MÄLARDALENS HÖGSKOLA
ESKILSTUNA VÄSTERÅS

EXPLORING MARKET FORCES FOR TRANSMISSION EXPANSION AND GRID STORAGE INTEGRATION

A technical-economic thesis about variation moderators for intermittent renewable power generation in the developed country of Sweden and the developing country of China

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ABSTRACT

Intermittent renewable power generation increases globally. In Sweden, installed wind power capacity has increased most of all electricity sources the last few years and China is today the world's largest wind power producer. This on-going development increases the demand of flexible regulating measures to reduce wind curtailment and secure a reliable electricity supply. Two technical solutions that can provide such flexibility is transmission expansion and integration of grid battery storage. The transmission grid can transmit energy geographically, while grid storages have the potential to store energy over time to provide energy output when necessary.

This master thesis examines market forces for transmission and grid storage development as variation moderators in a power system containing an increasing share of intermittent renewable power generation. Two countries with diverse market conditions are studied; a developed country as Sweden and a developing country as China. Since the market for grid battery storage is emerging, potential market entry barriers are investigated. A cost-benefit model has been created to examine which alternative of transmission expansion and lithium-ion battery storage integration is the most cost-effective in a system perspective. Several cases have been studied in the model, including cost reductions of lithium-ion batteries and the impact of wind curtailment.

Based on the results from the cost-benefit model and the market analysis, it can be concluded that cost reductions of lithium-ion batteries are crucial for grid storage market penetration. Another important driving force for future development of grid storage is establishment of a regulatory framework. Furthermore, grid storage is found to be most suitable for peak shaving and transmission deferral applications due to its flexibility. The fact that storage facilities can be realized in a shorter timeframe compared to transmission grid expansion is also an advantage for grid storage development, since problems related to congestion can be reduced earlier. However, uncertainties related to the low market experience of grid battery storage technologies can be in favour for transmission expansion in future investment decisions.

Keywords: *Grid storage, energy storage, lithium-ion battery, transmission grid expansion, variation moderator, variation management, regulating powers, intermittent power generation, market analysis, market entry barriers, cost-benefit model, cost-benefit analysis, driving forces, market drivers, China, Sweden, emerging technology, wind curtailment, congestion.*

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Figure 1: Martin Sundell and Pernilla Eriksson at North China Electric Power University in Beijing, China

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ABBREVIATIONS

Table 1: Abbreviations

ALCC	Annualized Life Cycle Cost
ACBA	Annualized Cost-Benefit Analysis
CAES	Compressed Air Energy Storage
CBA	Cost-Benefit Analysis
CHP	Combined Heat and Power
CNY	Chinese Yuan
CO_2	Carbon dioxide
CS	Consumer Surplus
CSG	China Southern Power Grid
DSM	Demand Side Management
DSO	Distribution System Operator
EU	European Union
GW	Gigawatt
GWh	Gigawatt hours
h	Hours
Hz	Hertz
ICT	Information & Communication Technology
km	Kilometer
kW	Kilowatt
kWh	Kilowatt hours
Li-ion	Lithium-ion
MW	Megawatt
MWh	Megawatt hours
Na-S	Sodium-sulphur
NDRC	National Development and Planning Commission
NEA	National Energy Administration
O&M	Operation & Maintenance
OECD	Organisation for Economic Co-operation and Development
PHS	Pumped hydro systems
RI	Reinvestment
SEK	Swedish Krona
SERC	State Electricity Power Regulatory Commission
SGCC	State Grid Corporation of China
SMES	Superconduction Magnetic Energy Storage
SPC	State Power Corporation
SS	Supplier Surplus
TSO	Transmission System Operator
TW	Terawatt
TWh	Terawatt hours
U.S.	United States
UK	United Kingdom

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1. INTRODUCTION

This chapter intends to give an introduction to the subject of this master thesis. Firstly, a wide background presentation to this thesis is provided. This includes underlying challenges that lays the foundation to this thesis. Thereafter the purpose is clarified, along with research questions and expected contributions of this study.

1.1 Background

Renewable energy sources continue to increase worldwide. Cost-competitiveness is improving as renewable energy sources are promoted by energy policies. Ambitions to intensify low-carbon energy technologies are increasing, both in developed and developing countries. (International Energy Agency, 2014) This leads to challenges in global and country-specific energy markets.

