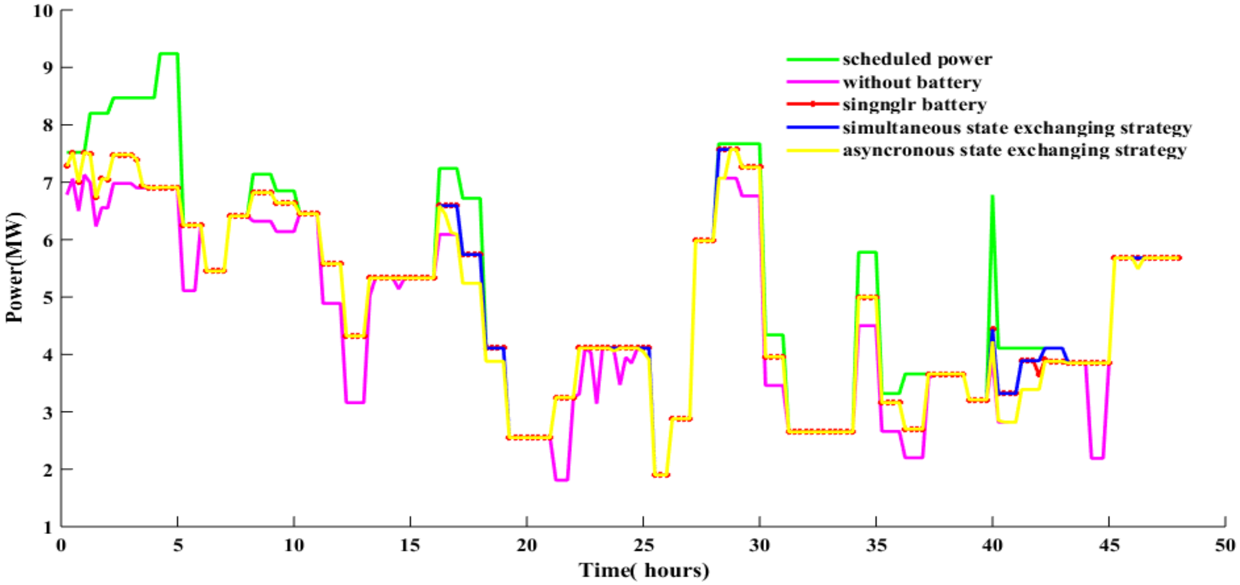

Figure 4.4 power curve of output of BESS-integrated wind farm when 2MW of battery is used under different state exchanging strategies

Table 4.5 the performance indices of BESS-integrated wind farm with 2MW battery

Operation Strategy	PMGS (%)	EIED (MWh)	ECU (MWh)
No battery	44.27	107.28	73.62
Single battery	63.02	54.23	63.66
Synchronous	58.85	61.05	73.15
Simultaneous	65.1	50.42	56.12

As shown on the table, the probability of the WF to meet the generation schedule is 44.27%. This is achieved by curtailing the surplus power when the actual wind power exceeds predetermined schedule. However, in the presence of BESS, curtailment option is taken only when batteries are fully charged or when the surplus energy is beyond the charging rate of the BESSs. The result shows that using two 2MW batteries, the wind farm has improved its probability of meeting the generation schedule from 44.27% to 58.85% to 65.1% by asynchronous and simultaneous state exchanging strategies respectively. When a single battery is used, PMGS was improved from

44.27% to 63.02%. Looking how the EIED was improved when 2MW battery is used, within 48 hours we can say the wind farm has saved 112,787.50, 91,701.83 and 105,229.98 ETB by simultaneous, asynchroneous and single battery operations respectively.

