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A New Paradigm Based on Battery Transportation and Logistics to Maximize the Wind and Solar Renewable Penetration – Technical Aspect

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A NEW PARADIGM BASED ON BATTERY TRANSPORTATION AND LOGISTICS TO MAXIMIZE THE WIND AND SOLAR RENEWABLE PENETRATION – TECHNICAL ASPECT

by

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ABSTRACT

A NEW PARADIGM BASED ON BATTERY TRANSPORTATION AND LOGISTICS TO MAXIMIZE THE WIND AND SOLAR RENEWABLE PENETRATION – TECHNICAL ASPECT

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Under the Supervision of Prof. David Yu

Concerns about the environmental degradation and global warming have placed greater importance to the development and application of renewable energy in recent years. Stand by energy source side, wind and solar farms have been continuously integrated into the power grids all over the world. Meanwhile on the end user side, not only EV and PHEV have been gaining market share in the automobile industry, but also the battery backup systems for home or industry have been introduced into public view. However, the randomness and intermittency of the renewable energy as well as the lack of transmission capability result in significant amount of wind and solar power curtailed. Besides, long charging time of batteries also hinders consumers' willingness to adapt the EV or PHEV over the conventional vehicles. More importantly, the current EV or PHEV practice did not resolve the fundamental goal of reducing the greenhouse gas. At the best, it relocates the pollution caused by car in the cities to the

pollution caused by the fossil fuel power plants in the rural area.

In this study, instead of investing money in Energy Storage Systems (ESS) used as a fixed facility for storing the renewable energy and smoothing out the power fluctuation, a novel approach of ESS utilization combined with logistics in order to maximize the wind and solar penetration is proposed. This approach will also fundamentally solve the issues associated with the EV and PHEV which are mentioned above.

The primary technical feasibility of the proposed method is discussed and analyzed with real data. The conclusion indicates that the proposed method is technically feasible and its prospect is quite promising via corresponding technology developed.

Keywords: battery, transportation, logistics, penetration, renewable energy

DEDICATION

Dedicated to my parents, my grandma and my girl friend

for everything you give to me

I love you all

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ACKNOWLEDGMENTS

To be honest, studying abroad is not in my life plan at first. But when the opportunity came to me, I finally took it and I really appreciated the decision I made. The experience at University of Wisconsin – Milwaukee (UWM) is rich and colorful, and there are so many people that I want to express my thanks.

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Finally, special thanks as well as apologizes to my girlfriend Yuqi Wang. I know we have a long-distance relationship for too long. However, I believe that those days are numbered. Miss you and love you.

Chapter 1

Introduction

1.1 Research Background

The world still relies on fossil fuels such as coal, oil and natural gas to power and heat the buildings and fuel the vehicles. However, these traditional energy sources are consumed rapidly at a speed which is significantly faster than their growth rate. Besides, the deteriorating environment is worse than ever before due to severe pollution resulted from the usage of massive fossil fuels. People have to seek new methods to create energy to meet the need. Apparently, being clean and sustainability are two essential properties of these new potential substitutes.

In such context, the promotion of renewable energy plays an important role in addressing the growing dependence on energy imports and in tackling climate change [1]. Renewable energies like wind power and solar power have drawn considerable attention from people both in the academia and industry and are now developing rapidly [2]. Take wind power as an example, wind power is now seen as a clean, cost-effective alternative to other forms of conventional electricity production with clear benefits to the environment and to the economy [3].

Over the past decade many countries have accelerated the renewable energy applications in the existing grid. According to the data from American Wind Energy Association (AWEA), in 2012 which was a booming growth year for wind power industrial in U.S., 13,131 megawatts (MW) of capacity was installed and the total installed capacity surged past the 60 gigawatt

(GW) milestone. Based on it, the U.S. government set a goal that the usage of wind power should account for 20% of electricity by 2030 [4, 5]. While in China, by the end of 2010, the total wind power capacity had reached 44.733 GW which surpassed the capacity in U.S. and ranked No.1 in world. The year-on-year growth incredibly achieved 73.3%. An official report predicts that by 2020, the total wind power capacity in China will get up to 230 GW while the corresponding generated energy will be 464900 gigawatt-hour (GWh), and by 2050, one-third of electricity will be provided by renewable energy such as wind and solar energy [6].

1.1.1 Wind and Solar Power Curtailment

Lack of local congestion and insufficient transmission capacity are two common reasons for curtailment. Besides, whether the collected data is reliable and uniform can also affect the outcome of curtailment.

Generally, curtailment of wind and solar power, via some form, exists in a lot of regions over the world while the relative magnitude differs from place to place. As for U.S., the regional curtailment levels in U.S. reported by the Electric Reliability Council of Texas (ERCOT) in past years is shown in Figure 1.1 [7]. From the figure we can see that the curtailment level even reached 17% in 2009. The reason stated in report is the wind generation came online ahead of transmission capacity. But we can also find that the annual curtailment of wind and solar resources appears to decrease even as the amount of wind power on the system increases. This is because that new facilities and technologies are adopted into the system including bigger transmission capacity, better automation control, more precise forecasting and other operating practices. All these components are helpful to resolve challenges for grid operators.

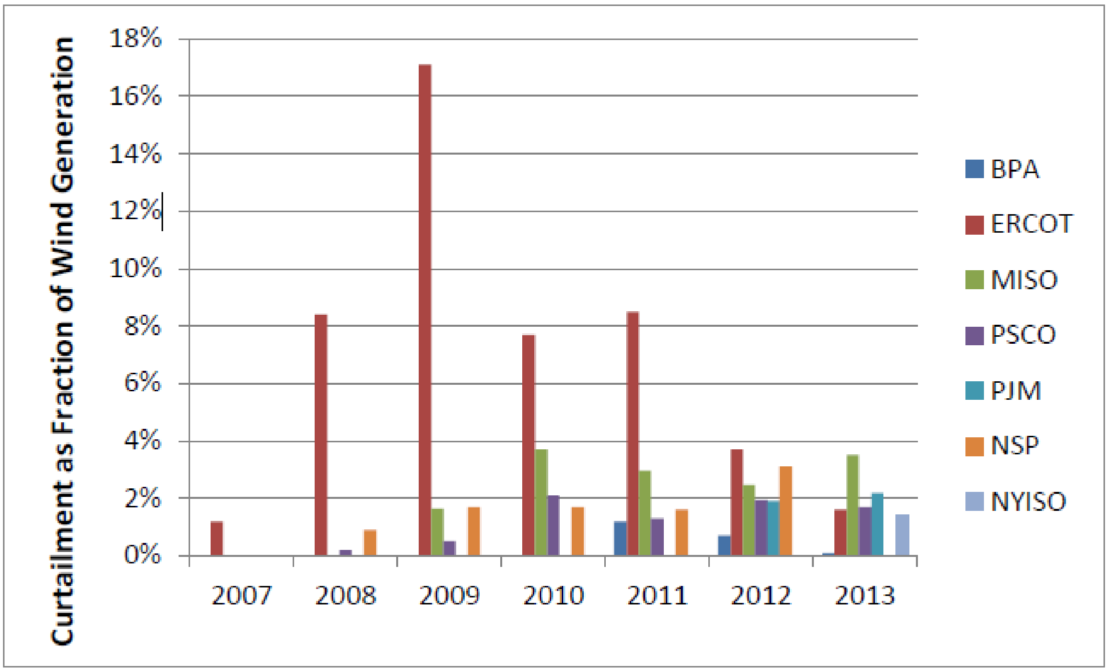

Figure 1.1: Curtailment levels by region, 2007-2013 [7]

However, the curtailment level varies dramatically in different regions and countries. Regarding to China, the largest market for wind power, the extent of wind curtailment is much severer. The top wind and solar power production provinces in China are urged to prioritize transmission of renewable energy over conventional energy sources in order to scale up the portion of clean energy. Under the circumstances, China has already installed wind power capacity more than any other country. But because of the shortage of transmission capacity connected between the projects in remote regions and end-users, large quantities of natural resources are wasted. According to official data, on average more than 15 percent of energy generated by wind and solar power suffered from curtailment in the first half year of 2015 which mainly because of the lack of local consumption [8]. The curtailment levels of several provinces of China are shown in Table 1.1. As a whole, the main reason in based on the fact that the best wind power resources are located in the northeast and the northwest of China.

However, the major load center are concentered in the southeast part of China which leads to significant imbalance and curtailment.

		Total installed capacity	Newly added on-grid installed capacity	Total on-grid capacity	On-grid wind power	Curtailed wind power	Wind curtailment
Ranking	Province	(10MW)	(10MW)	(10MW)	10^8 kWh	10^8 kWh	rate(%)
1	Gansu	568.44	60.73	555.16	32.38	25.25	25.25
2	Inner Mongolia	1624.44	426.59	1438.44	109.42	23.1	23.1
3	Jilin	317.64	30	293.63	17.84	21.02	21.02
4	Heilongjiang	277.55	52.99	262.55	26.65	14.39	14.39
5	Liaoning	469.26	57.75	403.95	33.42	10.45	10.45
6	Xinjiang	226.43	73.8	165.98	12.76	5.2	5.2
7	Yunnan	93.23	63.71	684.8	4.66	4.9	4.9
8	Hebei	607.53	411.3	499.13	44.33	3.86	3.86
9	Shandong	382.11	74.7	271.86	8.45	1.17	1.17
10	Guangdong	130.23	31.5	93.3	6.21	0.64	0.64

Table 1.1: Wind power put on the grid of main provinces in 2011 [9]

With the widespread growth of wind and solar energy penetrations, curtailment practices and even the use of strategies to mitigate the potential for curtailment, which may also exert a great impact on wind and solar energy project economics, are becoming increasingly significant. However, as the penetrations of wind and solar energy surge, it is also possible that changes in operating protocols would not reduce curtailments, but increase curtailment volumes as a fraction of total wind and solar generation.