A challenge on the global energy market is the declining nuclear capacity. This trend is acknowledged by the International Energy Agency (2014) as several nuclear plants are ageing or are non-profitable in OECD countries. The International Energy Agency (2014) predicts insufficient global nuclear capacity in 2025, where new reactors are providing a modest capacity increase.

In Sweden, power capacity from the three oldest nuclear power plants must be replaced by other energy sources. Svenska Kraftnät (2014c) does not expect these aging plants to be substituted by new nuclear power plants, resulting in less nuclear power in a near future. This might lead to future power shortage in the Swedish electricity mix, involving congestion and impaired power balance in some regions (Svenska Kraftnät, 2014c).

In order to cover the gap from nuclear power, and at the same time achieve energy and climate targets set by Sweden and the European Union (EU), the share of renewable energy sources in the power system is expected to increase (Svenska Kraftnät, 2014c). The European Commission (2015) includes a target of minimum of 27 percent share of renewable energy consumption by 2030. Sweden alone has set the energy target to 49 percent share of renewable energy already by 2020. This includes a target of reaching 30 TWh from wind power generation by 2020, corresponding to approximately 20 percent of Sweden's total electricity generation. (Swedish Energy Agency, 2011)

Similarly to Sweden, China also faces major challenges regarding the national electricity generation. High level of air pollution, particularly in large cities as Beijing, has led to regulated targets to reduce air pollutions in the fast growing country. (Reuters, 2014). A reduction of fossil fuel combustion together with enlarged public environmental awareness is expected to promote generation from renewable energy sources. China has agreed to reach its peak in carbon dioxide (CO_2) emissions in 2030 and by then have a 20 percent share of renewable energy. In order to reach this target, an amount of 1 000 GW non-carbon emitting power such as nuclear, solar and wind power must be installed. (Scientific American, 2014)

1.1.1 Wind Power Growth

Wind power has increased most of all electricity sources in Sweden the last few years and China is the world's largest wind power producer, as seen in Figure 3. The wind industry is promoted by governmental support systems in several countries all over the world, where mass production and technology development has contributed to cheaper turbines. As seen in Figure 2, the global installed wind capacity is increasing each year and has almost tripled the last five years, from 120 000 MW in 2008 to 320 000 MW in 2013. (Global Wind Energy Council, 2014)

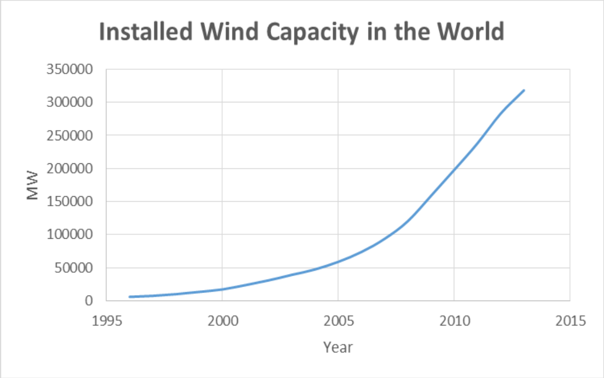

Figure 2: Installed Wind Capacity in the World, Source: (Global Wind Energy Council, 2014)

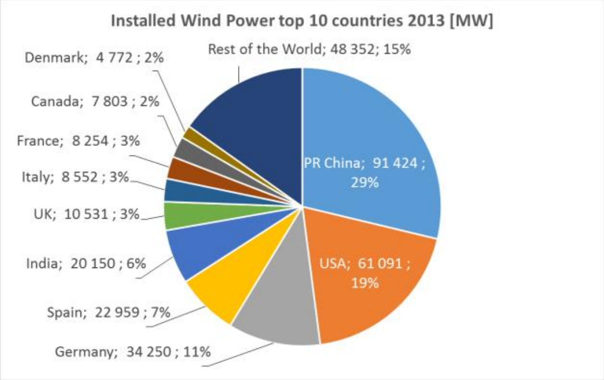

Figure 3: Installed Wind Power top 10 countries 2013 [MW], Source: (Global Wind Energy Council, 2014)

The installed wind power capacity has increased in Sweden but especially in China as Figure 4 shows. The increasing installed wind power capacity in Sweden and China also yields a higher share of wind power in the total generation capacity mix. Sweden had almost 10 percent wind power of total electricity production capacity year 2012 and China had more than 5 percent wind power installed same year. The growth in share of wind power capacity from 2005 to 2012 can be seen Figure 5 below.