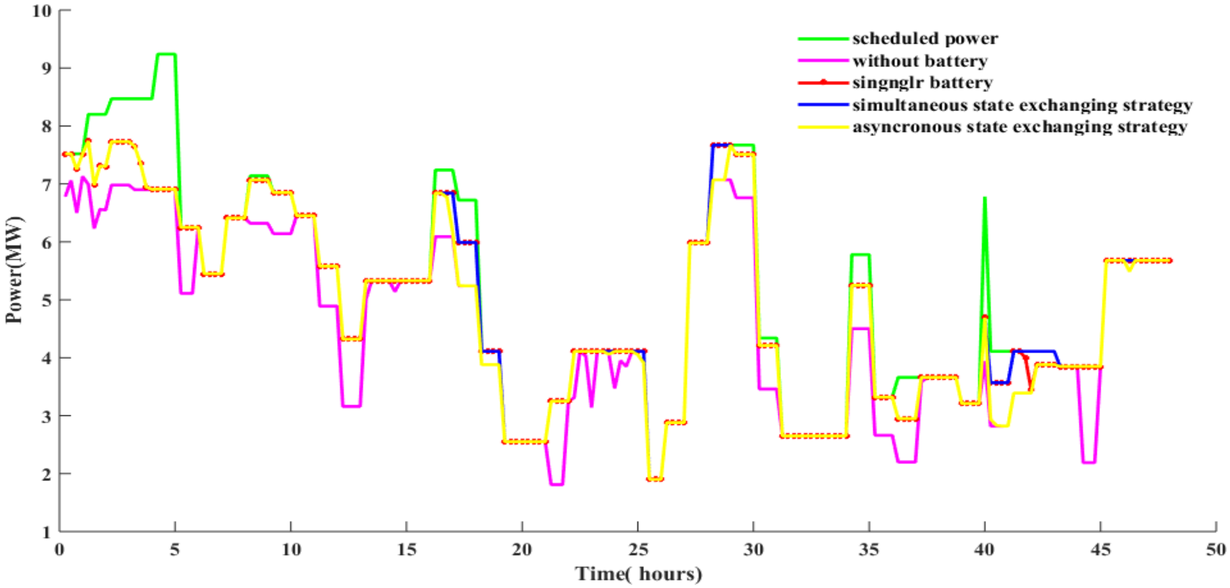

Figure 4.5 power curve of output of BESS-integrated wind farm when 3MW of battery is used under different state exchanging strategies

Table 4.6 the performance indices of BESS-integrated wind farm with 3MW battery

Operation strategy	PMGS (%)	EIED (MWh)	ECU (MWh)
No battery	44.27	107.28	73.62
Single battery	70.83	79.69	49.99
Asynchronous	64.06	49.85	61.95
Simultaneous	73.96	36.21	38.71

From the simulation 48 hours (192 dispatch intervals), in simultaneous state exchanging strategy, the probability of meeting generation schedule with 2MW and 3MW of battery is 65.1% and 73.96% respectively. On other days the PMGS of the wind farm with both battery sizes may be more than 80%or 90% or even lower than 60%. This shows that the accuracy of the forecast also affects the performance of the BESS integrated wind farm. Inaccurate forecasts will reduce the probability of the wind farm to meet the desired generation schedule whereas accurate forecasts will maximize the PMGS. The more dispatch intervals are considered, the better or accurate result will be obtained towards the performance of the BESS integrated wind farm. Taking this into consideration, 35,040 dispatch intervals were considered in simulation and PMGS of 70.88% and 76.81% was obtained for 2MW and 3MW batteries respectively.

Here a single battery operation and asynchronous state exchanging strategy are not discussed because of its negative economic performance. As discussed in the above sections, even though, the maximum profit was achieved at 2MW battery, the performances are much better when 3MW battery is used and its profit is not worst. Figure 4.6 shows the power injected by the BESS integrated wind farm on those 48 hours with 3MW and 2MW batteries. It is clear that the BESS-integrated wind farm output catches the schedule better with 3MW than 2MW.

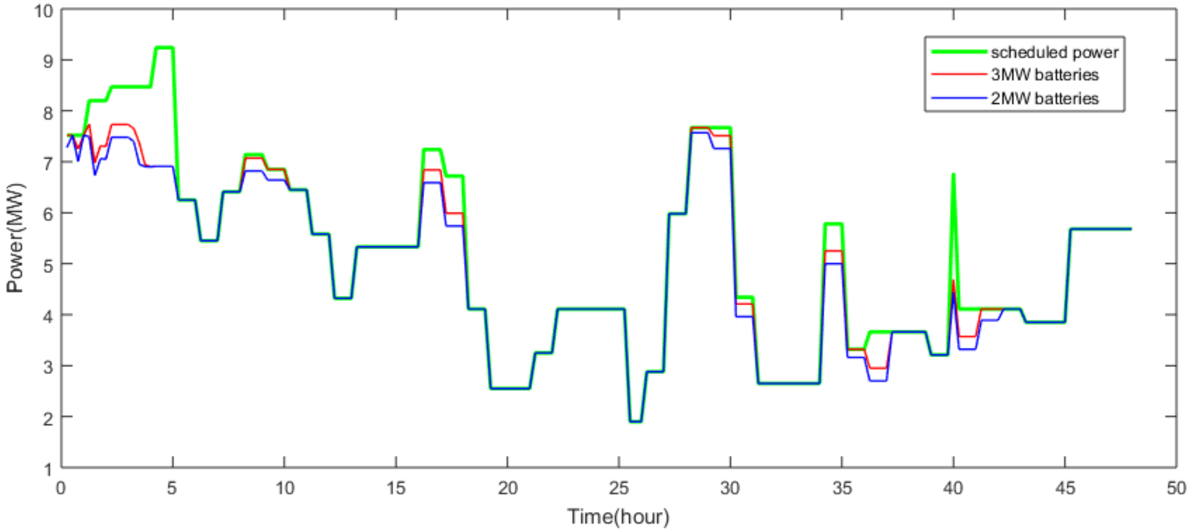

Figure 4.6 power curve of output of BESS-integrated wind farm under 2MW and 3MW of battery in simultaneous state exchanging strategies

