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Yuming Chen
University of Wisconsin-Milwaukee

A NEW PARADIGM OF MAXIMIZING THE WIND AND SOLAR PENETRATION– A ECONOMICAL ASSESSMENT

by

Yuming Chen

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ABSTRACT

A NEW PARADIGM OF MAXIMIZING THE WIND AND SOLAR PENETRATION– A ECONOMICAL ASSESSMENT

by

Yuming Chen

The University of Wisconsin-Milwaukee, 2016
Under the Supervision of Professor David C. Yu

Wind and solar energies are the most potential and widely-used renewable energies. But in most cases these energies cannot be maximized because of transmission line capacity and their remote location. Therefore, this thesis proposes a new paradigm which using battery transportation and logistics instead of transmission line, to maximize wind and solar energies. The main focus of this work is to investigate the economical feasibilities of this new paradigm.

In the first part, different models and application are presented. The purpose is finding an appropriate model which can make full use of existing grid resources such as transmission line and power distribution network.

In the second part, total costing of this new paradigm and details are listed. Different parts of cost are analyzed, such as costing of construction of wind farm, costing of battery and costing of transportation. Then, the tendency of all parts of costing with years is introduced based on the information from internet news, company files and organization forecasting.

In the third part, key parameters which infect costing most are listed, some assuming are presented for forecasting. Then, cost of this new paradigm is compared to traditional way. The trend line of the traditional way and the trend line of the new paradigm will cross over based on the projection.

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I. BACKGROUND

Nowadays, with the aggravation of environmental pollution and the lack of energy resources, renewable energy such as wind and solar is more and more widely used in last decades. Wind produced over 190 million MWh in U.S. in 2015, enough electric for about 17.5 million typical U.S. homes. China is close behind the U.S. at 185.1 million MWh. [1] But in another way, large amount of wind power has to be curtailed or wasted because of verity reasons. First, the majority of transmission lines do not have enough capacity to transmit the wind power that turbine generated. So gird has to cut off the power when power reach the limitation of capacity. Second, wind power is a fluctuant and random power than thermal power. In winter, generator unit take charge not only generate electricity but also generate heat, so system peaking regulation is a hard mission. Wind farms commissioning will deteriorate the regional power load characteristics and will put forward higher requirement on system peak regulation capacity. In most cases, system can not satisfy this requirement, the only thing it can do is curtail wind power. Actually, wind curtailment has become the crucial issue for the development of wind renewable energy. In 2014, annual wind curtailment rate in China is around 18% and the rate is even close to 40% in Gansu, Xinjiang and Jilin. [2] For wind farm operators, not only they can not obtain any profit from curtailed wind energy, but also pay maintain cost for operating the wind turbines. For customs, they would pay more for electricity because wind farm would transfer cost of wind curtailment to retail electricity price. For environment, people do not maximize the wind power, causing more wasting and pollution.

II. SOLUTION STATEMENT

A. Current solution

To solve the problem of wind curtailment, many methods are adopted.

The first method is construct fossil power plant near the wind farm. The purpose is solving the fluctuation and randomness of wind power through adjusting generated energy of heat-engine plant. But in this way, the advantage of renewable energy is gone. Heat-engine means pollution, and there is more pollution because heat-engine has to adjust output without a break.

The second method is using ESS (Energy Storage system) to store curtailed wind power such as battery, flywheel and compressing air. Converting electric energy to static energy in air or kinetic energy in flywheel. It is environment friendly and easy to realize. But the disadvantage is also obviously, air would leak with high speed not matter how you seal the unit. That means you can only store the energy for a short time, so does flywheel. And the cost of compressing air equipment and battery storage system is pricey.

B. A new solution based on battery

In this situation, a new paradigm is needed, which can maximize wind power, do not cause pollution and can store energy for a long time. Battery is one of the best solution. Not like transmission line capacity is limited by fluctuant load, battery itself is a load. That means there are no limitation if enough battery is waiting for charging, no wind energy is curtailed or wasted. So a new paradigm is presented. In this new paradigm, wind farm stores curtailed energy to batteries through charging station which near the wind farm, then using railway and roadway to transport batteries to different stations in cities. Customs can get battery in station by themselves, or battery would be delivered to customs' house. Empty battery would be transmitted back to wind farm, forming a loop. For electric vehicle users, they can swap battery in station instead of charge their battery. It can save a lot of time and reduce the cost of charging station.

There are two key points in this new paradigm. First is how many applications and models does it has, then finding one or two the most doable application from all of them. Secondly, is this paradigm feasible in economic aspect? After all, buying batteries and transportation cost may be a huge expenditure. Then, if the cost of this paradigm is more expansive than traditional way now, whether is it possible that the cost will reduce to the same level of traditional way after several years. Besides customers, profits of wind farm and company in charge transportation are also important measures of economic feasibility. Only when customers, wind farms and company all get benefits, this new paradigm can begin commercial operations.

III. ANALYSIS OF OPTIONS

This new paradigm can be applied to different situations. It can work independently or cooperate with power grid. Three different options of this new paradigm are listed below and analyzed.

A. Wind farms without transmission line connections

Many potential locations which have rich wind power are abandoned because it is too far away to build high-voltage transmission lines. Even it is possible to build transmission lines, the cost is so huge that grid prefer to abandoned the wind farm. But with the help of new paradigm, battery and railway can make it come true.

In this option, wind farm transmits all their electricity through battery and railway instead of only curtailed electricity.

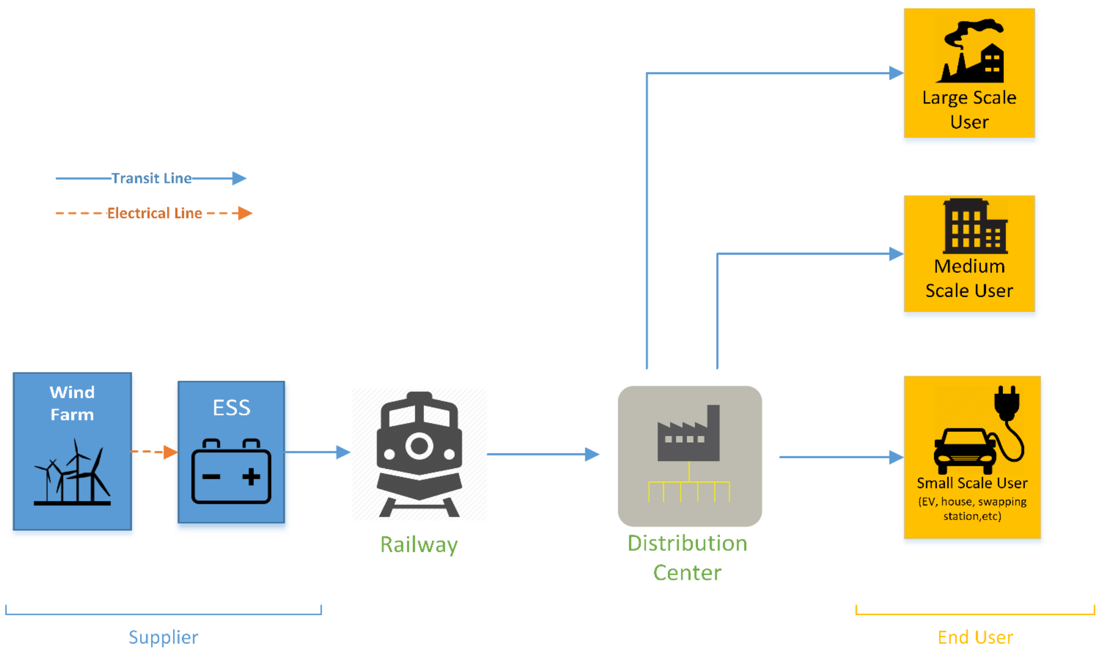

Figure III.1 Option 1 of New Paradigm

Choosing this option, wind farms can make full use of wind power and transfer more power to load from remote location. But to get this goal, a long distance railway track need be constructed. Although cost of railway is lower than cost of extreme high-voltage transmission line or DC transmission line, it also a big investment.