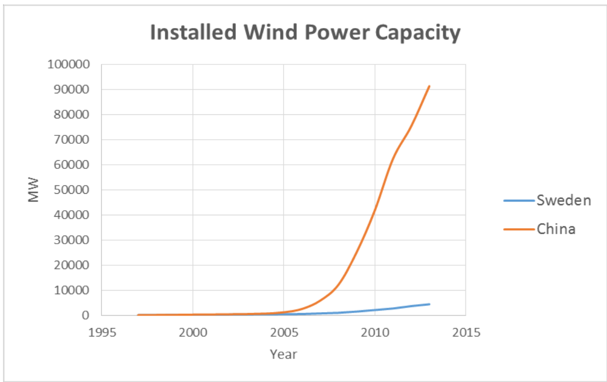

Figure 4: Installed Wind Power Capacity, Source: (The Wind Power, 2013a)

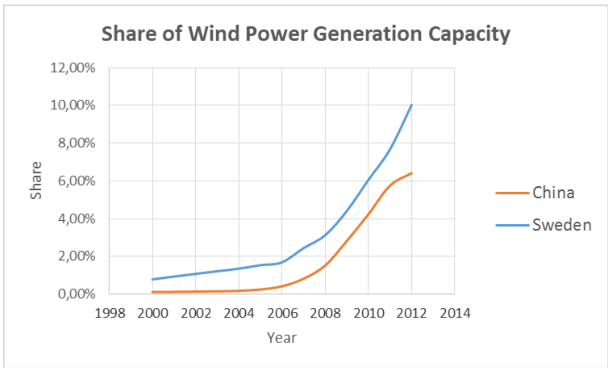

Figure 5: Share of Wind Power Generation Capacity, Source: (U.S. Energy Information Agency, 2012a) (The Wind Power, 2013b) (The Wind Power, 2013) (Energimyndigheten, 2014)

1.1.2 Intermittent Power Generation Challenges

Even though wind power increases rapidly due to its environmental benefits, new challenges arise in the power system. Wind power generation is more intermittent and unpredictable than conventional energy sources due to weather conditions with seasonally and daily variations. Seasonal variations are repeated annually and are hence relatively predictable. Unpredictable variations are caused by weather changes, leading to forecast errors and generation challenges. (The Boston Consulting Group, 2010)

Real-time balance between load and generation must be maintained. Output fluctuation from renewable energy sources influences system operation of frequency control, which often is accomplished by conventional thermal generators operated to adjust the frequency. (IEC, 2011) When generation from intermittent energy sources is high, load should increase or output from conventional power generators should be reduced. If scheduling is uncoordinated or if transmission capacity is limited, there is a risk that energy is curtailed. (Li, et al., 2015)

Wind energy curtailment occurs when wind is available but not utilized for electricity generation in wind power plants. When generation exceeds demand on windy days, there is a risk of extremely low electricity prices on the spot market. Surplus power generation can be exported, provided that there is sufficient transmission capacity, or energy is curtailed. When there is a large power demand and less wind, regulating measures and balancing power is required. (IEC, 2011) Intermittent energy sources thereby require variation moderators to reduce wind curtailment and meet demand.