Table 4.7 Input parameters of two 2MW Batteries and the two 3MW batteries

Parameters	Values of 2MW batteries	Values of 3MW batteries
ɳ	0.9	0.9
$\boldsymbol{SOC_{min}}$	10%	10%
$\boldsymbol{SOC_{max}}$	90%	90%
$\boldsymbol{P_{max}}$	2MW	3MW
$\boldsymbol{c\_rate}$	0.25	0.25
$\boldsymbol{price}$($)	130/kwh	130/kwh
Life cycle	10,000 cycles	10,000 cycles

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this study, a methodology is proposed to integrate BESS into WFs to enable the BESS-integrated WFs to meet the desired generation schedules to some extent. A series of indices, including PMGS, EIED, ECU, OBB, OCB, and OPB are proposed to evaluate the technical and economical performances on tracing the desired generation schedules. Case study on a real WF i.e Adama I wind farm was conducted to verify the effectiveness of the proposed methodology. The research work in this paper can provide theoretically support on designing a BESS-integrated WF. Three main contributions of this study are summarized as follows,

A dual battery operation, with two different state exchanging strategies of the BESS, named as simultaneous state exchanging strategy and asynchronous state exchanging strategy is proposed in this work. In this dual battery operation, impacts of state exchanging strategy on the performance BESS-integrated WFs are studied. It was found that the economic and technical performances of a wind farm were better when a simultaneous state exchanging strategy is implemented. At battery size of 2MW and 3MW, the probability of meeting the generation schedule was found 70.88% and 76.81% respectively and the corresponding profit was 2,597,046 and 1,628,165 ETB. On the other hand, when the asynchronous state exchanging strategy is adopted, for the same size, the PMGS was found to be 57.33% and 61.6% respectively. But the profit of the wind farm was negative in both battery sizes. When a single battery operation is used, the PMGS was found to be 62.62% and 69.74% for the respective battery sizes. However; the profit of wind farm was found totally negative. Therefore; as compered to a dual battery operation, even if the economic performances(OPB) are worst(negative), its performances on meeting the generation schedule were found better than asynchronous state exchanging strategy but lower than simultaneous state exchanging strategy. This shows the adopted state exchanging strategy as well as number of batterys integrated to the the wind farm has a direct impact on technical performance (PMGS, EIED and ECU) and economic aspects (OBB, OCB and OPB) of the wind farm. The case study proves that operation benefits attributed to the BESS can completely cover the operation costs of the BESS in the assumed power market mechanism only when simultaneous state exchanging strategy is adopted.

5.2 Future work

In fact, battery technical performances will be gradually degraded with battery aging and wear and consequently have impacts on the BESS-integrated WF. However, the extent of aging and wear of the BESS is not included here and will be taken into account in a future work. The time-dependent characters of wind power prediction errors will affect the chronological characters of wind power fluctuations and consequently have impacts on the technical and economic performances of the BESS. It is not considered in present work and will also be included in the future work. In addition, the impact of wind power fluctuation on grid voltage, frequency, and reactive power can be included in the future work.