B.   Wind farms with transmission access

Wind curtailment is common to see in most of existing wind farms. Due to the long distance and limitation of transmission line capacity, about 18% of wind power have been curtailed in China. Some wind farms even have to curtail 40% of wind power. Compared with zero profits of wind curtailment, wind farm is willing to sell this part of curtailed electricity to anyone, even in lower price. That is option B, wind farm with transmission access.

Some electricity will be transferred to grid through transmission line, another one will charge batteries and transferred to customs through railway.

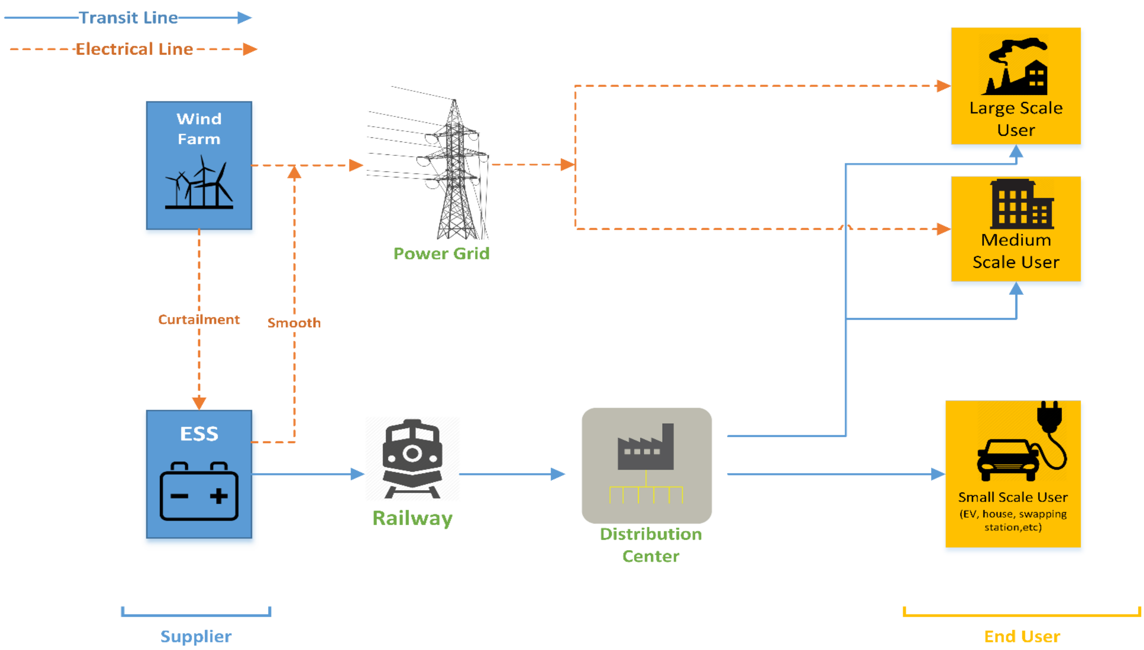

Figure III.2 Option 1 of New Paradigm

For wind farms, this option can help them rise profits from curtailed wind power. It can also lower investment because it takes advantage of existing transmission line. For power grid can also get benefits from this method. Battery can release or absorb energy, so power grid can transmit smoothed energy from wind farm. For users, they have more choice for electricity.

C. ESS with mid-voltage transmission line

Same with option A, only adding a med-voltage transmission line between wind farms and charging station. It is difficult to build charging stations in every wind farms when there are many small farms in a big area because of high-cost. So using mid-voltage or high voltage transmission lines transfer electricity from each farms to a near by railroad hub with a large charging station is a better choice. Cost of mid-voltage transmission line is much lower than ultra high-voltage transmission line or track for railway.

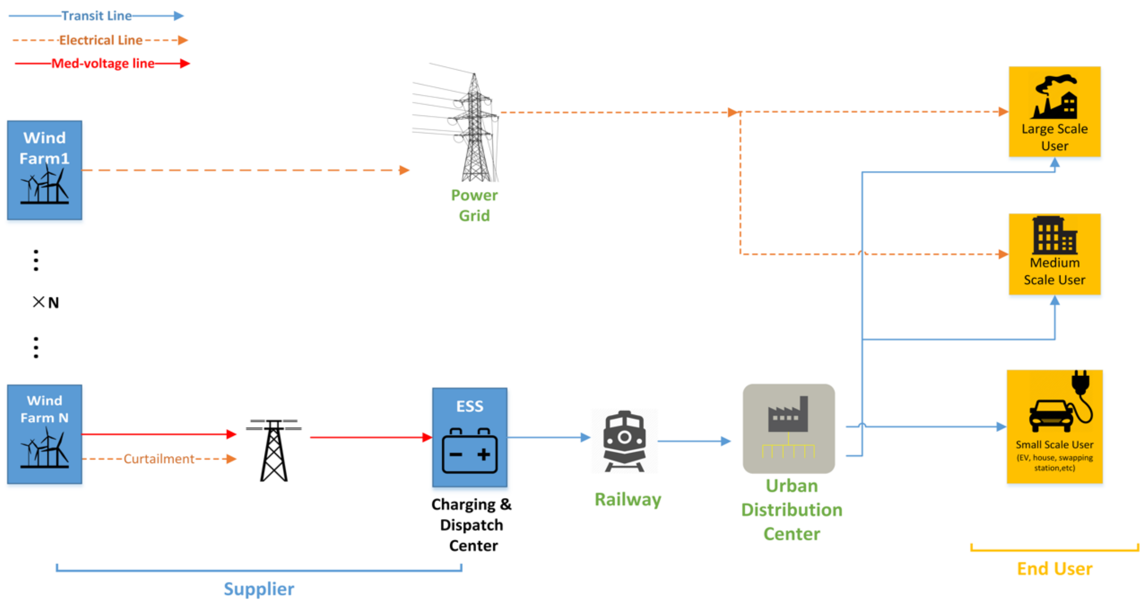

Figure III.3 Option 3 of New Paradigm

If there are a large amount of wind turbines in one huge wind farm, this option may be the best choice. Using mid-voltage transmission line, wind farm can only construct one charging station which connect all turbines with transmission lines instead of construct charging stations for each turbine. Cost of charging stations can be saved, transportation networks can also be simplified because of less charging stations.