It is essential to find a cost-effective solution for regulating power in order to secure the electricity supply. Power reserves systems currently available have either geographical or financial downsides. For example, hydropower has geographical limitations and is often too remote from potential wind sites. (Li, et al., 2012) To provide optimistic investment outlooks for renewable energy technologies, energy policies are crucial. Cost-competitiveness is improving in some countries, depending on market strategies. (International Energy Agency, 2014) The Boston Consulting Group (2010) has anticipated Europe to be the first area to face variation problems from intermittent power generation. A compensating capacity of 100 GW is expected to be required in 2025, due to increased amount of intermittent electricity generation. (The Boston Consulting Group, 2010)

1.1.3 Variation Moderators

Increased share of intermittent wind power in the system requires enhanced variation moderators to balance generation and varying demand at all times. Interconnections and integration of generation, transmission planning and market are all aspects affected by this change in the energy system. These aspects have different positions, time frames and impacts on the system, as displayed in Figure 6. The system wide impacts have been divided into three focus areas; balancing and adequacy of power and grid. Primary reserves are short-term reserves that need to be activated in seconds, for example frequency regulation. Secondary reserves are activated in 10 to 15 minutes, for example load following reserves. A higher share of wind power entails extra investment costs. These costs arise from operational balancing and grid reinforcement costs, such as large-scale energy storage and transmission investments. However, total operating costs and emissions can be reduced as wind replaces fossil fuels. (Holttinen, et al., 2011)

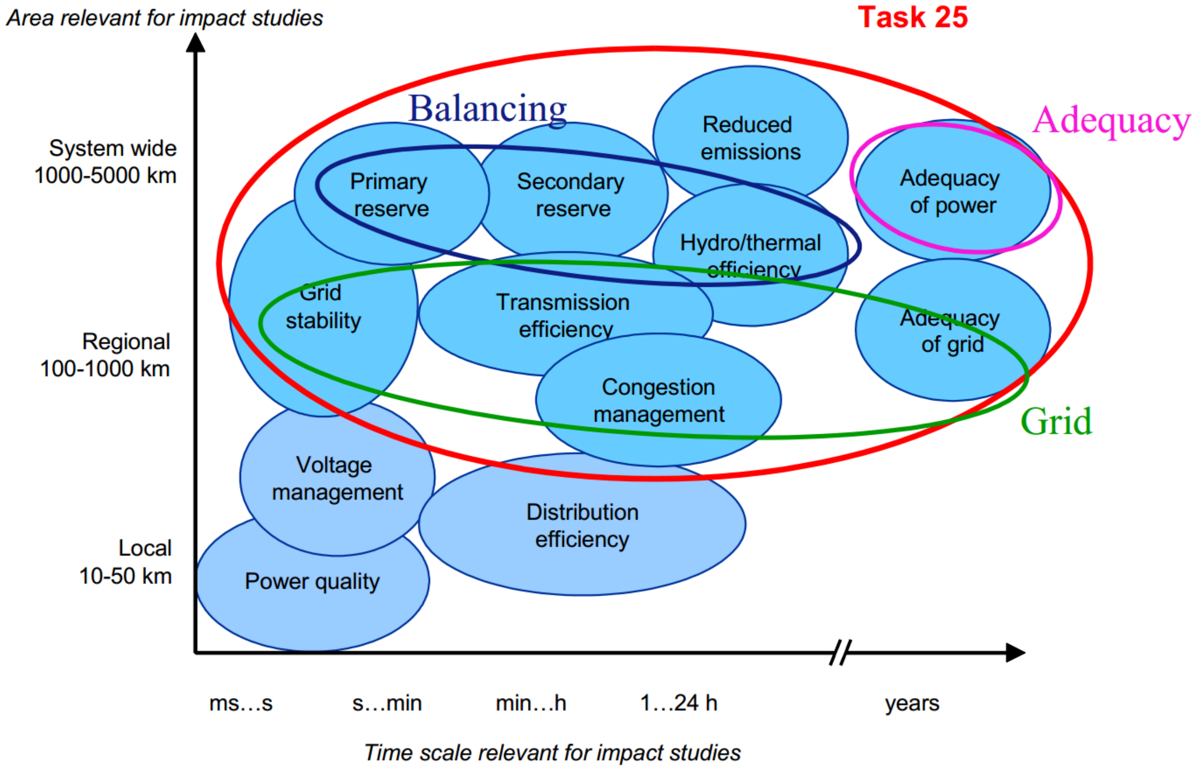

Figure 6: Impacts of wind power on power systems, displayed by time and spatial scales, Source: (Holttinen, et al., 2011, p. 180)

There are several examples of variations moderators that can provide flexibility to an intermittent power system. For example energy can be transferred through geographical transmission or stored over time in an energy storage.