1.1.2 BESS Background

To improve the penetration of renewable energy (especially wind power) in to the power

system network is essential to the sustainable development and climate change mitigation. However, the integration of large-scale renewable energy into power system is still an unsolved problem because its uncertainty and intermittency can have huge impacts on the whole system. One of the solutions being proposed to improve the reliability and performance of these systems is to integrate energy storage devices into the power system network [10]. The application of energy storage system (ESS) in improving power quality and in regulating voltage and frequency has been extensively discussed. A point of view that the energy storage system can be the key to the future development of renewable energy is predicted in [11]. Among the various storage technologies, battery technology has so far been the most widely adopted one for power system application. Due to its quick response ability, battery energy storage system (BESS) has an outstanding performance in this area such as smoothing the intermittence and improving the power quality.

Most of the researchers studied on this area regard BESS as a part of extra investment. To improve the cost performance, the attention is mainly focused on how to reduce the capacity of BESS as much as possible to save money as long as the output power meets the requirement of the electricity criterion. In other words, numerous algorithms are proposed to seek for the optimal capacity. The studies cover the battery type, cell capacity, power rate, as well as the combination with the supercapacitor such as electronic double layer capacitor (EDLC).

1.1.3 End-User Side Need

On the other hand, the EV and PHEV are on the rise over the world. They represent a

solution for the growing dependence on fossil fuels, since they achieve a remarkable reduction of air pollution [12]. Besides, EV and PHEV are cheaper to operate and have no tailpipe emissions. Additionally, high-capacity battery for home-use such as Power-wall is also carried out by some S&T corporations. It means at the end-user side, the need of clean and renewable energy is continuously growing and by no means will this trend stop in the future. However, how to integrate these types of vehicles with the existing power system is still affected by a lot issues. Compared with the traditional oil-based vehicles, in spite of travel ranges, the lengthy recharging time of EV is unacceptable to general public. It is worth mentioning, that because the EV and PHEV get charged by grid and most electricity in grid still come from traditional power plant, the current EV and PHEV practice actually did not resolve the big goal of reducing the air pollution. That is to say, it only transfers the pollution from cities to rural areas.

1.2 Starting Point and Objectives

Take all the factors into consideration, the starting point of this research is to find a method to solve the problems on generator side and end-user side. Improve the renewable penetration and reduce the pollution fundamentally.

In this study, instead of investing money in Energy Storage Systems (ESS) used as a fixed facility for storing the renewable energy and smoothing out the power fluctuation, a novel approach of ESS utilization in order to maximize the wind and solar penetration is proposed. This approach will also fundamentally solve the issues associated with the EV and PHEV which are mentioned above

The technical feasibility of this model is analyzed and discussed fundamentally in this

study. Based on this model, the capacity of battery in need is calculated and the logistics mode is presented.

Although most of the real-time data comes from a particular wind farm in China, the basic model and relevant analysis can also be applicable in U.S. and other countries. And it should be noted that the analyses and calculations in this research are developed upon the case of wind power. But this model can also be applied for the other forms of renewable energy.

Chapter 2

Configuration and Operating Description

This chapter presents the comparison between the traditional Wind farm-Transmission-User model and the new Wind farm-Transportation & Transmission-User model. The pros and cons of each model are listed and comparatively analyzed. Two applications of this new model are also proposed and presented.

2.1 Traditional Model

Generally, the wind farms are located at remote sites and connected to end users via High Voltage (HV) transmission lines or Ultra High Voltage (UHV) transmission lines. This model has five obvious disadvantages, as listed below.

a) The transmission lines especially the UHV transmission lines are extremely costly and time-consuming.

b) To smooth the output of wind power, the wind farm owner has to invest in a large-scale of ESS as a part of extra cost.

c) The wind power output is always restricted by the capacity of the transmission lines and the local congestion level, the two common reasons for curtailment.

d) The un-schedulable wind power also imposes restrictions on the scale of the wind farm as well as the wind power penetration. With enough flexible and schedulable capacity in grid is one of the prerequisites of the penetration improvement [13]. Actually, the

limited peak load regulation capacity of the grid is very likely to be the "bottleneck" of the renewable energy development.

e) In most cases, even for those countries with highest wind power penetration levels, feed-in tariff (the power purchase price that local distribution or transmission companies must pay for local renewable power generation being fed into the network) is necessary to reduce the financial risk for wind power investors. It apparently reflects the struggling situation of most wind farms that are hard to make profits without the support of government.

The above shortcomings hinder the greater wind and solar farm development in the remote regions of China or any other countries.

2.2 Configuration Description of The New Model

As is mentioned before, the battery transportation and logistics is very likely a possible method to solve all the problems above. The key of this model is using the battery transportation to deliver the electricity from remote wind or solar farms to end users. It should be noted that whether the existing transmission lines should be combined or not are two different applications and will depend on the analysis of the actual needs and economic aspects.

Other than the general ESS which is fixed and inseparable, in this model, the new ESS at wind farm is separable and can be transported out in the form of battery. The batteries charged at wind farms are as the same types as those utilized by end users such as the batteries for EV and PHEV. In accordance with the schedule time, the fully charged batteries will be replaced by other empty ones. And those fully charged batteries will be transported out to logistics

centers via railways or trucks and finally delivered to end users via sub-logistics centers such as Battery Swap Stations.

Apparently, distributing all the battery packs to wherever they need to meet the local demand is readily available on the ground of such an advanced logistics system at present. The logistic model is shown in Figure 2.1 that is similar to the FedEx or Amazon model. Besides, the ways of using these battery packs are various and unlimited. For example, apart from the EV, the power utilities can also aggregate a certain amount of battery packs to play a role as an ESS at some weak points to enhance the stability of the local grid.

Overall, if taking the dynamoelectric transportation into consideration, this pattern, the whole progress including generation, transportation and utilization is able to maximize the usage of the clean and renewable energy.

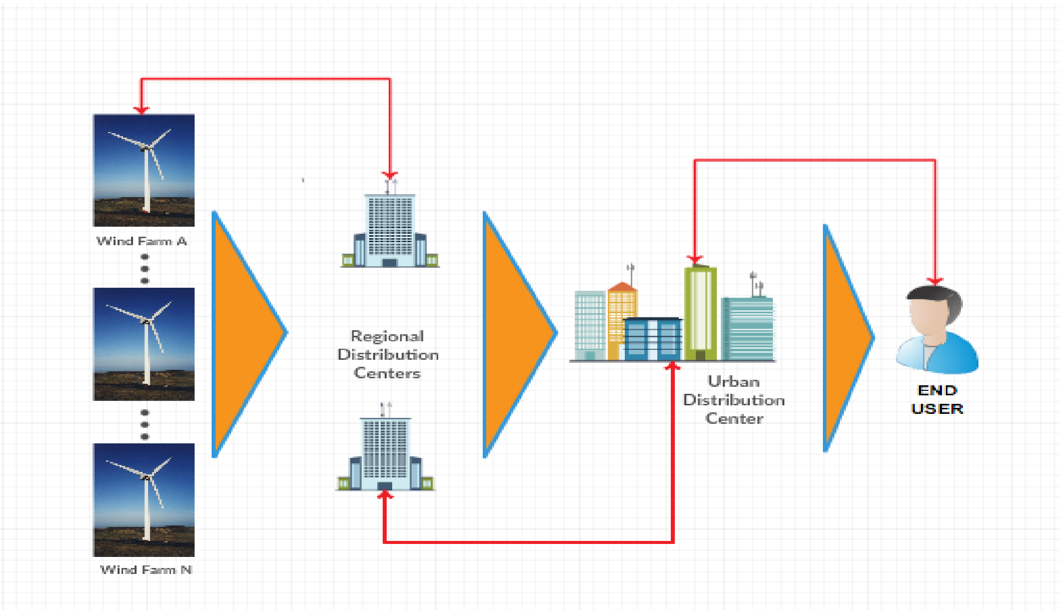

Figure 2.1: The logistic model [14]

2.3 Two Options

Based on whether or not integrating the transmission lines into the whole system, the

proposed new power delivery scheme can be implemented in two modes: a) Combined with existing transmission lines to convert the curtailed power and b) Deliver power from wind or solar farms without transmission lines.

2.3.1 Option 1 - With Existing Transmission Lines

For those wind farms where their power delivery to bulk grid is often curtailed or ceased either because of limited capability of transmission line or not enough local power consumption, ESS can be installed in existing wind farms or at a joint point of medium-high voltage transmission line nearby the railway station. ESS plays two important roles in this case: 1) Smoothing power intermittency at PCC; 2) Storing extra power (which is supposed to be curtailed, caused either by the limitation of power transmission line or by the capability of local consumption) into batteries and delivering via railway logistics to battery customers. The specific configuration is shown in Figure 2.2.

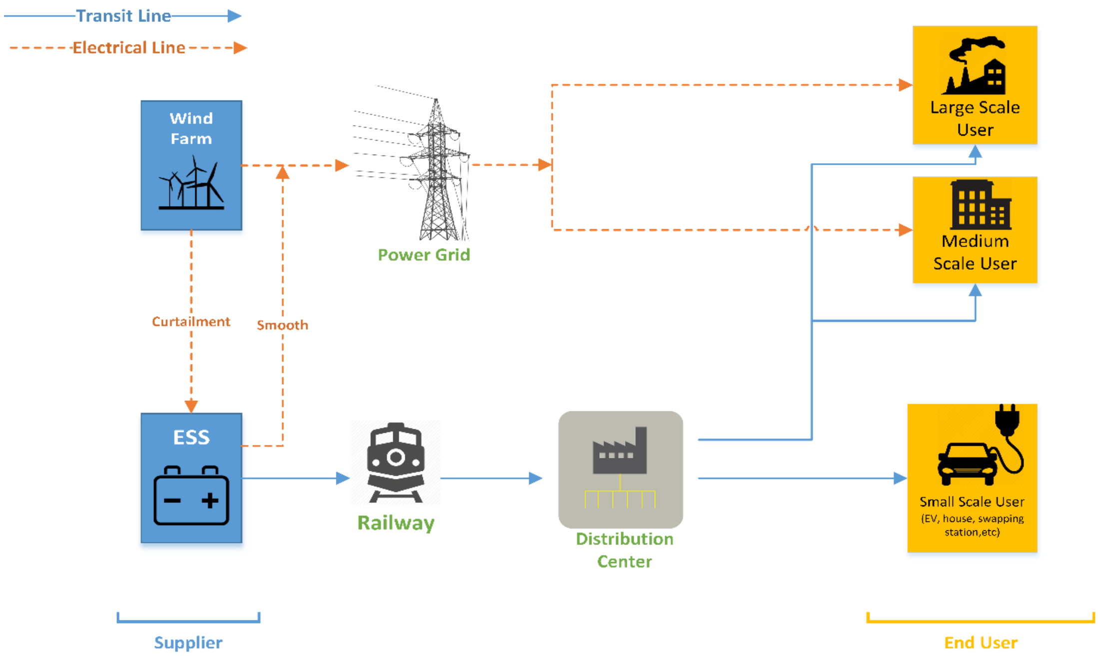

Figure 2.2: With transmission lines [14]

2.3.2 Option 2 - Without Transmission Lines

Instead of investing money in UHV transmission lines when building or planning big wind farms in remote areas, the investor can spend money on ESS and logistics. ESS becomes truly energy device delivering power to the customer with 100% renewable energy. It enables a rapid increase of renewable energy hosting capacity without any intermittent or uncertain impact to the power grid, as the wind farm and solar plant can be totally isolated from grid. And the specific configuration can be seen in Figure 2.3.