This chapter only listed 3 options, but in fact, there are still many other options and applications. One advantage of this new paradigm is it has a wide accommodation and can cooperate with various existing systems.

IV. ECONOMIC STUDY

4.1. Introduction

The key point to decide if this new paradigm could success or not is the cost. And whether this cost is acceptable is decided by customs. So this study chooses retail price for customs as the standard, the unit is dollar per kWh.

In total, the cost can be divided to 3 parts. First is the cost of wind farm. No matter whether buying electricity from wind farms, or construct a new wind farm, part 1 can reflect the cost of them. Second is the cost of battery. It is including acquisition cost, maintain cost and recycle cost. Third is the cost of transportation. Railway or roadway are needed between charging station and city.

In this chapter, three constituent parts of total cost would be put forward and analyzed. Then an equation about how to calculate the cost of each part would be obtained. Finally, an equation of total cost would be obtained. Total cost can be calculated by using this equation when all parameters are known.

4.2. Wind Farm(C1)

Cost of wind farm includes construction cost, maintain cost, inverters cost and charging station cost. Cost of construction depends on the capacity of wind farm. And cost of maintain depends on electric energy which turbine generated. Cost of typical farm and forecast in China is shown in the chart. [3]

Cost of typical wind farm in China

		2010	2020	2030	2050
Construction Cost ($/kW)	Land	1307	1154	1107	1076
	Offshore	2461	2153	1846	1538
Maintain Cost ($/kWh)	Land	0.0153	0.0153	0.0153	0.0153
	Offshore	0.0231	0.0231	0.0153	0.0153

Table IV.1 Construction and Maintain Cost of Typical Wind Farm in China

Cost of offshore farm is much higher than farm on land. For construction cost, it reduces about 1% per year. For maintain cost, hardware cost would reduce with time, but labor cost would increase. So maintain cost is unchanged in total. [3]

At option 3, construction cost of mid-voltage transmission line between wind farm and charging station also need be concerned. Constructing a 110kV transmission line cost about $160000 per kilometer. [4]

For inverters in charging station, the cost is about $30 per kW. And cost of construction of charging station depends on the capacity, it is about $0.2 per kWh. [5]

If assuming that the quantity of turbines in a wind farm is m and the total capacity of this wind farm is N_1 kW. The average running hours at full load is t_1 hour per day. The life span of each turbine is 25 years. The construction cost of wind farm is C_{con} dollars per kW.

The maintain cost of wind farm is \$0.0153/kWh. If med-voltage transmission line was applied, assuming that the distance between wind farm and charging station is x_1 kilometers.

So we can get the cost of every kWh this wind farm generated in its whole life time. And the whole life time means 25 years. So we can share the total cost, which including construction cost and maintain cost for 25 years, to each kilowatt hours that this wind farm generated in those years.

$$C_1 = \frac{N_1 \times C_{con} + N_1 \times 30 + N_1 \times t_1 \times 0.2 + 160000 \times x_1}{25 \times 365 \times N_1 \times t_1} + 0.0153 \quad (\$/\text{kWh})$$

4.3. Battery(C2)

Choosing 85kWh Li-ion battery in Tesla Model S electric car and LFP (Lithium Iron Phosphate) battery as examples.

According to the published data of 18650 Li-ion battery that Tesla used, it has at least 500 cycle life (capacity reduces to 80%). [6] In most cases, the cycle life is longer. Theoretical cycle life is 1000, so choosing 750 as the average cycle life of Li-ion battery when calculating. For BYD LFP battery, the cycle life is at least 2000. So choosing 2500 as the average cycle life of LFP battery. [7-8]

These two types of battery also have different price. From the data in 2015, the price of Tesla Li-ion battery is \$193/kWh. And for BYD LFP battery, it is \$300/kWh. [9]

When calculating the cost of battery per kWh in the whole cycle life, both purchase cost of battery and cycle life cause significant impact. For example, the Tesla 85kWh battery has about 750 cycle life, so it is reasonable to think that this battery can support 63750kWh in its whole life (85x750). Assuming that the battery price is \$ P /kWh and the cycle life of battery is L . According to the thinking mentioned before, the cost of every kWh in the whole life time of battery can be calculated.

$$C_2 = \frac{P}{L} \quad (\$/kWh)$$

4.4. Transportation(C3)

The cost of transportation depends on the weight of battery, distance and type of transportation. Different kinds of battery have different energy density, causing differences in weight. Increasing distance would increase cost significantly. Freight rate by Railway and roadway are also different.

Assuming that the energy density of battery is D Wh/kg, and the distance between charging station and city is x_2 kilometers.

A. For roadway

There are many roadway transport company, the one selected in this study is \$0.1/ton/kilometer. [10]

So the cost of transportation can be calculated.

$$C_3 = \frac{0.1 \times x_2}{D} \quad (\$/kWh)$$

The advantage of roadway is flexibility. Trunks and vans can reach almost everywhere, they are not limited by landform and railway track. But its cost is more expansive than the cost when using railway.

b. For railway

The National Ministry of Railway is the only choice in China, and the price can be found in official website. When transporting 100 tons Li-ion battery, the relation of cost and distance is shown in the figure. All cost includes terminal handing charge at railway station. [11]

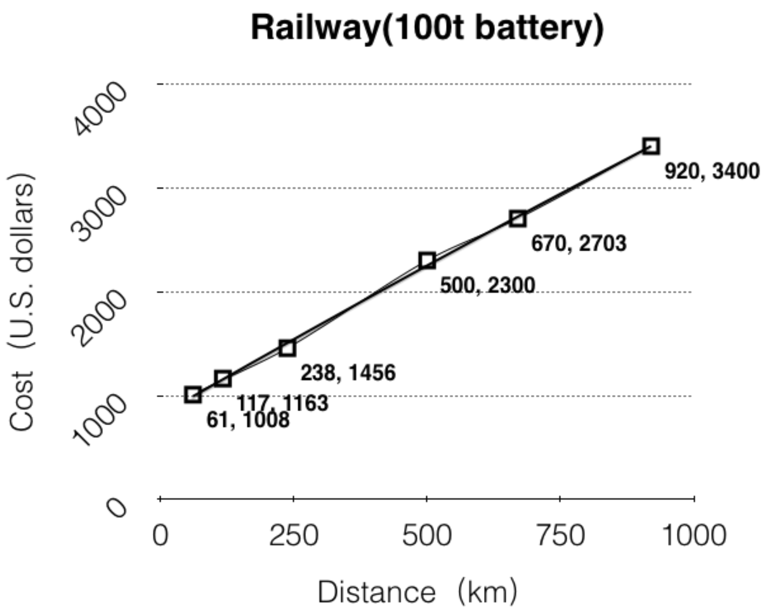

Figure IV.1 Transportation Cost of Railway

From the figure, it is not hard to see that the cost and distance have approximated linear relation. Using the fitting formula to verify it.

$$y = -0.0002 \times x_2^2 + 2.9574 \times x_2 + 812.05$$

According to the fitting formula of y(cost) and x(distance), the quadratic term is so small that can be ignored. So the relation between cost and distance can similarly be seen as a linear relation.

$$y = 2.9574 \times x_2 + 812.05$$

Follow the calculation method of roadway, the cost of railway can be obtained. 100000 in denominator means 100 ton.

$$C_3 = \frac{2.9574 \times x_2 + 812.05}{100000 \times D} \quad (\$/kWh)$$

One of the advantages of railway over the roadway is cost. And train can also load more batteries than trunk. But the disadvantages are also obvious, transportation route is limited by track, transit time is restricted to schedule of time table.