1.1.3.1 Transmission

The electric power transmission systems transmit electricity from electric generators, such as hydro power plants, nuclear power plants or wind power plants, to electrical substations located near load centres. To reduce losses over long distances, electricity is transmitted at high voltages, 120 kV or above. (World Nuclear Association, 2015) Since transmission infrastructure depends on country specific conditions, further details are explained in chapter 3 for the transmission infrastructure in Sweden and China. By having a well-developed transmission grid, power generation from example wind farms can be transmitted to another geographical location, provided that the transmission capacity is sufficient. Trustworthy forecasts of weather and demand are advantageous to transmit a stable power supply (The Boston Consulting Group, 2010).

1.1.3.2 Energy Storage

Another option to regulate power from intermittent generation is by storing energy over time. There are numerous of research work that advocates integration of large-scale energy storage into the power system with the purpose to provide variation capacity in the intermittent power system. Various energy storage technologies keep developing towards grid usage (Anuta, et al., 2014) (Evans, et al., 2012) (The Boston Consulting Group, 2010) (Lund & Münster, 2003). To compensate for short and long term energy interruptions there is also a need for different types of energy storages. Individual needs will be important in the choice of energy storage systems, but incorporation of several energy storage systems will also be necessary as large amount of energy is required (Evans, et al., 2012). However, integration of large-scale energy storage technologies is associated with potential market entry barriers, since the market for several storage technologies is not yet mature.

Energy can be stored in many different forms and can be divided into four different categories; mechanical, electrical, thermal and chemical energy, each offering different advantages and disadvantages. (Evans, et al., 2012) In Table 2, advantages and disadvantages have been summarized for storage technologies appropriate for intermittent balancing.

Table 2 Advantages and disadvantages of storage technologies, Source: (Insight_E, 2014) (Evans, et al., 2012)

Technology	Advantages	Disadvantages
Mechanical strorage		
PHS	Large scale, efficient, commercial	Site dependent, low energy density, potential environmental impact
CAES	Cost efficient, large scale, scalable	Low energy density, large scale requires natural storage cavity (can be limited)
Flywheel	High power density, efficient, scalable	Cost, energy density
Electrical storage		
Capacitors	Long cycle life, high efficency	Low energy density
Supercapacitors	Power density, response time, efficient, cycle time	Low energy density, relatively high cost
SMES	Power density, response time, efficient	Low energy density, cost, commercialisation
Thermal storage		
Steam accumulator	Relatively low cost, manufacturing	Low energy density
Hot water accumulator	High heat density, high energy density, long life cycle	Slow charge and discharge rate
Chemical storage		
Lead-acid battery	Wide availability, reasonable low cost	Low specific energy and power, short life time, high maintenance, temperature sensitive,
Na-S battery	Long life cycle, high energy density, mature	High cost, high self-discharge, temperature sensitive
Li-ion battery	High energy and power density, scalable, high efficiency, no memory effect, low self-discharge, other applications drives cost down	High cost, material safety concerns
Flow battery	High energy and power density, large scale	Commercialisation, high cost, corrosion issues

As Table 2 shows, there are many different technologies for storing energy. One of them are lithium-ion (Li-ion) batteries which is a fast developing technology. It has high energy to weight ratio, high efficiency, high energy and power density. No memory effect and low self-discharge are also some advantages with Li-ion batteries. The cost is currently high and it has some safety concerns regarding the materials in the batteries, which require sophisticated battery management. (Evans, et al., 2012) However, costs are expected to decrease as other industries drive the technology development forward (Insight_E, 2014) (Eyer & Corey, 2010). This can also be seen in Figure 7 below. Several references from the industry believe that Li-ion batteries will be a market leading technology for grid storage applications (Climate Spectator, 2014) (Nykvist & Nilsson, 2015). Considering this development, Li-ion battery storage technology becomes interesting to further examine in this thesis.