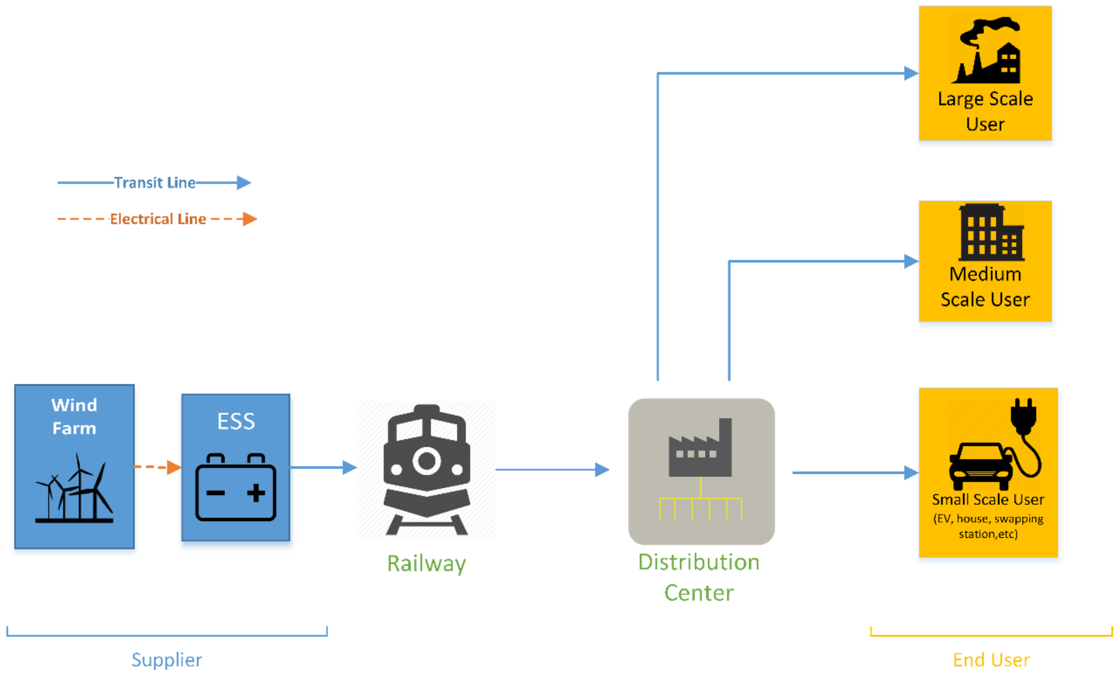

Figure 2.3: Without transmission lines [14]

Actually, based on this new model, the specific configuration can be various according to the economic analysis. For example, for those wind farms in special topography condition that batteries are not easy to deliver out, the med-transmission lines can help it out with a relatively low cost. The possible configuration is presented in Figure 2.4.

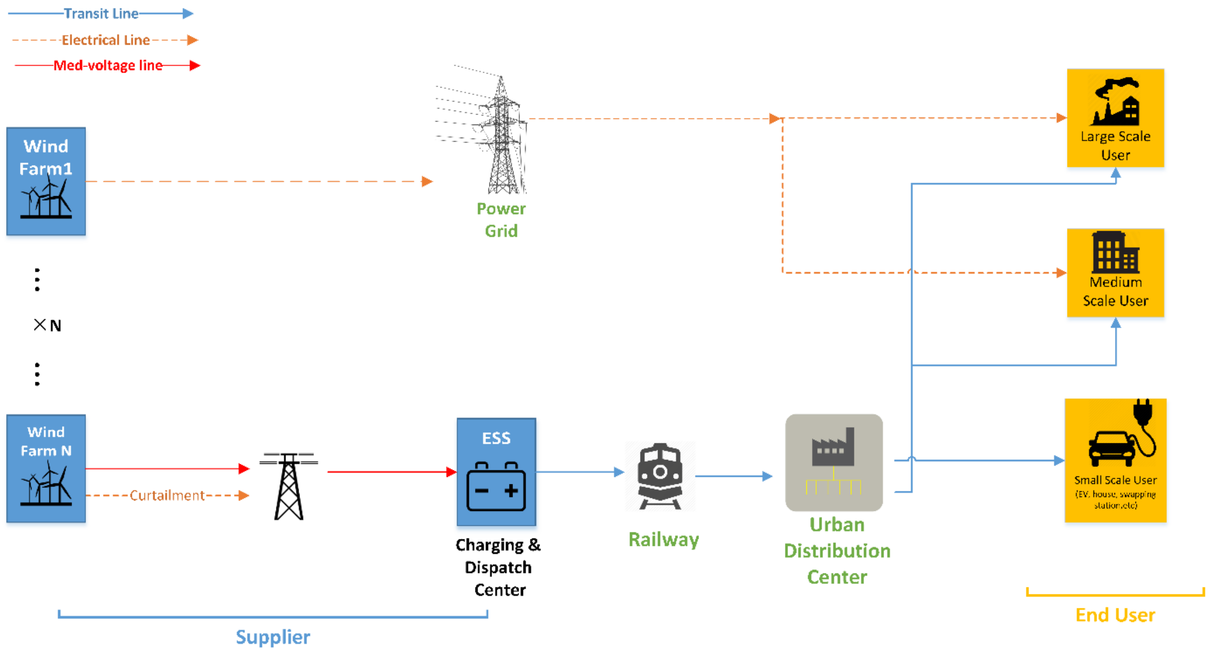

Figure 2.4: Configuration with med-voltage transmission lines [14]

2.4 Unique Features and Advantages

The unique features and advantages of this method include:

(1) Able to capture almost all the energy at the wind farm or solar plant without any curtailment, and intermittency is no longer an issue associated with the renewable energy.

(2) Shipping the fully charged batteries to the distribution center and then to end users is through the transportation network, not through the high voltage transmission network which can also guarantee green energy in the batteries.

(3) The reliability will be increased and back up electricity can be easily implemented.

(4) At the end-user side, this approach will encourage the battery swap, instead of charging. It will also encourage battery system standardization and avoid the potential impacts on the grid caused by a number of EVs charging at the same time.

(5) It will help the government enforce the carbon emission standardization for the industry.

(6) It enables the renewable power schedulable just like the traditional power resources.

(7) In most cases, as electricity market prices and wind power production will both change with time, the large-scale of batteries could store the energy during high wind and low price periods [10]. Obviously, it will make the wind power much more competitive in the market and drive the development of the wind power to a great extent.

(8) In the application combined with transmission lines, the cost for smoothing the output is saved since the batteries for storing the "curtailed" energy can also be used to smooth the output at same time. ESSs associated with the wind and solar farms are no longer viewed as a cost, but revenue producers.

(9) Provide major incentive for battery technology advancement (an enabling technology).

(10) Transportation infrastructure provides much higher benefits to the society than transmission infrastructure.

Chapter 3

Technical Feasibility Analysis

Chapter 3 analyzes the technical feasibility of this model in terms of the potential factors. A possible charging strategy with the flow chart is also introduced.

3.1 Maximum Power Point Tracking Technique

Widely used with photovoltaic (PV) solar systems and wind turbines, maximum power point tracking (MPPT) is a technique to maximize available power output. It is not a mechanical tracking system but a fully electronic system that calculates and varies different operating points to enable the device operating at the optimal condition. Besides, the operators also use the similar principle to control the curtailment level for specific demand. The typical MPPT technique in terms of wind turbine will be described below.

According to the Newtonian kinetic energy formula, the kinetic energy of the air with mass m moving at velocity v can be represented as

$$E_k = \frac{1}{2} m v^2 \tag{3.1}$$

Divided by time, power through area A can be derived

$$P_A = \frac{1}{2}\left(\frac{m\ passing\ through\ A}{t}\right) v^2 \tag{3.2}$$

The mass flow rate is

$$m_{fr} = \frac{m\ passing\ through\ A}{t} = \rho A v \tag{3.3}$$

where ρ represents the air density.

Combining 3.2 and 3.3

$$P_A = \frac{1}{2}(\rho A v)v^2$$

$$\rightarrow P_A = \frac{1}{2}\rho A v^3 \tag{3.4}$$

where $P_A(Watts)$ is the power in the wind, $\rho(kg/m^3)$ is the air density $(1.225kg/m^3\ at\ 15C^{\circ}\ under\ 1atm)$, $v(m/s)$ is the wind speed and $A(m^2)$ is the cross-sectional area that wind passes through.

In this way, the equation (3.4) represents the power in the wind. Wind turbines are used to extract the energy from the kinetic power of the wind. However, since the wind is slowed but not stopped in the course, wind turbines cannot capture 100 percent power in the wind. According to Betz limit, theoretically the maximum amount of energy that can be extracted by a wind turbine's rotor is about 59.3%. And therefore, a coefficient named Coefficient of Power (C_P) is combined into the equation (3.4) which reflects a measurement of how efficiently the specified turbine extracts the energy from the wind.

$$C_P = \frac{Electricity\ produced\ by\ wind\ turbine}{Total\ energy\ available\ in\ the\ wind} \tag{3.5}$$

Then the power captured by wind turbine can be computed as

$$P_A = \frac{1}{2}C_P \rho A v^3 \tag{3.6}$$

As to the calculation of C_P, it will refer to the Tip Speed Ratio (TSR) of a turbine (λ) that is an essential factor to the efficiency of the turbine. Take the loss of generator, rotor, transmission lines and some other devices into consideration, the relationship between λ and C_P is shown in the Figure 3.1.