4.5. Total Cost(C)

Cost of wind farm, battery and transportation make up the total cost, so the total cost of electricity($/kWh) can be calculated by adding these three parts together.

$$C = C_1 + C_2 + C_3$$

$$= \frac{N_1 \times C_{con} + N_1 \times 30 + N_1 \times t_1 \times 0.2 + 160000 \times x_1}{25 \times 365 \times N_1 \times t_1} + 0.0153$$

$$+ \frac{P}{L} + \begin{cases} \frac{0.1 \times x_2}{D} (Roadway) \\ \frac{2.9574 \times x_2 + 812.05}{100000 \times D} (Railway) \end{cases} \quad (\$/\text{kWh})$$

N_1 : the total capacity of wind farm (kW)

t_1 : average running hours at full load (hours/day)

x_1 : the distance between wind farm and charging station (kilometers)

C_{con} : the unit construction cost of wind farm (dollars/kW)

P : the retail price of battery (dollars/kWh)

L : the cycle life of battery (times)

x_2 : the distance between charging station and city (kilometers)

D : the energy density of battery (Wh/kg)

According to this equation, the approximant cost of electricity per kWh can be calculated. Some factors such as the battery recovery price are not considered because they are hard to obtain or lack of accuracy. Some are estimated values. For example, the life time of wind turbines are 25 years, but when calculating the the cost per kWh, the life times of mid-voltage transmission line and charging station are also regarded as 25 years. In fact, they may be in service for more years.

V. COST ANALYSIS

5.1. Introduction

Unlike the yearly increased grid retail price of electricity, retail price of this new method would decrease because it is based on renewable energy and battery instead of fossil fuel. Shortage of fossil fuel increase the generating cost. But wind energy is total free and the price of battery is decreasing because of gradually mature technology and research of new types of battery. It is true that the total cost of this new method is currently much higher than conventional method. But as time goes by, its cost would be lower than traditional cost.

In this chapter, several key comparisons of retail price of traditional method and new method would be made under various assumptions.

5.2. Trend Lines

A. Wind farm

As mentioned in 4.2, the construction cost of wind farm reduces about 1% per year until 2020. After that, the rate of decrease becomes slower. For maintain cost, hardware cost would reduce with time, but labor cost would increase. So maintain cost is unchanged in total.

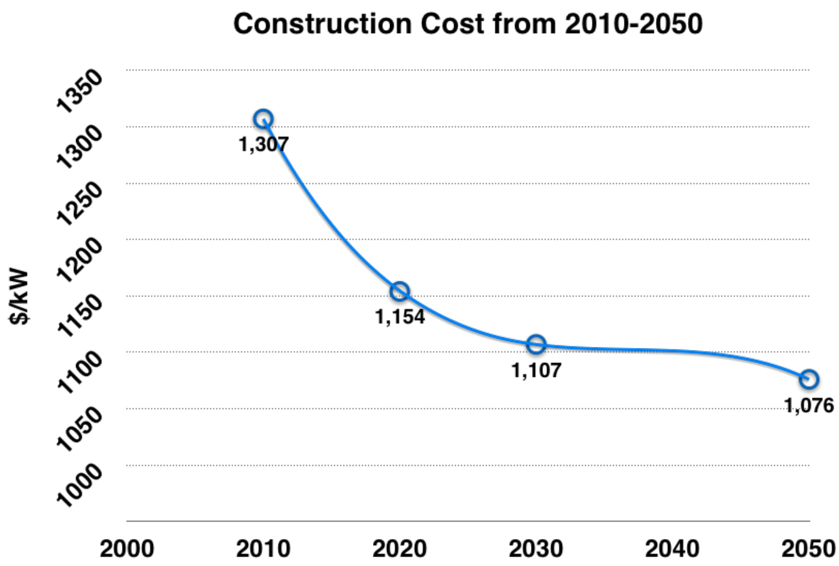

Figure V.1 Construction Cost of Wind Farm

For the cost of transmission line, the rate of decrease is too slow to consider. The construction cost of charging station only shares a small part of cost of wind farm, so it can be ignored. And the cost of inverters will reduce 9% per year until 2018.

B. Battery

At Avicenne APEC 2013, experts gave a forecasting of Li-ion battery cost in 2015 and 2020. They think the price of Li-ion battery would decrease 7% per year, and it would be $268/kWh in 2015 and $193/kWh in 2020. Positive materials and negative materials of battery are the most expansive parts in Li-ion battery. Price dropping of battery [12-13]

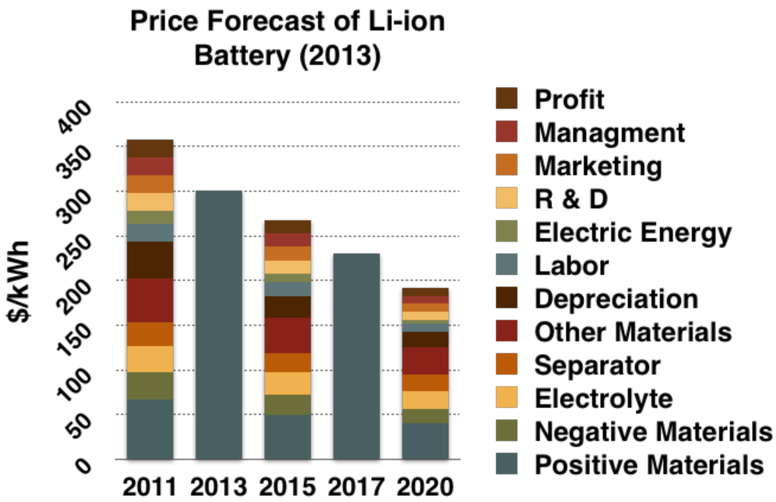

Figure V.2 Price Forecast of Li-ion Battery

Developing speed of industrial product is much faster than forecasting. Li-ion battery, as one of the core technology of electro-vehicle, is investigated for reach lower cost and higher power. For example, Tesla has already achieved the goal of cost forecasting of 2020 in 2015. Using the equation in 4.3, the cost of battery per kWh in its whole cycle life can be calculated. In this calculation, it is assumed that the cycle life for Li-ion battery and LFP are 750 and 2500, respectively.