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APPENDIX A

Code for single battery operation

```
clear
clc
 E_metered=[];%% Import metered production [MWh]or actual %
E_plan=[];% scheduled Energy within each 15 minute

%Input data
eff = 0.90 ; % Battery round? t r i p e f f i c i e n c y
deltat = 0.25 ; % Time? step of study [ h ]
Pb_max =  % Maximum charge/di s charge c ap a city [MW]
Eb_max = ; % Energy c ap a city of the battery [MWh]
Eb_start = 0.9*Eb_max; % I n i t i a l SOC of b att e ry
SOC_min= 0.1;% minimum state of charege of the battery
SOC_max = 0.9;%maximum state of charge of the battery

% starting conditions
i = 1;
If E_plan ( i ) == E_metered ( i )% actual energy  is the same as planned
energy
Ec ( i ) = 0 ;  % energy charged to the battery at a time
Ed ( i ) = 0 ; % energy discharged from the battery at a time
E_cu(i)=0;    %energy curtailed at the dispatch interval
E_nt(i)=0;   % expected energy but not supplied at the interval

elseif E_plan( i ) > E_metered ( i ) %an actual energy is less than scheduled
so some energy should be supplied by battery
  Ec ( i ) = 0 ;     % no charging, what  needed is discharging and if
unsatisfied the rest of energy will be recorded as E_nt
  E_cu(i)=0;      % no curtailed energy
if( E_plan ( i ) - E_metered ( i ) ) < Pb_max * deltat %  Pb_max * deltat is
maximum energy that can be drawned into or out of the battery within 15
minutes
if( E_plan ( i ) - E_metered ( i ) ) < ( Eb_start -  SOC_min * Eb_max )*eff%(
Eb_start -  SOC_min * Eb_max )*eff is available energy in thebattery at the
time
Ed( i ) = E_plan ( i ) - E_metered ( i ) ; % amount of discharged energy
E_nt(i)=0;% the battery can satisfy energy diviation, so energy not supplied
will be zero
else % energy deviation is greater than energy available in the battery. in
this case only the available energy will be discharged and the rest will be
taken as energy not enjected
Ed( i ) = ( Eb_start - SOC_min * Eb_max ) * eff ;
E_nt(i)=E_plan ( i )-Ed( i );
end
else % the change or the deviation is greater tha maximum energy that can be
drawned from the battery at agive time which is 15 minute
if Pb_max * deltat < ( Eb_start - SOC_min * Eb_max) * eff % checking if
remaining energy inthe battery can be drawned with a given period of time or
not
Ed( i ) = Pb_max * deltat ;
E_nt(i)=E_plan ( i )-Ed( i );%not injected
else % the battery can not draw the energy with in it in the given period of
time. this is to say a mount of energy discharged from thebattery is limited
by time
```

```
Ed( i ) = ( Eb_start - SOC_min * Eb_max ) * eff ;
E_nt(i)=E_plan ( i )-Ed( i );%not injected
end
end
else % actual power from wind is greater than the scheduled power, in this
case the wind farm can meet the schedule without battery. the surplus energy
will be stored in battery. so Ed and E_nt are set to be zero
Ed( i ) = 0 ;
E_nt(i)=0;
if( E_metered ( i ) - E_plan ( i ) ) < Pb_max * deltat
if( E_metered ( i ) -E_plan ( i ) ) < ( Eb_max * SOC_max- Eb_start )
Ec( i ) = E_metered ( i ) - E_plan ( i ) ;
E_cu(i)=0;
else
Ec( i ) = Eb_max * SOC_max - Eb_start ;
E_cu(i)=( E_metered ( i ) -E_plan ( i ) ) - ( Eb_max * SOC_max- Eb_start );
end
else
if Pb_max * deltat < ( Eb_max * SOC_max -Eb_start)
Ec ( i ) = Pb_max * deltat ;
E_cu(i)=( E_metered ( i ) - E_plan ( i ) ) - Pb_max * deltat;
else
Ec( i ) = Eb_max * SOC_max - Eb_start ;
E_cu(i)=( E_metered ( i ) - E_plan ( i ) ) - ( Eb_max * SOC_max -Eb_start);
end
end
end
Eb ( i ) = Eb_start + Ec( i ) - Ed( i ) ;% energy available in battery at the
end of each dispatch interval
P_wb(i) = E_metered(i) + Ed(i)- Ec(i)-E_cu(i); % power injected to grid  from
BESS- integrated WF
% Main operation
for i = 2 : length( E_metered )
if E_plan ( i ) == E_metered ( i )
 Ec( i ) = 0 ;
 Ed( i ) = 0 ;
 E_cu(i)=0;
 E_nt(i)=0;
elseif E_plan( i ) > E_metered ( i )
    Ec( i ) = 0 ;
    E_cu(i)=0;
if( E_plan ( i ) - E_metered ( i ) ) < Pb_max * deltat
if( E_plan ( i ) - E_metered ( i ) ) < ( Eb ( i -1) -SOC_min * Eb_max ) * eff
% ( Eb ( i -1) energy available in the battery from the previous dispatch
interval
Ed( i ) = E_plan ( i ) -E_metered ( i ) ;
E_nt(i)=E_plan ( i )-Ed( i );
else
Ed( i ) = ( Eb ( i -1) - SOC_min * Eb_max ) * eff;
E_nt(i)=E_plan ( i )-Ed( i );% not enjected=
end
else
if Pb_max * deltat < ( Eb ( i -1) - SOC_min * Eb_max )* eff
Ed ( i ) = Pb_max * deltat ;
E_nt(i)=E_plan ( i )-Ed( i );%
for full code, contact the author
```