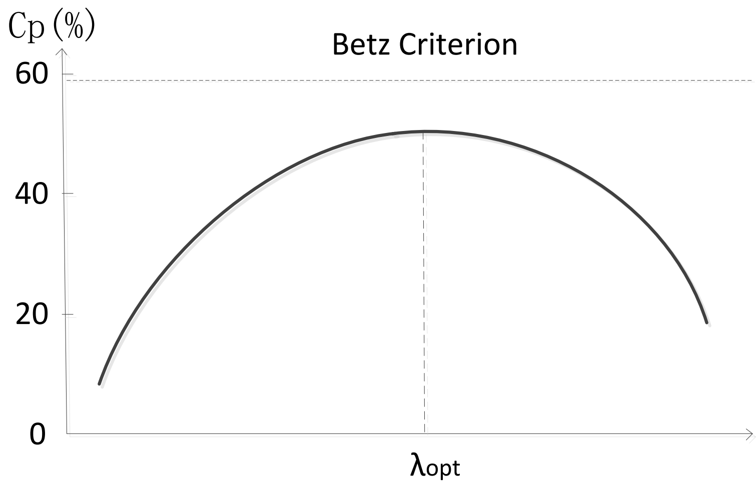

Figure 3.1: $C_P - \lambda$ curve of a wind turbine

And

$$\lambda = \frac{\omega_m R}{v} \tag{3.7}$$

where ω_m is the angular velocity of the rotor and R is the blade radius.

When the blade pitch angle is determined, a certain wind speed always corresponds to a certain ω_m and related C_P that represents the best efficiency. Obviously, that ω_m achieves the highest output according to the equations. Similarly, at various wind speeds, we can always get a “best” point as shown in Figure 3.2. After connecting all the points in series, we can get a curve that shows the relationship between the maximum output and the wind speed.

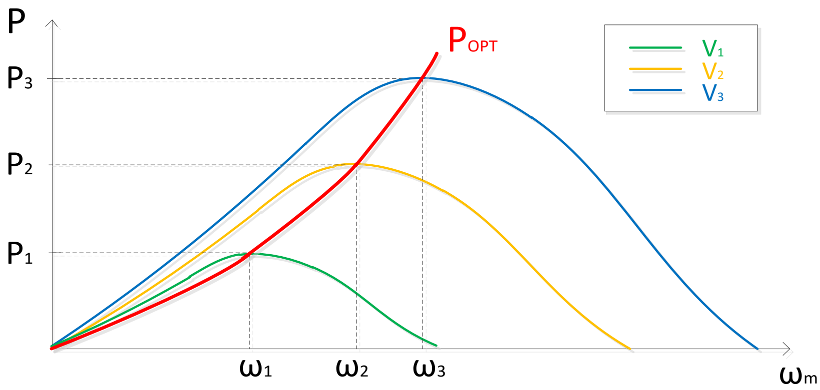

Figure 3.2: Power characteristics of different wind speed

Through the adjustment of either blade pitch or active power output, the turbines can always be operated at the optimal ω_m in order to track the curve. And various methods and algorithms can be used to implement this process automatically such as active-reactive power decoupling control.

3.2 Battery

There is no doubt that the battery is one of the best methods to connect the renewable energy to the end users. Different kinds of batteries vary widely by manufacturer and specific application. And thus it is very important to choose the appropriate battery to make this new model technical and economic feasible. Several properties such as life span, efficiency, depth of discharge, self-discharge, energy density and cost are worth to be discussed upon this model. Besides, since the batteries will be delivered out via transportation, the weight should also be considered.

3.2.1 Battery Types

Different application requires divergent properties. With respect to the model in this research, the battery type which is most suitable for ESS is not necessarily suitable for usage in the end-user side. Based on the features in need, Table 3.1 lists the similarities and differentials between two usages.

	ESS	End User
Similarity	Long life span; Deep discharge depth; Low self-discharge; High efficiency	
Differentia	Fixed; Large power rating and energy rating	Portable; High energy density; High specific energy

Table 3.1: Similarities and differentials between two applications

Of the various battery technologies, some seem to be suitable for this model are listed in Table 3.2. The data comes from [15] and WIKIPEDIA.

Battery Type	Property
Lead acid	efficiency = 70-90%, life span 1000-2000 cycles at 70% depth of discharge, 33-42Wh/kg, 60-110Wh/L, self-discharge 2-10%/month
Sodium Sulphur	efficiency = 89-92%, life span 2500 cycles at 100% depth of discharge, 100Wh/kg, no self-discharge, operating temperature $325^{\circ}C$
Vanadium redox	efficiency = 75-85%, life span > 10000 cycles, 10-30Wh/kg, 15-25Wh/L, negligible self-discharge, independency in designing power size and energy capacity
Metal air	efficiency = 50%, life span few 100 cycles, 450-650Wh/kg, negligible self-discharge, difficult to recharge
Lithium ion	efficiency > 95%, life span 3000 cycles at 80% depth of discharge, 90-190Wh/kg, negligible self-discharge

Table 3.2: Battery characteristics

Among these sorts, lead acid battery's efficiency is too low and its specific energy and energy density cannot compare to the ones of Lithium ion. Sodium Sulphur battery is suitable for large-scale ESS but because its operating temperature is very high and pure sodium presents a hazard, it is not a good option for end users. Although vanadium redox battery theoretically has an infinite life span, its specific energy and energy density are insufficient to meet the

demand of EV. Metal-air battery is still in experimental stage. In spite of its incredibly high specific energy, the difficulty of recharging and the short life span are two main obstacles for its marketization. Over all, at least so far, the lithium ion battery, without any apparent shortcoming, is the best choice for this new model.

3.2.2 Cost of Lithium-ion Battery

Generally, the major disadvantage of the lithium ion battery is the high cost. However, due to the widely research and continuous development, not only the performance is improved significantly, but also the cost (US$/kWh) drops rapidly, Figure 3.3 shows the price curve of lithium ion battery from 2010 to 2016.

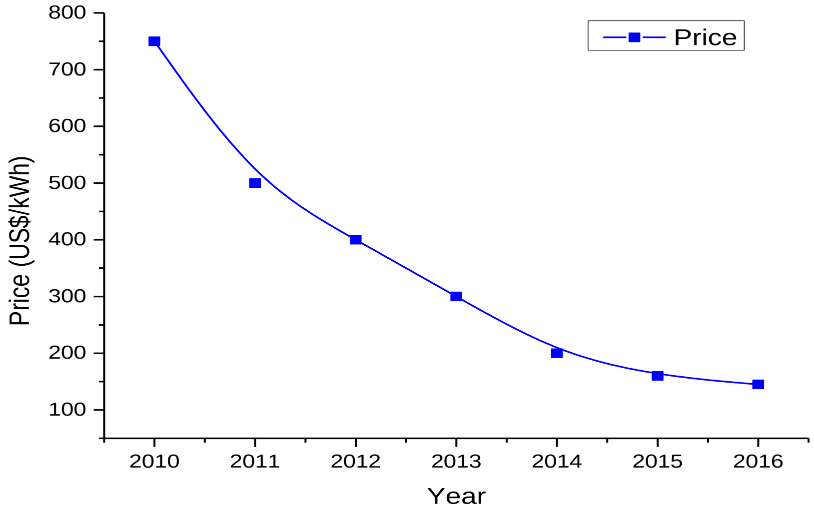

Figure 3.3: Price curve of lithium ion battery

The battery price came down to 1/3 that was ten years before the estimation. The U.S. Department of Energy has set a goal that for its sponsored battery project the price should be no more than US$125 per kWh by 2022. In fact, most EV manufacturers refuse to discuss the actual costs for batteries in detail because it involves much speculation and debate. However,

at GM's (General Motors) annual Global Business Conference in 2015, along with the disclosure, they expected a price of US$100 per kWh for lithium ion battery by the end of 2021.

3.2.3 Efficiency Comparison

Evaluating whether this new model is technical feasible, an important element is the efficiency compared to traditional transmission and distribution (T&D) lines. As is shown in Table 3.2, the change-discharge efficiency of the lithium ion battery is over 95% and the self-discharge is negligible. As for T&D lines, taking the main part of a typical T&D network into consideration, the average values of losses for each part are listed below:

a. 1-2% – Step-up transformer between generator and Transmission line

b. 2-4% – Transmission line

c. 1-2% – Step-down transformer between Transmission line and Distribution network

d. 4-6% – Distribution network transformers and cables

The total losses are in the range between 8 and 15%.

Figure 3.4 shows the real data of electric power transmission and distribution losses (% of output) within different countries in 2012 [16].

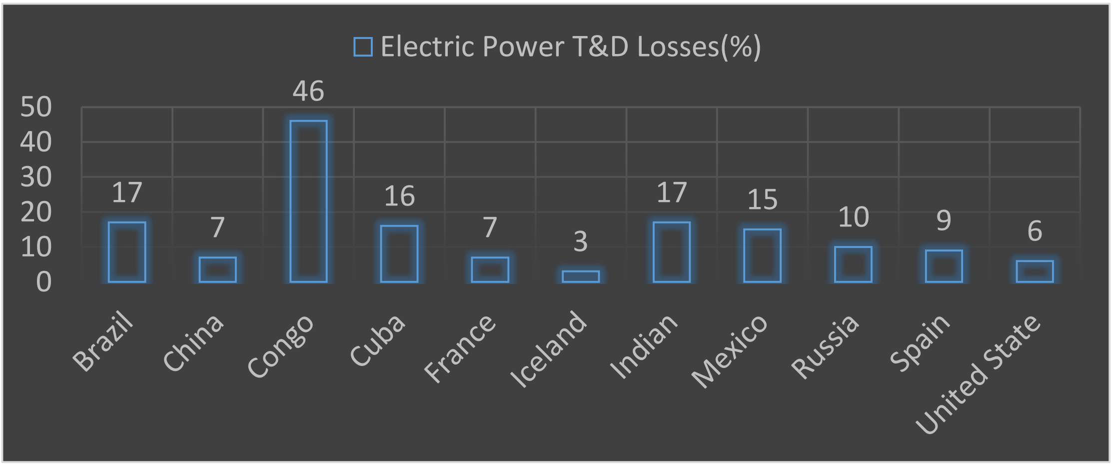

Figure 3.4: The Electric Power T&D Losses (%) in 2012

Obviously, in most cases, lithium-ion battery is better than the T&D network in terms of the efficiency of energy delivery. Except a few developed countries, many other countries especially some developing countries have great losses on T&D network. Moreover, it should be noted that even in current mode, when people charge their EV or other battery devices, the loss of charging-discharging process exists as well.