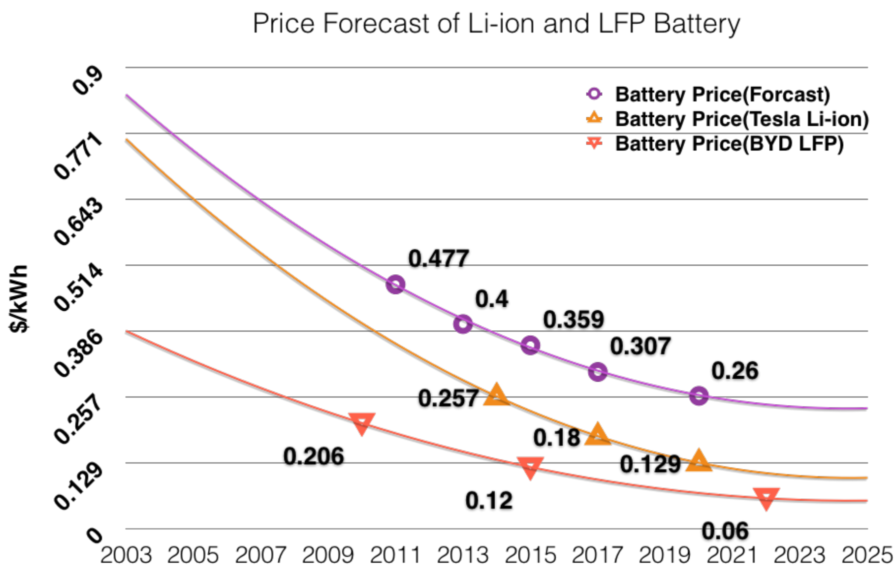

Figure V.3 Price Forecast of Li-ion and LFP Battery

We can get some results from this figure. First, price of Tesla Li-ion battery is lower than experts' forecast because of the development of Tesla battery factory. Costumers can use cheap battery earlier than they thought. Second, price of BYD LFP battery is lower than Tesla's because LFP battery has longer cycle life. Although LFP battery has price advantage, lower energy density may increase the cost of transportation, that is what I would analyze in next part.

C. Retail price of electricity in Power Grid

For power grid, generating cost increases every year because fossil fuel is becoming more expansive. Factoring in the increasing profit, the retail price would also increase. [14-16]

Table V.1 Purchase Price, Retail Price and Profit in China and U.S.

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
China Grid Purchase Price	0.0425	0.0444	0.0475	0.0497	0.0511	0.0542	0.057	0.0581	0.062	0.064	0.0667	0.0652
China Retail Price	0.068	0.0716	0.0758	0.078	0.0803	0.0817	0.083	0.0891	0.0911	0.0950	0.0993	0.1011
Profit	0.0051	0.0054	0.0056	0.0056	0.0058	0.0055	0.0052	0.0062	0.0058	0.0062	0.0065	0.0071
U.S. Retail Price		0.0895	0.0945	0.1040	0.1065	0.1126	0.1151	0.1154	0.1172	0.1188	0.1213	0.1252

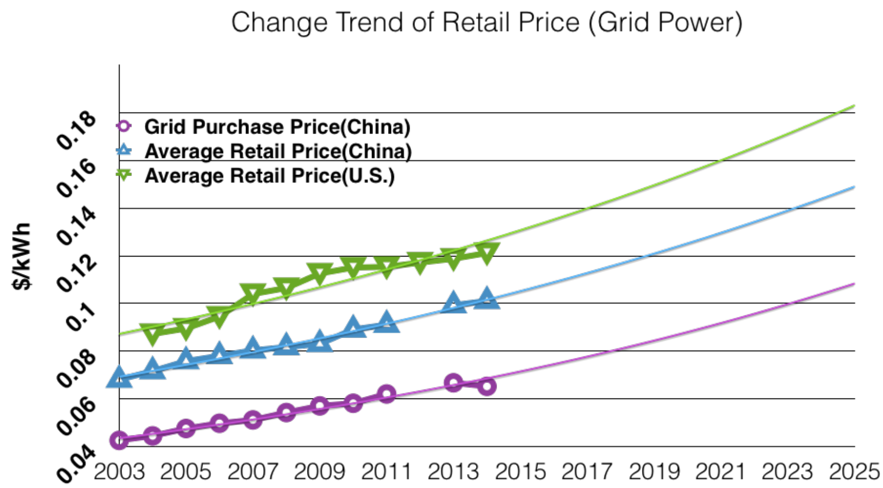

Figure V.4 Change Trend of Grid Power Retail Price

No matter in China or in U.S., the retail price increases every year since 2003, and it is reasonable to believe that this trend would not stop and the price would be higher in the future.

5.3. Comparison of Retail Price

Using the equation of calculating total cost in 4.5, adding the cost of wind farm, battery and transportation, to calculate the cost. Then factoring in profit, a retail price of electricity in this new method can be estimated.

Assuming that the distance between charging station and city is 500 kilometers, and the distance between wind farm and charging station is 10 kilometers. Average running hours at full load is 5 hours per day. Total capacity of wind farm is 1.5MW. Construction cost, price of Li-ion battery and price of LFP battery can be obtained by figures listed before. Energy density of Li-ion is 225Wh/kg and that of LFP is 130Wh/kg. Cycle life of Li-ion is 750 and that of LFP is 2500. Also assuming that the profit of new method is same as the profit of grid power.

After these assumption, every parameter that be needed to calculate total cost is known. The results are shown in figure. [9]

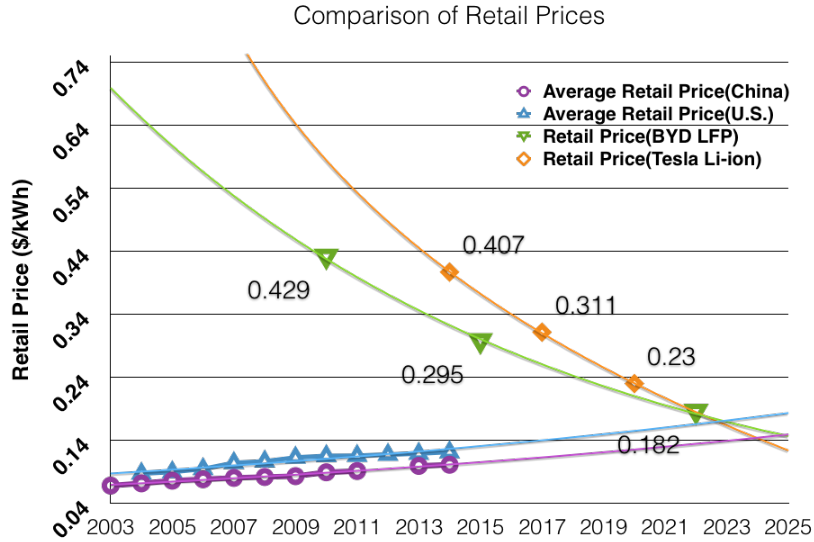

Figure V.5 Comparison of Retail Price

Knowing the total cost of new paradigm based on battery and logistics, retail price can be got when consider profit of wind farm and logistics company, which is 0.01 dollars per kWh. This profit is same with the profit of power grid. Some information can be got from the figure and trend lines. First, retail price of LFP battery is lower than Li-ion battery because of its longer cycle life. Although lower energy density of LFP causes more cost when transporting, cost of transportation does not share a big part of total cost. With time goes by, price advantage of LFP battery would shrink. Second, the retail price when using battery is much higher than electricity retail price nowadays, but after 8 to 10 years, they would be equal. After that, price advantage of new method would appear.