Code for PMGS

```
% probability of meeting generation schedul
num=0;
for i=1:length(E_plan)
    if E_plan(i)== P_wb( i )
        num=num+1;
    end
end
p=num./numel(E_plan);
```

code for number of cycles

```
%number of shiftings to determine the number of charge discharge cycles
for i= 3:length(Eb) % assuming that for the first two intervals the battery
was not totally discharged.
   num(2)=0;
   num(1)=0;
if Eb(i)>Eb(i-1)%battery is charging
    if Eb(i-1)<Eb(i-2)%was discharging previous discharge interval
        c =1;
    elseif  Eb(i-1)== Eb(i-2) % battery was neither charging nor discharging.
in thsi cas it will check for the other previous dispatch interval
        for k=(i-2):0
            if Eb(k)~= Eb(i-1)
                if Eb(k)<Eb(i-1)
                num(k)= 1;
                else
                    num(k)=0;
                end
            end
             c =num(k);
        end
```

for full code, contact the author

APPENDIX B

Code for simultaneous state exchanging strategy

```
clear
clc
        E_metered=[];%% Import metered production [MWh]or actual %
        E_plan=[];% scheduled Energy within each 15 minute
        %Input data
        eff = 0.90 ; % Battery round? t r i p e f f i c i e n c y
        deltat = 0.25 ; % Time? step of study [ h ]
        Pb_max =  % Maximum charge/di s charge capacity [MW]
        Eb1_max  =;% Energy c ap a city of the b att e ry 1 [MWh]
        Eb2_max =;% Energy c ap a city of the b att e ry 2 [MWh]
        SOC_min= 0.1;% minimum state of charege of the battery
        SOC_max = 0.9;%maximum state of charge of the battery
        Eb1_start = 0.1*Eb1_max;% starting condition of battery 1 is set to
be minimum
        Eb2_start  =0.9*Eb2_max; % Starting conditions of battery two was set
to be full
     %initial condition
  i = 1 ;% first dispatch interval
if E_plan ( i ) == E_metered ( i )% actual energy  is the same as planned
energy  in this case the wind farm will not need any support from the BESS.
so all charging and discharging powers are set zero
Ec1 ( i ) = 0 ;% charging energy of battery 1
Ec2 ( i ) = 0 ;% charging energy of battery 2
Ed1 ( i ) = 0 ;% discharging energy of battery 1
Ed2 ( i ) = 0 ;% discharging energy of battery 2
E_cu(i)=0;              %energy curtailed
E_nt(i)=0;              % energy not ejected
elseif E_plan( i ) > E_metered ( i )%  scheduled power is greater than actual
wind power. in this case all charging powers are set zero, curtailled power
is also zero. amount of discharging energy will be determined based on the
constraints
Ec1 ( i ) = 0 ;
Ec2 ( i ) = 0;
Ed1 ( i ) = 0;% at initioal condition battery 1 was low charge so it cannot
discharge
E_cu(i)=0;
if( E_plan ( i ) - E_metered ( i ) ) < Pb_max * deltat%  Pb_max * deltat is
maximum energy that can be drawned into or out of the battery within 15
minutes
if( E_plan ( i ) - E_metered ( i ) ) < ( Eb2_start -  SOC_min * Eb2_max
)*eff%( Eb_start -  SOC_min * Eb_max )*eff is available energy in thebattery
at the time
Ed2( i ) = E_plan ( i ) - E_metered ( i ) ;% amount of discharged energy
E_nt(i)=0;% since battery 2 has sufficiently filled the gap, there is no
E_nt(i)
else% energy deviation is greater than energy available in the battery. in
this case only the available energy will be discharged and the rest will be
taken as energy not ejected
Ed2( i ) = ( Eb2_start - SOC_min * Eb2_max ) * eff ;
E_nt(i)=( E_plan ( i ) - E_metered ( i ) ) - ( Eb2_start -  SOC_min * Eb2_max
)*eff;
end
```

```
else% the change or the deviation is greater tha maximum energy that can be
drawned from the battery at agive time which is 15 minute
 if Pb_max * deltat < ( Eb2_start - SOC_min * Eb2_max) * eff% checking if
remaining energy inthe battery can be drawned with a given period of time or
not
Ed2( i ) = Pb_max * deltat ;
E_nt(i)=( E_plan ( i ) - E_metered ( i ) ) -Pb_max * deltat;
else
Ed2( i ) = ( Eb2_start - SOC_min * Eb2_max ) * eff ;
E_nt(i)=( E_plan ( i ) - E_metered ( i ) ) - ( Eb2_start -  SOC_min * Eb2_max
)*eff;
 end
end
else % actaual wind power output is greater than the schedule at  a time,
discharging power of both batteries is set zero, en_t set zero. since at the
starting condition of B2 is maximum, it cannot take any charge. so charging
power of B2 is set zero. the amount of energy charged in B2 is will be
determined based on certain constraints
Ed1( i ) = 0 ;%
Ed2  ( i ) = 0 ;
Ec2  ( i ) = 0 ;
E_nt( i )=  0;
if( E_metered ( i ) - E_plan ( i ) ) < Pb_max * deltat
if( E_metered ( i ) -E_plan ( i ) ) < ( Eb1_max * SOC_max - Eb1_start
)%Eb1_max * SOC_max - Eb1_start is eneravailable in the battery
Ec1( i ) = E_metered ( i ) - E_plan ( i ) ;
E_cu(i) = 0 ;
else
Ec1( i ) = Eb1_max * SOC_max - Eb1_start ;
E_cu(i) =( E_metered ( i ) -E_plan ( i ) ) - ( Eb1_max * SOC_max - Eb1_start
);
end
else
if Pb_max * deltat < ( Eb1_max * SOC_max -Eb1_start)
Ec1  ( i ) = Pb_max * deltat ;
E_cu(i) = ( E_metered ( i ) -E_plan ( i ) )- Pb_max * deltat ;
else
Ec1(  i ) = Eb1_max * SOC_max - Eb1_start ;
E_cu(i) = ( E_metered ( i ) -E_plan ( i ) )- Eb1_max * SOC_max - Eb1_start  ;
end
end
end
Eb1  ( i ) = Eb1_start + Ec1( i ) - Ed1( i );%availablr Eenergy in B1 at the
end of the dispatch interval i
Eb2( i ) = Eb2_start + Ec2( i ) - Ed2( i ) ;%availablr Eenergy in B2 at the
end of the dispatch interval i
P_wb( i )=  E_metered(i) + Ed2(i)+ Ed1(i)- Ec1(i)-Ec2(i)- E_cu(i) ;% % power
injected to grid  from BESS- integrated WF at each dispatch interval

% Main operation
for i = 2 : length( E_metered )
     if E_plan(i) == E_metered(i)% the actual energy is directly injected to


for full code, contact the author
```