3.2.4 Intermittency Issues on Battery Life Span

As we all know, a notable nature of wind power or solar power is their intermittency. Based on this issue in regard to battery life span, two applications of this model should be discussed separately.

3.2.4.1 Option without Transmission Lines

In this application, all of the wind power captured by turbines will be stored into the batteries. There is no need to smooth the wind power output because the wind farm is not connected to the grid. Therefore, no matter how the wind speed tremendously changes, at wind farm side, only charging process exists. The discharging will not appear at all. So, the only problem is that will the intermittent charging process negatively affect the battery’s life span? In my perspective, the answer should be no. In contrast, the possible interruptions during the charging process may accelerate the charging speed by inhibiting the polarization.

Fast charging has received extensive attention due to the development of EV and the renewable energy. Quite a lot of fast charging topologies are proposed over the years with their own merits and drawbacks. Among these topologies, pulse charging is a hot topic in this area.

Apparently, the speed of ions moving in electrolyte is much slower than the speed of electrons in conductor. The intervals between each pulse can significantly eliminate the polarization effect because they enable the chemical reaction to keep up with the speed of the injected electrical energy. So literally as long as the charging rate is controlled in the reasonable range, the battery's life span will not reduce due to the intermittence.

3.2.4.2 Option with Transmission Lines

Under this circumstance, the batteries for storing the energy which are supposed to be curtailed are similar to another application discussed above. The only difference is that these batteries are also used to smooth the power output from wind farms to the grid. For this part, the frequent charge-discharge process will indeed have an adverse influence on battery's life span. However, it is unavoidable as long as the batteries are playing a role for smoothing the power output, no matter in this new model or the existing model. And very likely, the discharging process may help to eliminate the polarization effect just like the negative pulse's effect in pulse charging technology [17].

3.3 Transport Capacity and Energy Consumption

If the transportation is driven by electricity, then the whole process will be 100 percent of clean and renewable energy. And the consumption of the transportation can be directly associated with the efficiency. Therefore, we assume that the batteries are transported via electric railways.

The number of batteries that should be transported depends on the specific wind power

condition in scheduled time. Therefore, to assess the transport capacity for battery transportation, some assumptions and restrictions are necessary.

The consumption should be restricted in 5 percent of total energy transported which is close to the loss in transmission and distribution lines in developed countries [16]. Figure 3.5 shows the relationship between the train speed and drawbar power [18]. Normally, the speed of a typical freight train is 90 km/h, and thus the drawbar power is approximately 1.3MW.

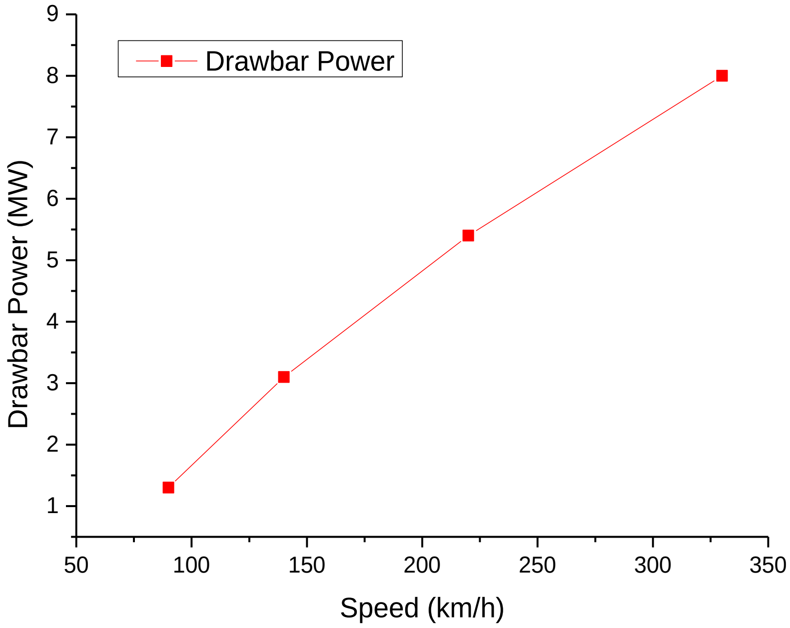

Figure 3.5: Relationship between train speed and drawbar power

Average level of load weight is about 65-75 carts for one locomotive, and each cart can hold 60t to 70t loads. So the whole load capacity is about 4500t [19]. For each cart, the volume is about $77m^3$. So the equivalent density is about $909\text{kg}/m^3$.

The researches seldom discuss the density of lithium ion batteries, so the battery Tesla 18650 is assumed to be analyzed in this chapter. For its core part, the weight and volume of each pack is 360kg and $0.4m^3$ [20] respectively. And the density is $900\text{kg}/m^3$ which is

approximately equal to 909kg/m^3. The values are so close that we can almost consider that if the weight meets the requirement, then the volume will not be a problem.

The consumption of the train is

$$E = \frac{S \cdot P}{\nu} \tag{3.8}$$

Where S (km) is the distance, P (MW) is the drawbar power and ν (km/h) is the speed of the train. It should be noted that a particular ν corresponds to a particular P.

Assume the consumption occupies 5 percent of the whole transported energy. The number of battery packs is

$$N = \frac{E}{0.05} \cdot \frac{1}{85/1000} \tag{3.9}$$

And the whole weight W (t) should be no more than the total load capability of 4500t.

$$W = N \cdot 360/1000 \leq 4500 \tag{3.10}$$

For example, a distance of 500 km is applied and thus the transportation time is 6 hours and the corresponding consumption is 7.8MWh. The total number of battery packs need to be transported is about 1836 with a weight of 660t which is much less than 4500t. Therefore, the load capability can meet the demand in general.

If we assume all the load capacity are used to transport batteries, then the total number of batteries is 4500*1000/360=12500 which equals to 1062.5MWh. Therefore, the energy consumption of transportation only accounts for 0.7% of the whole energy in delivery. If we change the train's speed, different portions of energy consumption are represented in Figure 3.6.

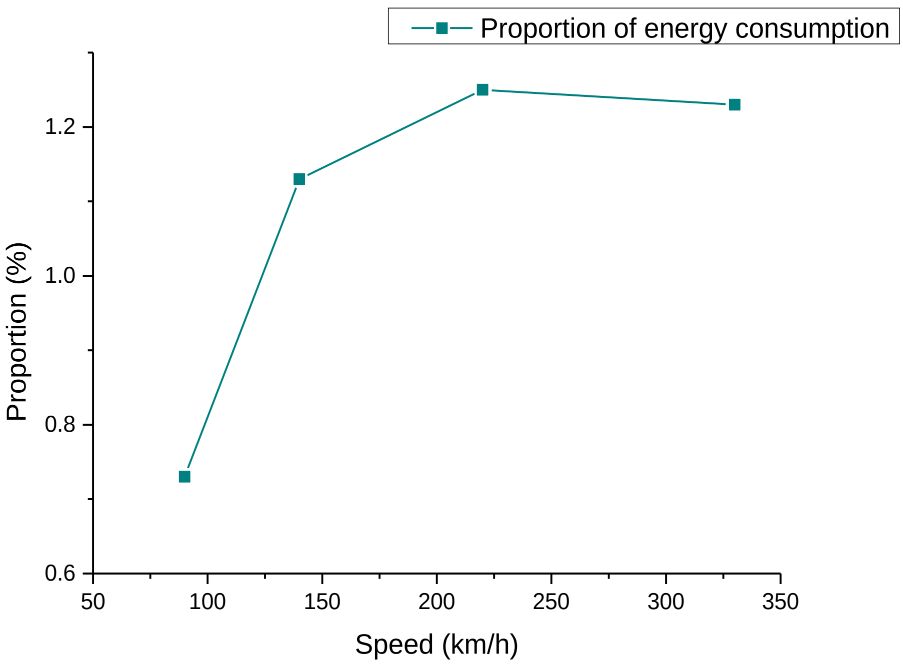

Figure 3.6: The proportion of energy consumption based on different speed

3.4 Efficiency with All Primary Components Involved

The efficiency mainly includes 4 parts:

1 Charge-discharge efficiency of lithium-ion battery (>95%)

2 Loss of inverter and converter (1%)

3 Self-discharge (negligible)

4 Energy consumption of transportation (1%)

So the final efficiency should be more than 93% which is close to transmission lines' efficiency in advanced countries.

3.5 Number of Batteries Based on Charging and Transportation Time

The number of batteries in this new model will depend on many factors. To estimate the

number will need a few assumptions. First, one day (24 hours) is assumed to be the charging time, and during this time, X batteries can be fully charged. Secondly, we assume that one way from wind farm to end user will take 12 hours as for a low speed freight train. Third, we assume the end-user side can congest all the generated energy in time. Under such circumstance, the number of batteries in need should be 3X. The illustration is presented in Figure 3.7.