5.4. Prediction of Key Parameters

Although there are many parameters when calculating the total cost and retail price, only a few parameters are crucial and can affect the cost significantly. The share of different parts can be calculated under assumed conditions in 5.3.

Total Cost Analyze ($/kWh)

	C1 Wind farm					C2 Battery	C3 Transportation
% of total cost	10.8%					64.3%	24.9%
	farm construction	maintain	transmission line	inverters	station construction	1.battery type 2.price 3.cycle life	1.transportation type 2.energy density 3.distance
% of total cost	6.59%	3.52%	0.54%	0.15%	0%		
relevant parameters	1.construction cost 2.average running hours	unchanged	1.distance 2.average running hours 3.capacity 4.construction	1.inverter price 2.average running hours	1.station cost		

Table V.1 Total Cost Analyses of New Paradigm

According to this chart, cost of battery and transportation share about 90% of total cost. So key parameters can be found in these 2 parts of cost.

The cost of battery depends on battery type, and different types of battery determines the price and cycle life. Li-ion battery has enormous potential and more researchers are studying in Li-ion battery instead of LFP battery. So this study only analyzes key parameters when applying Li-ion battery. In this precondition, key parameters are battery price and cycle life.

The cost of transportation depends on distance, transportation type and energy density of battery. As it mentioned in 4.4, railway is a better way for long distance transport with heavy load, so this study only analyzes key parameters in using railway to transport the ESS. Energy density of Li-ion battery was increasing with a very slow speed in the past several years, and it close to theoretical energy density of Li-ion battery. Unless there is a new type of Li-ion battery or huge breakthroughs, energy density can be regarded as constant. So key parameters of transportation are distance between charging station and city.

A. Battery price

Just as the battery industry did not predict that Tesla would reduce the price of Li-ion battery to under \$200/kWh in 2015, five years earlier than initially expected, Battery industry may still underestimate the continuing development of battery advancement. Assuming that the battery cost reduces by 50% again in the forecasting cost, a revised retail price trend can be obtained in Figure V.6.

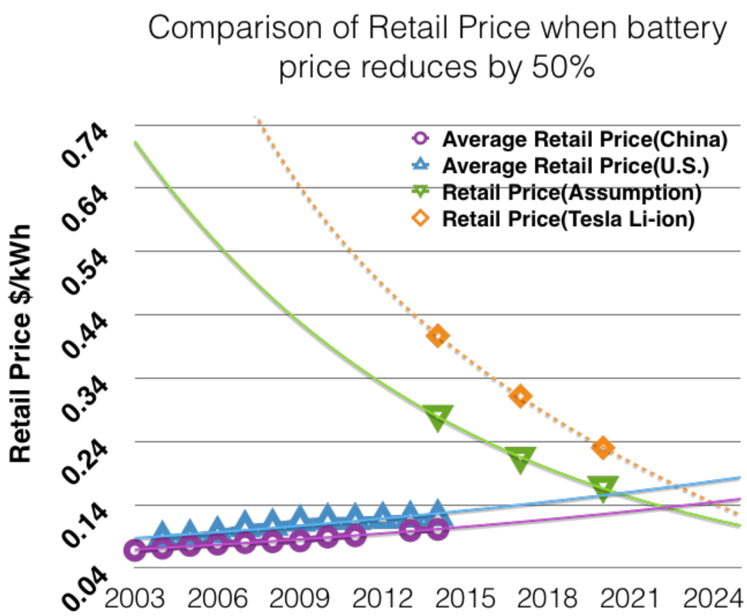

Figure V.6 Comparison of Retail Price when Battery Price Reduces by 50%

The cost of battery shares more than 60% of total cost, so reducing battery price would reduce retail price significantly. The retail price of traditional method and the one of new method would be equal in 2021, 2 or 3 years earlier than forecast.

B. Cycle life

When calculating total cost, we choosing 750 as cycle life. The theoretical cycle life of Li-ion battery is 1000 and it may be increase with the development of battery technology. It is reasonable to assuming that the cycle life is 1000. Figure as follows.

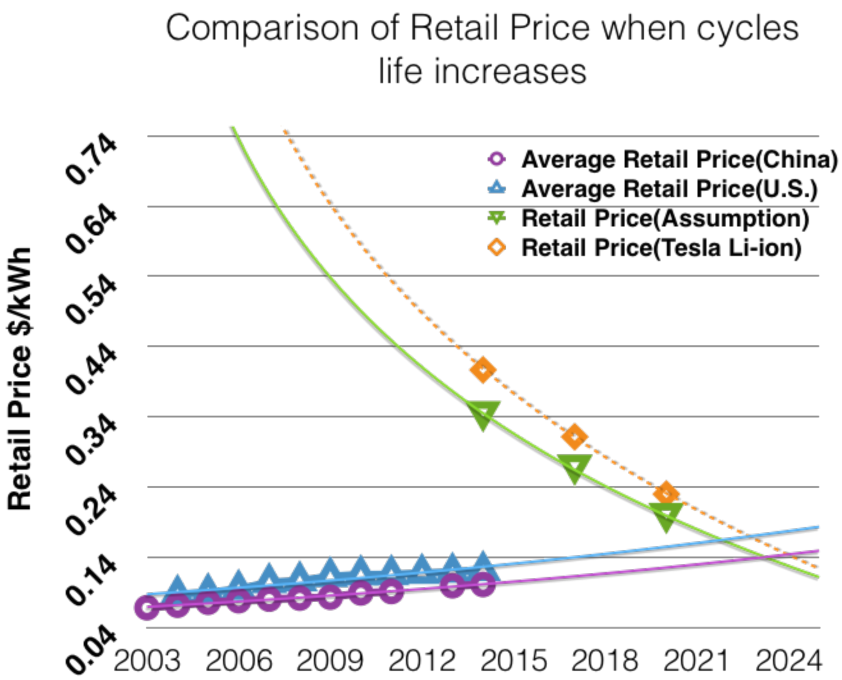

Figure V.7 Comparison of Retail Price when Cycles Life Increase to 1000

Increasing cycle life can also reduce retail price obviously.

C. Distance

Distance between charging station and city is the third key parameter. If distance was not 500 kilometers which I assumed before, how the price should change? The closer distance between charging station and city are, the lower cost of transportation is. The distance between charging station and city is regarded as 500 kilometers in earlier calculations because the distance between many existing wind farm and load center is around 500 kilometers. But in fact, there are still plenty of wind farm very far from city or so close to city. It is necessary to analyze different retail price under different distance. Assuming that there are several wind farms which are 100, 300, 500, 1000 and 1500 kilometers from city. Figure as follows, different lines represent retail price with different distances.