Code for PMGS

```
  num=0;
for i=1:length(E_plan)
    if E_plan(i)== P_wb( i )
        num=num+1;
    end
end
p=num./numel(E_plan) ;
```

Code for number of cycles for BESS 1

```
%number of shiftings or charge/ discharge cycles of B2
% b2(i)>b2(i-1)>b2(i-2) charging    b2(i)< b2(i-1)< b2(i-2) dicharging
for i= 3:length(Eb2)
   num2(2)=0;
   num2(1)=0;
if Eb2(i)>Eb2(i-1)%chargin
     c=0;
    if Eb2(i-1)<Eb2(i-2)%was discharging
        c =1;
    elseif  Eb2(i-1)== Eb2(i-2)
        for k=(i-2):0
            if Eb2(k)~= Eb2(i-1)
                if Eb2(k)<Eb2(i-1)
                num2(k)= 1;
                else
                    num2(k)=0;
                end
            end
             c =num2(k);
        end
```

for full code, contact the author

Code for number of cycles for BESS 2

```
%%number of shiftings or charge/ discharge cycles of B1
 % b1(i)>b1(i-1)>b1(i-2) charging    b(i)< b(i-1)< b(i-2) dicharging
for i= 3:length(Eb1)
   num1(2)=0;
   num1(1)=0;
if Eb1(i)>Eb1(i-1)%chargin
     c=0;
    if Eb1(i-1)<Eb1(i-2)%was discharging
        c =1;
    elseif  Eb1(i-1)== Eb1(i-2)
        for k=(i-2):0
            if Eb1(k)~= Eb1(i-1)
                if Eb1(k)<Eb1(i-1)
                num1(k)= 1;
                else
                    num1(k)=0;
                end
            end
             c =num1(k);
        end
```