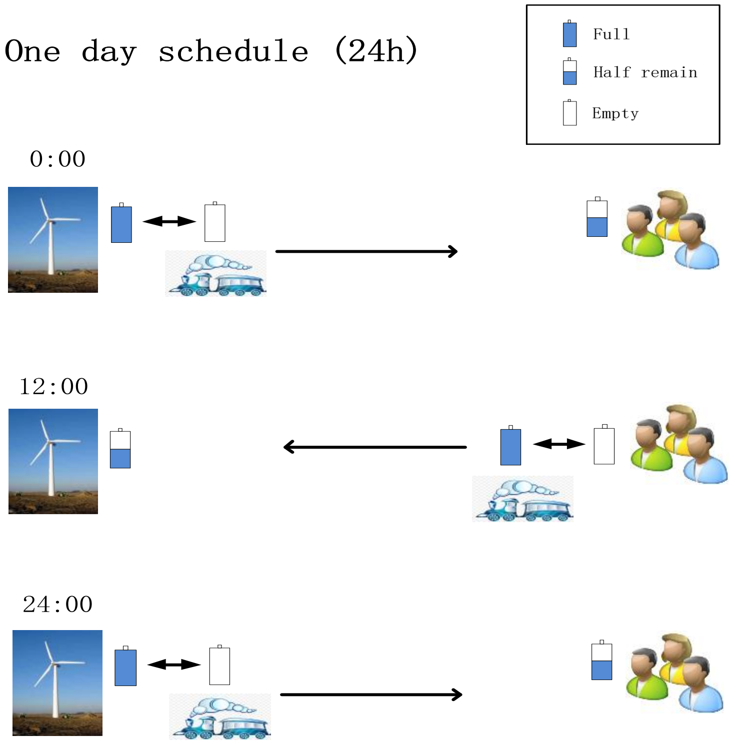

Figure 3.7: Case based on one day charging and one round trip of transportation

As we can see, at 0:00 X fully charged batteries are exchanged with another X empty batteries. And the train with X full batteries starts going to end-user side. At the same time, the batteries at end-user side are assumed to be half remain. After 12 hours, when the train arrived at end-user side, the batteries there are just empty and ready for exchange. After exchange, the train begins to return to wind farm side with X empty batteries. Meanwhile the batteries at wind farm side are half charged. At 24:00, when the train arrives at wind farm again, a new circulation begins.

On the ground of one day schedule, if we assume the schedule period is A days, and during this course, the trains back and forth B times. Then the total amount of batteries in need will be

$$\mathrm{N} = \frac{3X \cdot A}{B} \tag{3.11}$$

3.6 Topological Configuration

The topological configuration with transmission line is shown in Figure 3.8. Similar to the existing ESS model, the battery packs are connected to the DC bus via a DC/DC converter. The main difference is that the batteries are not fixed. They are detachable. Between each battery pack and the DC bus, there is a circuit breaker (CB) and a switch. Under such circumstance, the battery pack can be detached and replaced via the operation of switches and CBs. And with the battery SOC (Stage of charge) management, the charging strategy that either charge a portion first or charge all the packs at the same time is flexible and thus it can meet different demands.

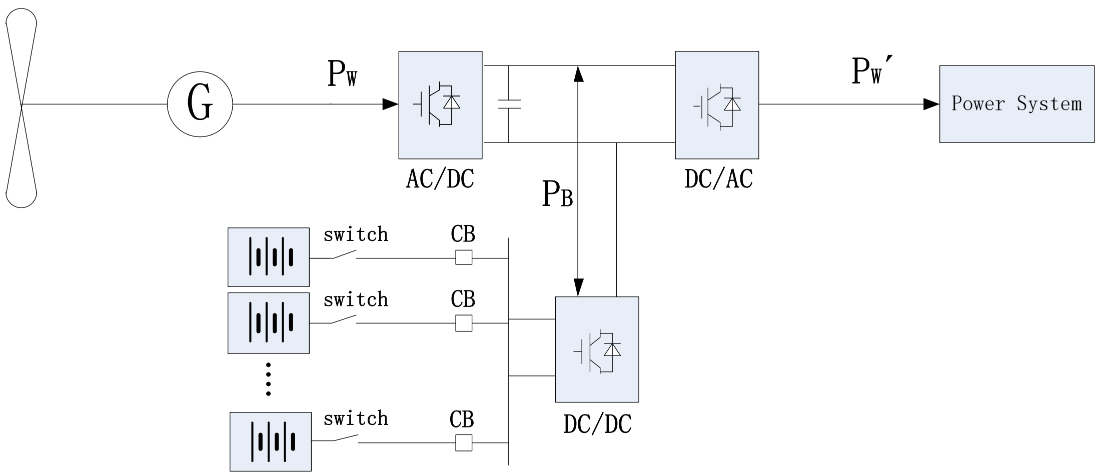

Figure 3.8: The topological configuration

The batteries are installed at low voltage side between the turbines and the step-up transformer. The batteries as well as the related charging devices can be either aggregated or distributed configured. According to [21], with respect of fluctuation harmonic content (FHC), the two configurations are almost same effective. However, based on management and economic aspects, aggregated configuration might be a better choice for this model. But it should be further considered and verified in future research.

Chapter 4

Case Study and Analysis

This chapter is aimed on the simulation to show the wind curtailment and to assess whether or not the batteries for storing curtailed energy is enough for smoothing purpose (Option 1). The simulation of the stochastic wind speed and the smoothing process are the preparatory work for the case study in the end.

4.1 Simulation of Stochastic Wind Speed

Basically, the stochastic wind speed simulation consists of four parts: 1 fundamental wind speed V_A 2 random wind speed V_B 3 gust wind speed V_C 4 ramp wind speed V_D

$$V_w = V_A + V_B + V_C + V_D \tag{4.1}$$

V_A is determined by real data of wind speed and Weibull distribution parameters, and in this study it is an assumed constant. V_B represents the small fluctuation of wind speed. V_C can be derived as

$$V_C = \begin{cases} 0\ (t < T_{C1}) \\ V_g\ (T_{C1} \le t \le T_{C2}) \\ 0(t > T_{C2}) \end{cases} \tag{4.2}$$

where

$$V_g = \frac{G_{max}}{2} \cdot \left[1 - cos\left(2\pi \cdot \frac{t}{T_{C2}-T_{C1}} - \frac{T_{C2}}{T_{C2}-T_{C1}}\right)\right] \tag{4.3}$$

T_{C1}, T_{C2}, G_{max} represents the starting time, end time and maximum speed of the gust respectively.

V_D can be derived as

$$V_D = \begin{cases} 0(t < T_{R1}) \\ V_R(T_{R1} \leq t \leq T_{R2}) \\ R_{max}(T_{R2} \leq t \leq T_{R3}) \\ 0(t > T_{R3}) \end{cases} \quad (4.4)$$

where

$$V_R = R_{max}\left[1 - \frac{t/T_{R2}}{T_{R1}-T_{R2}}\right] \quad (4.5)$$

T_{R1}, T_{R2}, T_{R3}, R_{max} represents the starting time, rising end time, duration time and maximum speed of the ramp wind respectively.

Based on the equations aforementioned, the stochastic wind speed has been modeled in MATLAB/Simulink as is shown in Figure 4.1.

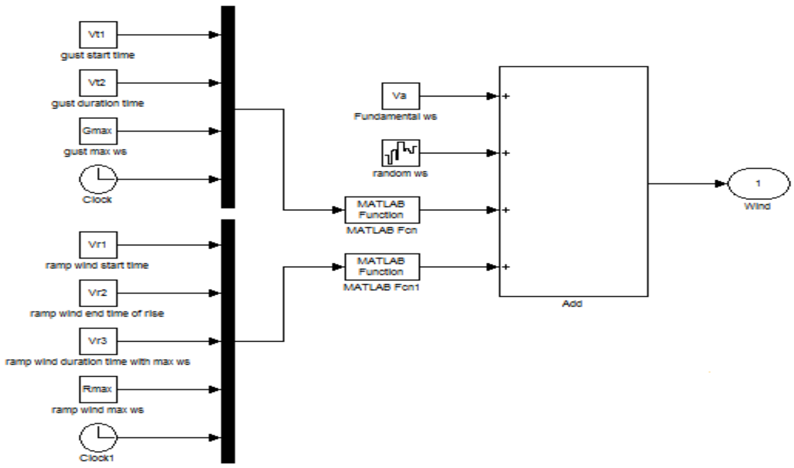

Figure 4.1: The stochastic wind speed model in MATLAB/Simulink

With the different combination of each parameter values, divergent wind speed cases can be obtained such as the one shown in Figure 4.2.

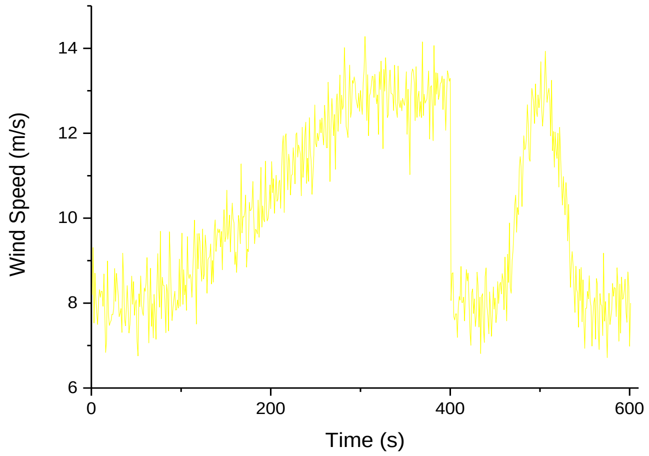

Figure 4.2: Stochastic wind speed simulation

4.2 Simulation of Power Output Smoothing

As is introduced in Chapter 3, the original power output of the wind turbines can be derived according to the wind speed (shown in Figure 4.3). To smooth out variable power output, there are several smoothing control methods to manage the output of BESS. In this study, a low pass filter is applied to generate the "target" power output which is acceptable by the grid as is shown in Figure 4.4.