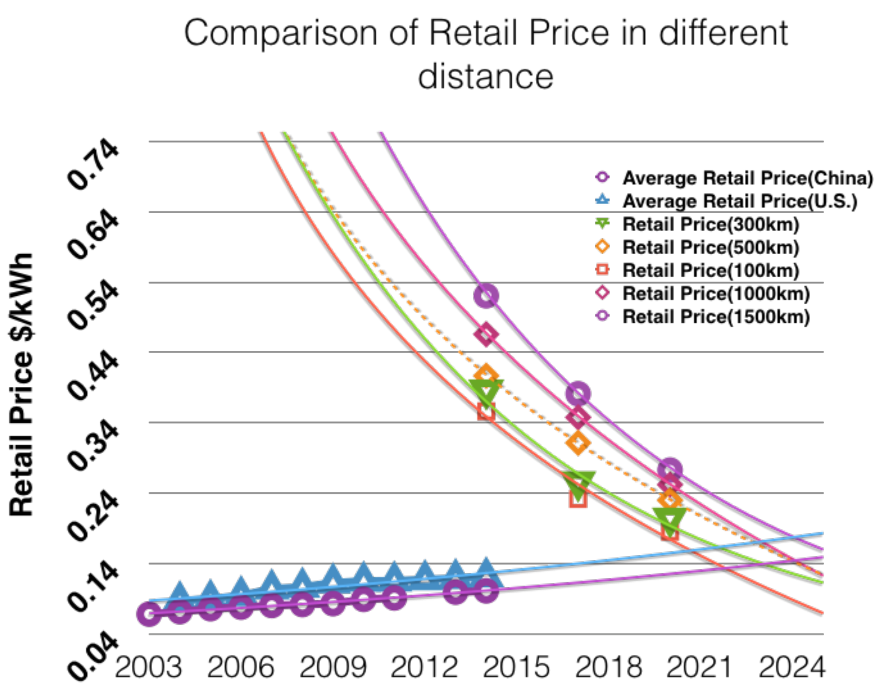

Figure V.8 Comparison of Retail Price in Different Distance

Trying to choice a wind farm which close to city is an effective way to reduce retail price. But it is also acceptable that choosing remote wind farm because the effect of distance is weaker than cycle life and battery price.

According to those figures above, a conclusion can be drawn that changing key parameters would change retail price obviously. So these key parameters should be given priority to consider when adopting this new method.

VI. CASE STUDY

6.1. Introduction

Whether or not this new method can be successful not only depends on the retail price for customers, but also depends on the profits of wind farm and company in charge of transportation.

From previous chapters, it can be seen that the retail price of traditional method and the proposed method would be equal after several years, meaning customers can use cheaper electricity in the near future. This chapter would try to analyze the profits of wind farm and transport company from a case study.

6.2. Wind Curtailment Case

As it mentioned before, wind curtailment is a serious problem in many countries, especially in China. In 2014, annual wind curtailment rate in China is around 18% and the rate is even close to 40% in Gansu, Xinjiang and Jilin. Through this new method, curtailed wind energy can be charged into battery and shipped out. Wind farms can gain profits from curtailed energy .

Wind farms which has wind curtailment problem usually not too far from city. So assuming the distance between charging station and city is 500km, and other parameters are all same with the assumed parameters in 5.3. Also assuming that the curtailment rate is 20%, meaning wind farms used to waste 20% of energy they generated.

Wind farms could not make a profit from curtailed wind energy in the past, but now they can profit from it. So assuming that transport company purchase with 25% of original price. In these situation, several figures can be obtained.

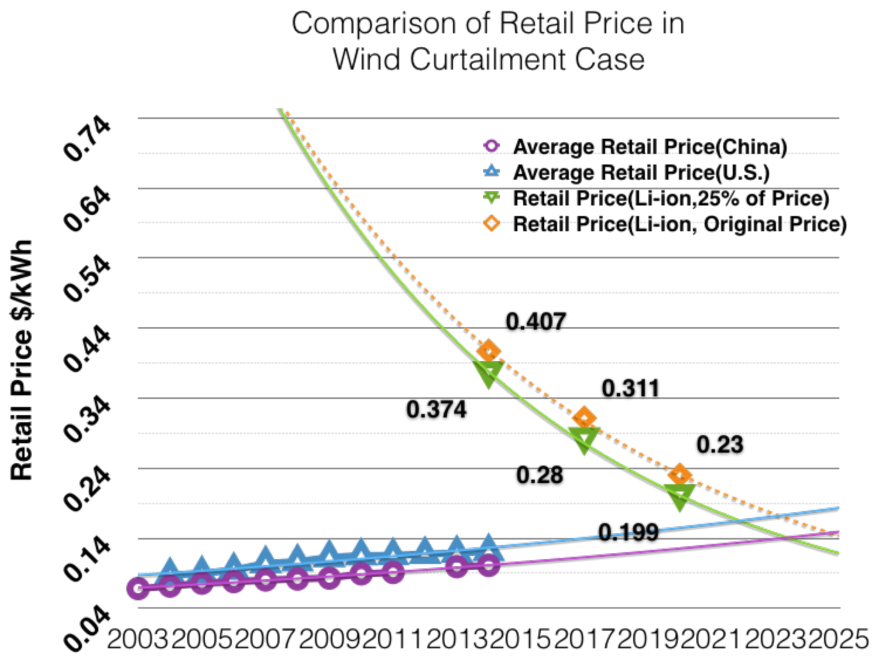

Figure VI.1 Comparison of Retail Price in Wind Curtailment Case

For customers, retail price would reduce because transport company purchase electricity from wind farm at the lower price.

In 2014, China Grid purchase price is \$0.0652/kWh, and cost of wind farm is about \$0.04322/kWh. Concerned about other output such as labor, it is reasonable that assuming the profit of wind farm is $0.01/kWh. When purchase curtailed energy with 25% of original price, which is $0.011/kWh, figure of comparison of wind farm profit can be drawn.

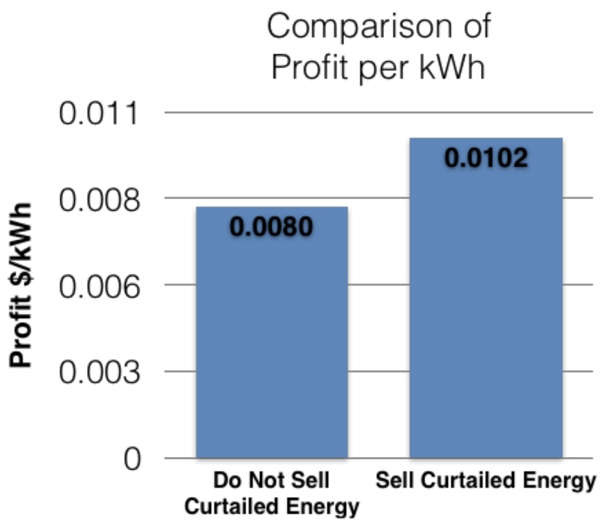

Figure VI.2 Comparison of Profit per kWh of Wind Farm

According to this figure, wind farm can earn 0.0022 dollars per kilowatt-hours. The profit of wind farm would raise 27.5%. For wind farms with higher curtailment rate, if they also sell their curtailed energy, the profit would much more than this case. For transport company, since it purchases electricity with price that is lower than 25% of original price, its profit will be even more.