for full code, contact the author

APPENDIX C

CODE FOR ASSYNCHRONOUS STATE EXCHANGE STRATEGY

```
clear
clc
 E_metered=[];%% Import metered production [MWh]or actual %
E_plan=[];% scheduled Energy within each 15 minute
%Input data
%Input data
        eff = 0.90 ; % Battery round?t r i p e f f i c i e n c y
        deltat = 0.25 ; % Time?step of study [ h ]
        Pb_max =  % Maximum charge/di s charge c ap a city [MW]
        Eb1_max  =;% Energy c ap a city of the b att e ry 1 [MWh]
        Eb2_max =48;% Energy c ap a city of the b att e ry 2 [MWh]
        SOC_min= 0.1;% minimum state of charege of the battery
        SOC_max = 0.9;%maximum state of charge of the battery
        Eb1_start = 0.1*Eb1_max;% starting condition of battery 1 is set to
be minimum
        Eb2_start  =0.9*Eb2_max; % Starting conditions of battery two was set
to be full
  %initial condition
  i = 1 ;% first dispatch interval
if E_plan ( i ) == E_metered ( i )% actual energy  is the same as planned
energy  in this case the wind farm will not need any support from the BESS.
so all charging and discharging powers are set zero
Ec1  ( i ) = 0 ;% charging energy of battery 1
Ec2  ( i ) = 0 ;% charging energy of battery 2
Ed1  ( i ) = 0 ;% discharging energy of battery 1
Ed2  ( i ) = 0 ;% discharging energy of battery 2
E_cu(i)=0;             %energy curtailed
E_nt(i)=0;             % energy not enjected
elseif E_plan( i ) > E_metered ( i )%  scheduled power is greater than actual
wind power. In this case all charging powers are set zero, curtailed power is
also zero. Amount of discharging energy will be determined based on the
constraints
Ec1  ( i ) = 0 ;
Ec2  ( i ) = 0;
Ed1  ( i ) = 0;% at initioal condition battery 1 was low charge so it cannot
discharge
E_cu(i)=0;
if( E_plan ( i ) - E_metered ( i ) ) < Pb_max * deltat%  Pb_max * deltat is
maximum energy that can be drawned into or out of the battery within 15
minutes
if( E_plan ( i ) - E_metered ( i ) ) < ( Eb2_start -  SOC_min * Eb2_max
)*eff%( Eb_start -  SOC_min * Eb_max )*eff is available energy in thebattery
at the time
Ed2( i ) = E_plan ( i ) - E_metered ( i ) ;% amount of discharged energy
E_nt(i)=0;% since battery 2 has sufficiently filled the gap, there is no
E_nt(i)
else% energy deviation is greater than energy available in the battery. in
this case only the available energy will be discharged and the rest will be
taken as energy not enjected
Ed2( i ) = ( Eb2_start - SOC_min * Eb2_max ) * eff ;
E_nt(i)=( E_plan ( i ) - E_metered ( i ) ) - ( Eb2_start -  SOC_min * Eb2_max
)*eff;
end
```

```
else% the change or the deviation is greater tha maximum energy that can be
drawned from the battery at agive time which is 15 minute
 if Pb_max * deltat < ( Eb2_start - SOC_min * Eb2_max) * eff% checking if
remaining energy inthe battery can be drawned with a given period of time or
not
Ed2( i ) = Pb_max * deltat ;
E_nt(i)=( E_plan ( i ) - E_metered ( i ) ) -Pb_max * deltat;
else
Ed2( i ) = ( Eb2_start - SOC_min * Eb2_max ) * eff ;
E_nt(i)=( E_plan ( i ) - E_metered ( i ) ) - ( Eb2_start -  SOC_min * Eb2_max
)*eff;
 end
end
else % actaual wind power output is greater than the schedule at  a time,
discharging power of both batteries is set zero, en_t set zero. since at the
starting condition of B2 is maximum, it cannot take any charge. so charging
power of B2 is sset zero. the amount of energy charged in B2 is will be
determined based on certain constraints
Ed1( i ) = 0 ;%
Ed2  ( i ) = 0 ;
Ec2  ( i ) = 0 ;
E_nt( i )=  0;
if( E_metered ( i ) - E_plan ( i ) ) < Pb_max * deltat
if( E_metered ( i ) -E_plan ( i ) ) < ( Eb1_max * SOC_max - Eb1_start
)%Eb1_max * SOC_max - Eb1_start is eneravailable in the battery
Ec1( i ) = E_metered ( i ) - E_plan ( i ) ;
E_cu(i) = 0 ;
else
Ec1( i ) = Eb1_max * SOC_max - Eb1_start ;
E_cu(i) =( E_metered ( i ) -E_plan ( i ) ) - ( Eb1_max * SOC_max - Eb1_start
);
end
else
if Pb_max * deltat < ( Eb1_max * SOC_max -Eb1_start)
Ec1  ( i ) = Pb_max * deltat ;
E_cu(i) = ( E_metered ( i ) -E_plan ( i ) )- Pb_max * deltat ;
else
Ec1(  i ) = Eb1_max * SOC_max - Eb1_start ;
E_cu(i) = ( E_metered ( i ) -E_plan ( i ) )- Eb1_max * SOC_max - Eb1_start  ;
end
end
end
Eb1  ( i ) = Eb1_start + Ec1( i ) - Ed1( i );%available Energy in B1 at the
end of the dispatch interval i
Eb2( i ) = Eb2_start + Ec2( i ) - Ed2( i ) ;%available Energy in B2 at the
end of the dispatch interval i
P_wb( i )=  E_metered(i) + Ed2(i)+ Ed1(i)- Ec1(i)-Ec2(i)- E_cu(i) ;% % power
injected to grid  from BESS- integrated WF at each dispatch interval

% Main operation
for i = 2 : length( E_metered )
     if E_plan(i) == E_metered(i) % the actual energy is directly injected to
grid with out any support from battery. so all charging and discharging
energies to gether with curtailed energy and E_nt are set to be zero
                 Ec1  ( i ) = 0 ;
                 Ec2  ( i ) = 0 ;
                 Ed1   ( i ) = 0 ;
```

```
                  Ed2 ( i ) = 0 ;
                  E_cu( i ) = 0 ;
                  E_nt  ( i ) = 0;
     elseif E_plan(i) > E_metered(i) % the wind farm needs the battry support
for full code, contact the author
```