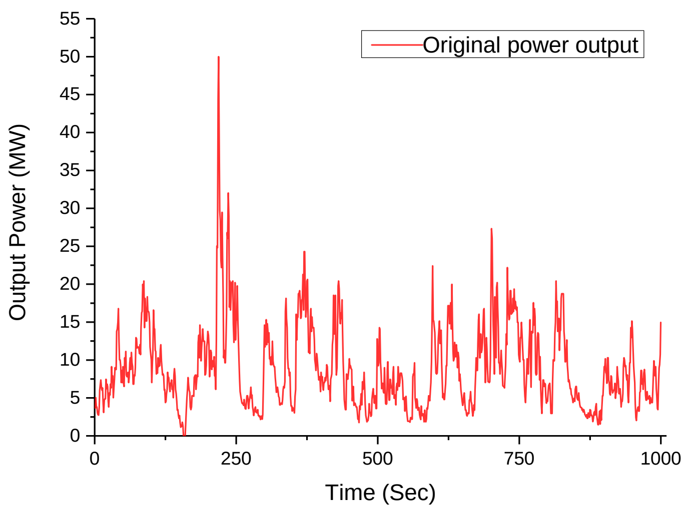

Figure 4.3: The original power output of the wind turbines

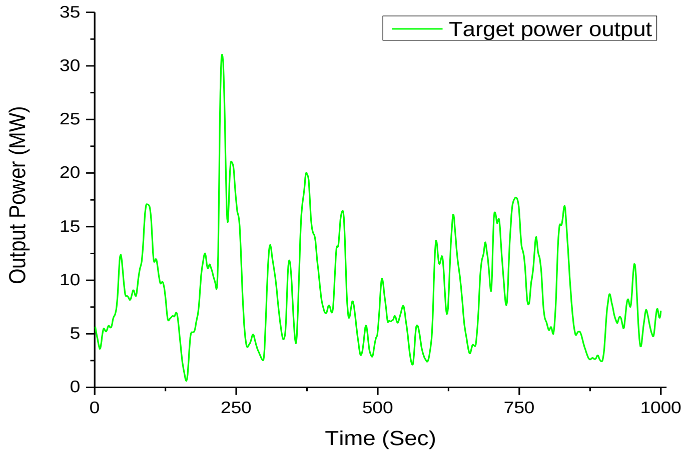

Figure 4.4: The target power output

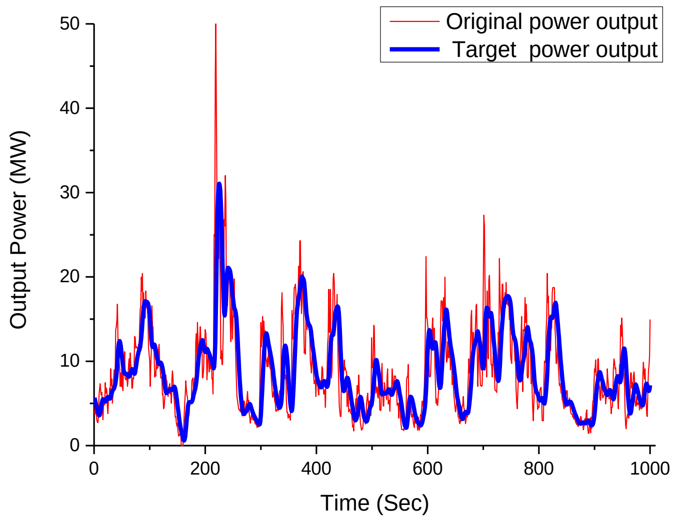

Figure 4.5: The comparison between the original output and target output

Figure 4.5 represents the comparison of two curves by putting them together. The difference between the original power output and the target power output becomes the charging-discharging output of the BESS which can be observed from Figure 4.6.

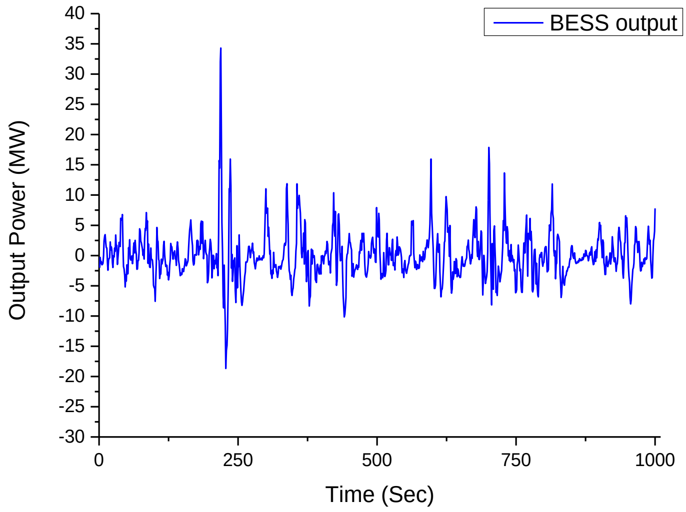

Figure 4.6: The output of BESS

4.3 Take Curtailment and Electricity Criterion into Consideration (First Application)

Different countries as well as different rated power of wind farm always have different electricity criterion for power output. In this study, to assess the batteries' power and energy size, the electricity criterion upon the output of wind farm in China is applied which is shown in Table 4.1.

Installed capacity of wind farm (MW)	The maximum change of active power in 10 minutes (MW)	The maximum change of active power in 1 minute (MW)
< 30	10	3
30 ~ 150	Installed capacity/3	Installed capacity/10
>150	50	15

Table 4.1: The maximum change of active power output of wind farm in China

The wind speed data used in this section comes from a monitoring station. The type of the

wind turbine is WD103-2500T, and the specific parameters are shown in Table A1, Appendix A. A 50MW wind farm is assumed to consist of 20 units of same type wind turbines. It should be noted that Wake Effect and Tower Shadow Effect are not considered here.

The original power output of wind turbine in 24 hours is shown in Figure 4.7. As is introduced before, the curtailment level mainly determined by the capacity of transmission lines and the limitation command given by AGC in real time. In this study, the curtailment level for each hour is assumed to track the curve in Figure 4.8 as per unit value with respect to the rated power of the wind farm.

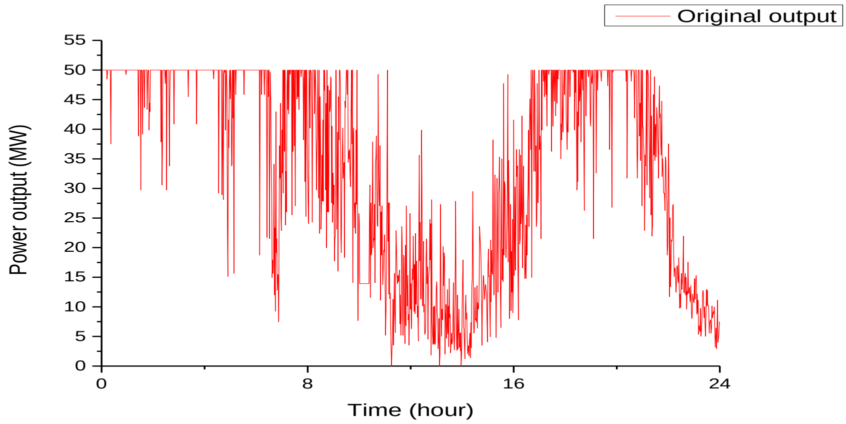

Figure 4.7: Original power output in 24 hours

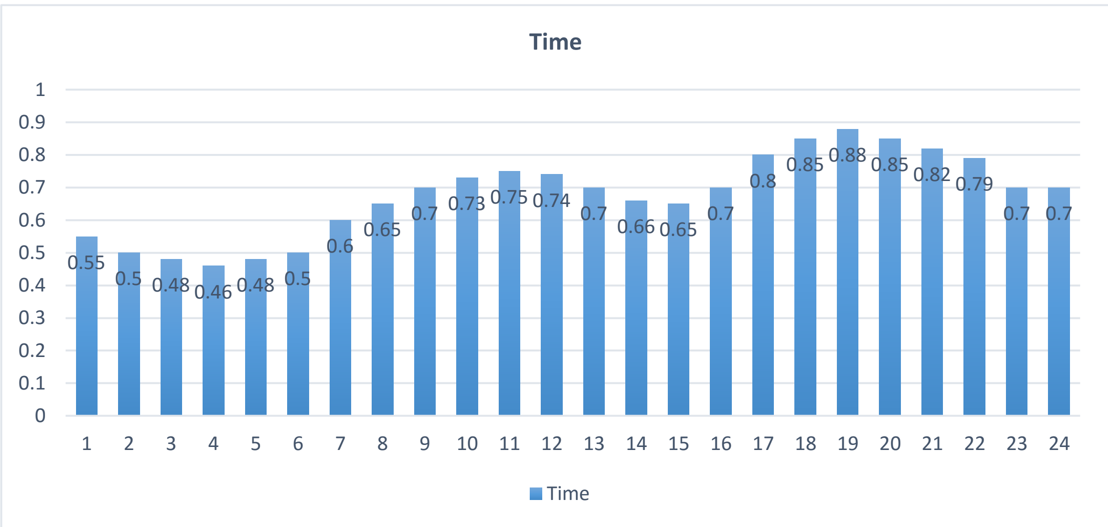

Figure 4.8: Wind power curtailment level

After combining the original power output with the curtailment level, the power output after curtailment is shown in Figure 4.9. That part of curtailed power is stored in the BESS as is shown in Figure 4.10.