In addition, power grid in China is trying to reduce purchase price from wind farm for more profit and promoting wind power technology development. But many wind farms can not survive with lower wind energy purchasing price. A figure of comparison between profit of selling electricity to transport company with 25% of original price and profit of selling electricity to grid power is shown in Figure VI.3. [17]

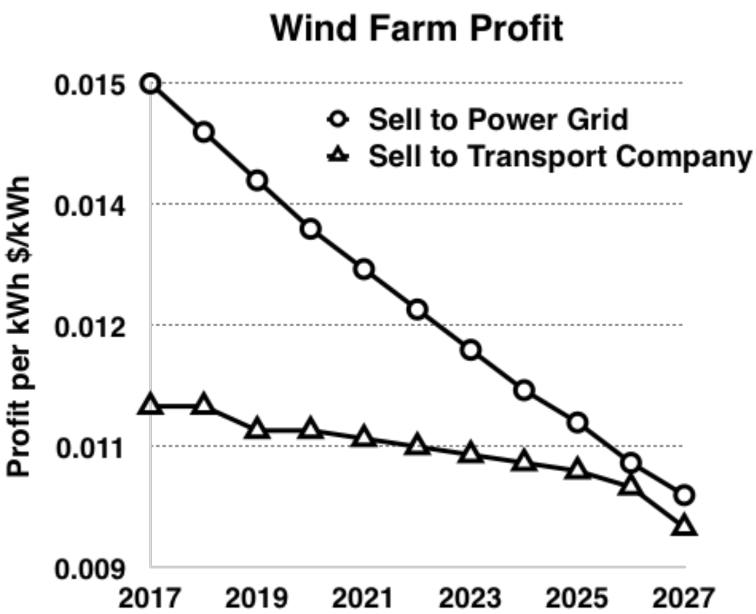

Figure VI.3 Comparison of Wind Farm Profit when Selling to Different Company

Initially, the profit of selling curtailed energy to transport company is lower than the profit when selling to power grid. But as time goes by, selling to transport company would result in more profit because it drops more gently. If power grid continues to reduce purchase price, wind farms may choosing sell all electricity they generated to transport company instead of only curtailed energy in the future.

On account of the retail price of new method is still higher than grid power retail price even through purchasing curtailed electricity with lower price, signing long-term contracts with customers is a better way for both users and company.

Signing a long-term contract with a constant price which is a little higher than grid power retail price, customers may spend more money at the beginning. But as time goes by, grid power retail price increase very quickly, customers would start to cost less so soon. For a long term, users can save money. For transport company, signing a contract can help minimizing losses and increase its credit. Although company would loss in the beginning because it sells electricity to users with a price below cost, as time goes by, cost would decrease and company would start to earn.

Assuming that company signs a 10-years contract with customers and company purchase with 25% of original price. Figures of price spread and profit of company can be drawn.

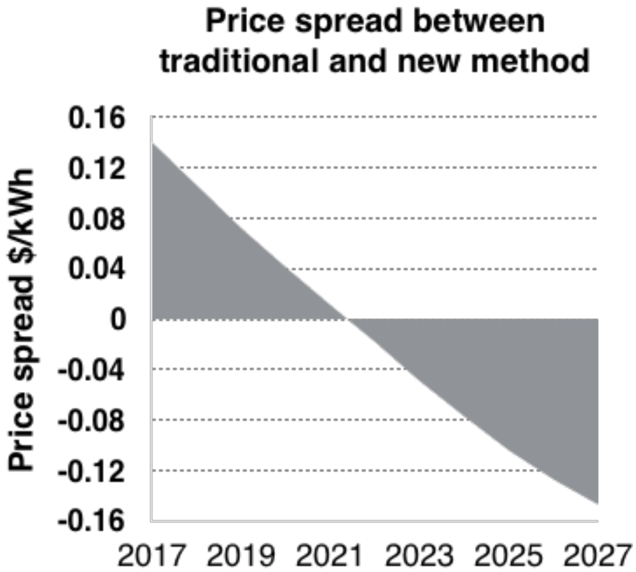

Figure VI.4 Price Spread between Traditional and New Method

Price spread is retail price of new method subtracts power grid retail price. The former is higher than the latter until 2021, after that the former would have widening price advantage. According to this figure, area means total price spread during this time, so customers would start to enjoy lower retail price after 2021 and save money after 2025.

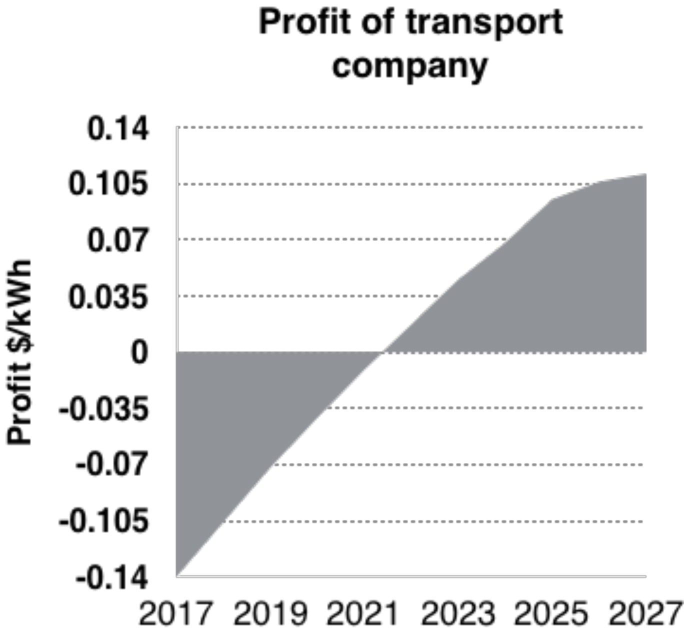

Figure VI.5 Profit of Transport Company

For transport company, it losses until 2021, after that it start to earn profit from every kilowatt-hours. After 2025, principal would be returned.

Based on this case study, transport company and customers get benefits in a long term although they need face situations of higher retail price and losses in the beginning. And for wind farm, it can increase profit immediately.

VII. CONCLUSION

This new paradigm based on battery transportation and logistics is an innovative and efficient method with numerous advantages. It solves problems like wind curtailment and waste of wind energy. It is environmental friendly and avoids high investment of transmission lines. This paradigm also has many options and models. That means it can be applied to different situations. The cost of battery is the main reason of high retail price. But as time goes by, cost of battery would drop so quickly because of the development of battery technology. According to the comparison with power grid retail price and its change trend, retail price based on battery and logistics is higher than retail price based on power grid nowadays. After several years, which mainly depends on trend lines of key parameters mentioned before, retail prices would be equal. In the future, retail price based on battery and logistics would be lower than retail price based on power grid. With the development of technology, the cost of new paradigm may be acceptable faster than we expected. According to the case study, not only customers, but also wind farm and transport company can get benefits from this paradigm.

Although this study only conducts some preliminary analyses and prediction, the results are encouraging. Economical studies of wind farms with curtailment are also conducted. The results indicate that more wind farms would like to cooperate with company which is willing to purchase curtailed energy. Customers would accept this new electric power supply method because of its price. More companies and people would like to be involved in this business for its profit and potential.

It is believed that this paradigm would be a breakthrough for both environment and economy and it is worthy of further investigation.

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