Code for PMGS

```
     num=0;
for i=1:length(E_plan)
    if E_plan(i)== P_wb( i )
       num=num+1;
    end
end
p=num./numel(E_plan) ;
```

code for number of cycles for battery 2

```
%number of shifting or charge/discharge cycles of battery 2
% b2(i)>b2(i-1)>b2(i-2) charging    b2(i)< b2(i-1)< b2(i-2) discharging
for i= 3:length(Eb2)% for the first two dispatch intervals both batteries are
assumed to be in the state the same as initial
   num2(2)=0;
   num2(1)=0;
if Eb2(i)>Eb2(i-1)%charging
     c=0;
    if Eb2(i-1)<Eb2(i-2)%was discharging
        c =1;
    elseif  Eb2(i-1)== Eb2(i-2)

for full code, contact the author
        num2(i)=0;
    end
else
    num2(i)=0;
end
end
```

code for number of cycles for battery 1

```
% charging/ discharging cycle of  B1
% b1(i)>b1(i-1)>b1(i-2) charging    b(i)< b(i-1)< b(i-2) dicharging
for i= 3:length(Eb1)
   num1(2)=0;
   num1(1)=0;
if Eb1(i)>Eb1(i-1)%chargin
     c=0;
    if Eb1(i-1)<Eb1(i-2)%was discharging
        c =1;
    elseif  Eb1(i-1)== Eb1(i-2)
        for k=(i-2):0
            if Eb1(k)~= Eb1(i-1)
                if Eb1(k)<Eb1(i-1)


for full code, contact the author
```

APPENDIX D

Code For Plots

PMGS plot

```
%input data
MW=% different battery size in mw
PMGS_simul= %probability of meeting the generation schedule at different
battery size in simultaneous state exchanging strategy
PMGS_synch=%probability of meeting the generation schedule at different
battery size in asynchronous state exchanging strategy
PMGS_single=%probability of meeting the generation schedule at different
battery size in a single battery operation
% plot
plot(MW,PMGS_simul,'g')% g is for green
hold on
plot(MW,PMGS_synch,'y')% y for yellow
hold on
plot(MW,PMGS_single,'r')% r for red
```

EIED PLOT

```
%input data
MW=% different battery sizes in mw
E_nt_simul=% total energy   which was expected and not injected to grid at
different size in simultaneous state exchanging strategy
E_nt_synch=% total energy which was expected and not injected to grid at
differnt size in asynchronous state exchanging strategy
E_nt_single=% total energy which was expected and not injected to grid at
differnt size in single battery operation
%Plotting the graph
plot(MW,E_nt_simul,'color')
hold on
plot(MW,E_nt_synch,'color')
hold on
plot(MW,E_nt_single, 'color')
```

ECU PLOT

```
%input data
MW=[];%battery size from zero to max
E_cu_simul= ;% total energy curtailed at different size in simultaneous state
exchanging strategy
E_cu_synch=%% total energy curtailed at different size in asynchronous state
exchanging strategy
E_cu_single=%% total energy curtailed at different size in single battery
operation
%ploting the graph
plot(MW,E_cu_simul,'color')
hold on
plot(MW,E_cu_synch,'color')
hold on
plot(MW,E_cu_single,'color')
```