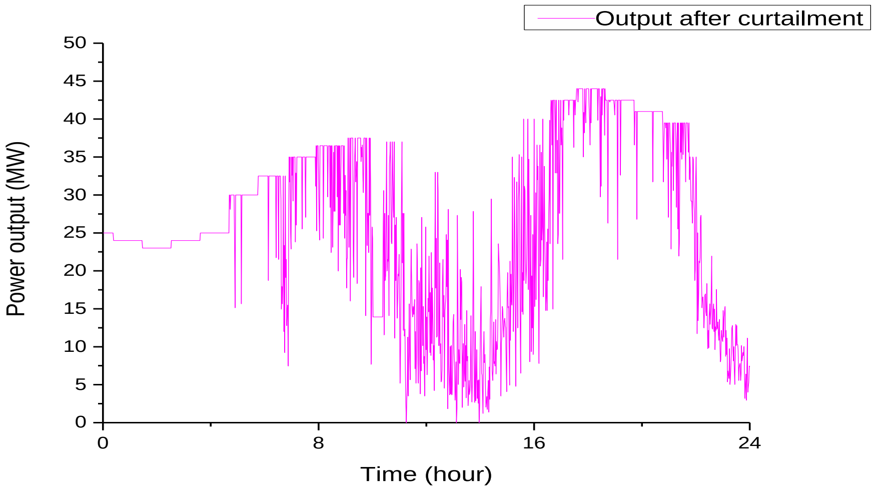

Figure 4.9: Power output after curtailment

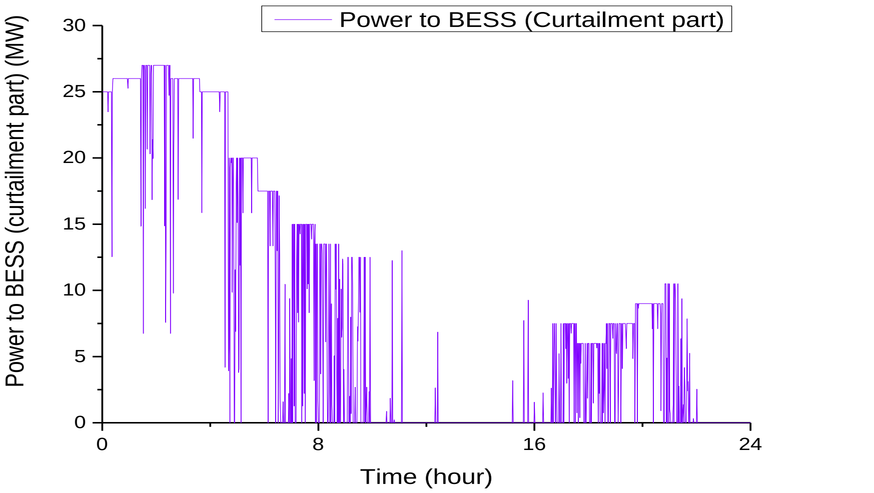

Figure 4.10: Curtailed power stored into BESS

Even after the curtailment, the rest power output still need to meet the electricity criterion of wind power. As the rated power output of the wind farm assumed here is 50MW. Therefore,

the fluctuation of its power output should be less than 17MW in ten minutes and be less than 5MW in one minute. After the smoothing, the power output is shown in Figure 4.11. And the BESS used to store the curtailment energy also plays a role as smoothing the fluctuation. For smoothing part, the output of BESS is presented in Figure 4.12. Adding two parts of BESS output together, the final output of BESS is shown in Figure 4.13.

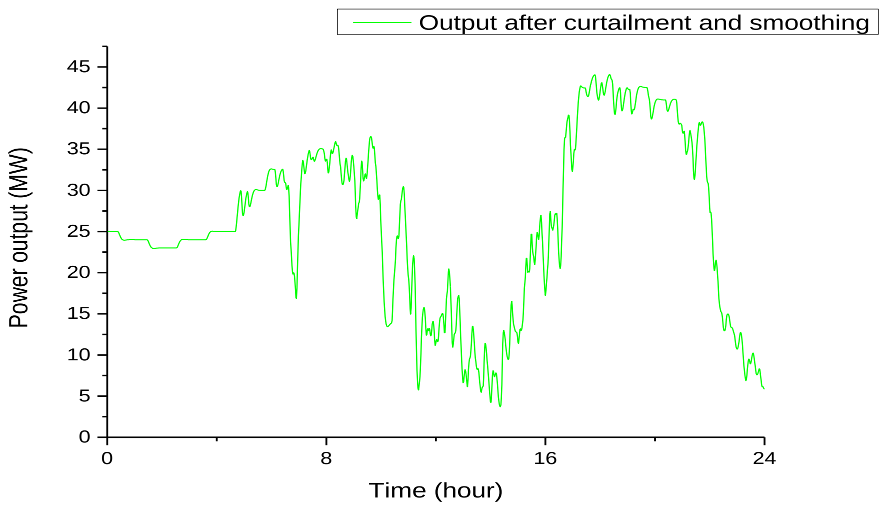

Figure 4.11: Power output after curtailment and smoothing

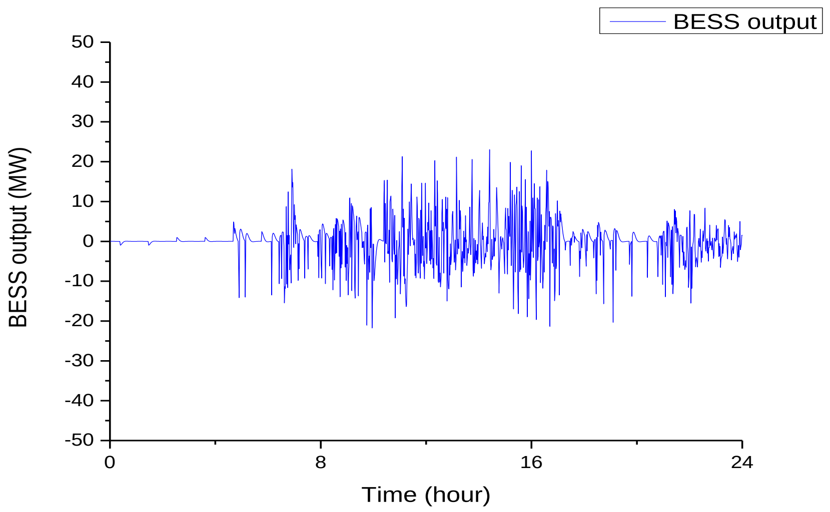

Figure 4.12: BESS output for smoothing part

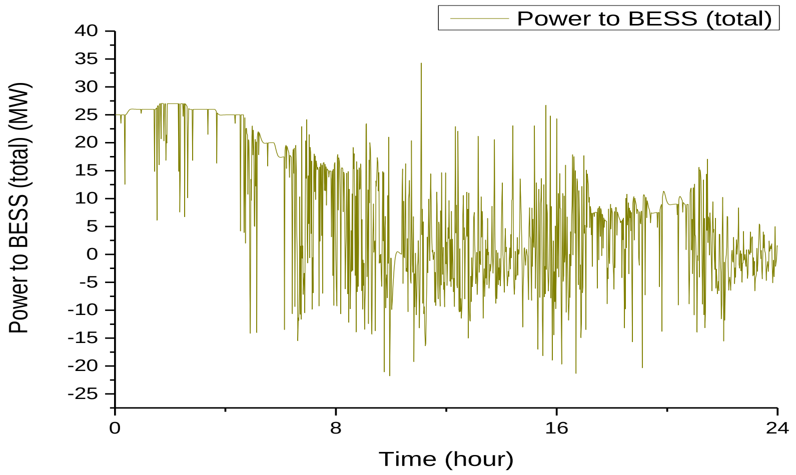

Figure 4.13: Final power profile of BESS

In this case, the whole energy output of wind turbines is 840.2708MWh, and the curtailment is 221.0464MWh which accounts for 26.3 percent of the whole energy output. The energy size for smoothing usage is 112.0557MWh which is much less than the BESS capacity for storing the curtailed energy. And the power size for smoothing usage is 23.0598MW that compared with the energy size in need, it should not be a problem here. Because that the smoothing process includes both charging and discharging with almost same frequency. So in the end net energy for smoothing is 0.4427MWh which is negligible. Obviously, in the first application (with transmission lines), the energy size for storing the curtailed part of energy is enough for smoothing purpose.

It should be mentioned that the optimal cutoff frequency is calculated by program and applied in smoothing process which is 0.0028 here.

Chapter 5
Conclusion

In this study, instead of investing money in Energy Storage Systems (ESS) used as a fixed facility for storing the renewable energy and smoothing out the power fluctuation, a novel approach of ESS utilization combined with logistics in order to maximize the wind and solar penetration is proposed.

The possible configuration is described and the mode of logistics is also presented. The specific structure can be various according to divergent goals. Two applications are proposed and the unique features and advantages are described and compared with traditional model.

The technical feasibility of this model is analyzed and discussed fundamentally in this thesis. On the ground of this new model, battery parameters including battery type, cost, efficiency and life span are presented and compared. Take energy consumption of transportation into consideration, the preliminary efficiency of this model is estimated. And based on reasonable assumption, the simple logistics mode is described and the number of batteries in need is evaluated.

The possible topological configuration on wind farm side is described and the production of stochastic wind speed is modeled. Low Pass Filter (LPF) is used to smooth the power output. Consider the curtailment as well as smoothing process, the energy size and power size of batteries in need is calculated and analyzed. In the first application (with transmission lines), the energy size for storing the curtailed part of energy is enough for power output smoothing with a large margin.

Chapter 6
Challenges and Future Works

Since the proposed model is a brand new method to maximize the penetration of renewable energy, in spite of the aspects had been discussed in this thesis, there are still quite a lot of problems and challenges not concerned, especially because it will refer to a large scale of batteries. Some of them are listed below:

1. Economic feasibility
2. Safety issues
3. Battery recycle
4. Battery swap and standardization
5. Transportation bottleneck
6. Constructing large charging facilities at the wind and solar farms

All the issues above should be further studied and discussed in detail. However, with the development of battery technology and industry of renewable energy, this model is very likely to be realized in future in order to solve the problems of energy utilization not only at production side but also at end-user side.

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APPENDIX

Parameters of WD103-2500T Wind Turbine

Type	WD103-2500T
Rated Power	2500kw
Power Factor	-0.95~+0.95
Cut-in Wind Speed	3m/s
Rated Wind Speed	10.7m/s
Cut-off Wind Speed	25m/s
Limited Wind Speed	70m/s
Type of Wind Farm	GLS
Operating Temperature	$-20℃\sim45℃$ (normal) $-30℃\sim45℃$ (low)
Wheel	
Diameter	103.6m
Cross-sectional Area	$8430m^2$
Number of blades	3
Rated Speed	8.4rpm-13.9rpm
Transmission Ratio	83.4
Generator	
Type	DFIG
Rated Power	2600kw
Frequency of Grid	50Hz
Converting Capacity	1125/1375KVA
Tower	
Type	Conical steel structure
Height of Wheel Hub	80m, 90m, 100m
Weight and Size (kg/mm)	
Engine Room	94140/11460*4240*4287
Wheel Hub	24000/4785*4265*3750
Blade	11600/50500*2400*3700