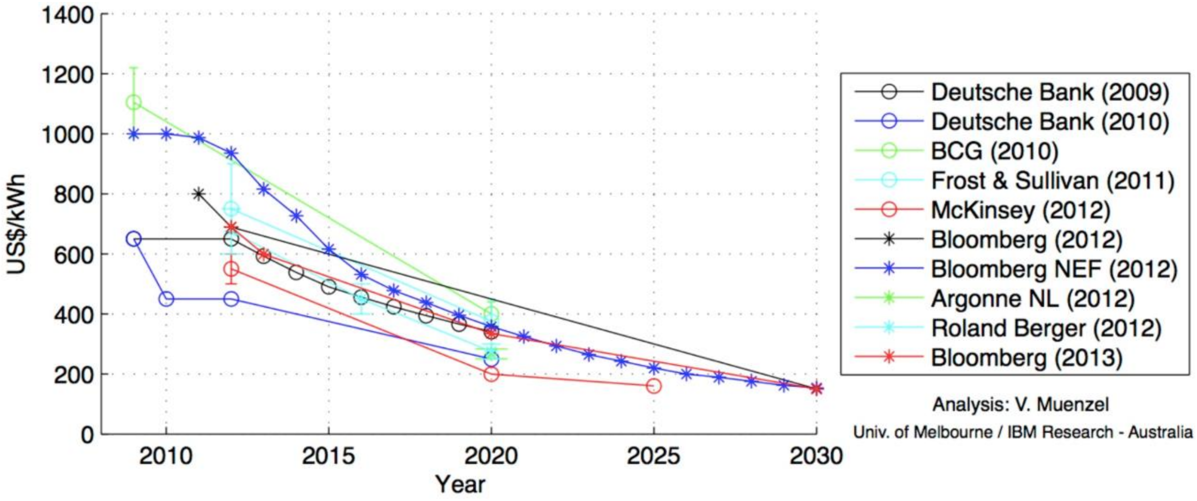

Figure 7: Predicted cost trends for full automotive Li-ion battery packs. Source: (Climate Spectator, 2014)

1.2 Purpose

This master thesis consists of two parts. The initial purpose is to explore market forces for transmission and grid storage development as variation moderators for intermittent power generation. Since battery grid storage is an emerging technology, market entry barriers for integrating storage into the grid aims to be identified.

The second part of the thesis aims to investigate the most beneficial combination of grid storage integration and transmission expansion in the future power system, in a system perspective.

1.3 Research Questions

In order to fulfil the purpose of the study, the following research questions have been addressed:

RQ1: What are the market entry barriers for integrating energy storage into the grid and what drives the development of grid storage and transmission, respectively?

RQ2: How do these market forces affect the choice of variation moderators in the future energy infrastructure?

1.4 Expected Contributions

Several technical solutions are today available providing flexibility in the future power system. According to the International Energy Agency (2014), the main question is not how to bring flexibility to the power system, but which alternative is the most lucrative. This master thesis is expected to investigate the most lucrative combination of grid storage integration and transmission expansion by introducing a cost-benefit model.

Previous work within the area partly includes regional integration with separate plans of variation management. Göransson (2014) examines power system containing a large share of wind power and emphasis that intermittent energy sources will play an important role in the future. However, what kind of technologies complementing these intermittent energy sources is yet uncertain. (Göransson, 2014) Variation moderators such as transmission and storage, which this master thesis will focus on, can provide regulation of intermittent wind power. Previous research work indicates a lack of research within the area. According to Göransson (2014) an important subject in future work is to:

> *"...find a balance between centralized (e.g., transmission investments and trade with hydropower-rich Nordic countries) and decentralized (e.g., regional storage and DSM) efforts to manage variations."*

This master thesis will cover two potential solutions to manage variations from intermittent energy sources. The thesis is expected to contribute to a greater basis of research within the area and provide market indications for future investment decisions when planning Sweden's and China's power systems. By increased knowledge about driving forces, potential barriers, costs and benefits that influence the market conditions for these variation moderators, this master thesis imply material for decision making on the future power market.

The thesis is also expected to contribute to a general system perspective of introducing grid storage on the global power market. However, since grid infrastructure is country specific, a comparison is performed between transmission and storage in two diverse market conditions. Craig & Douglas (2005) support the international viewpoint and emphasize the importance of performing research with a global perspective, as markets constantly change and businesses are becoming more global.

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2. METHODOLOGY

This chapter covers the methodology of this research work. Firstly, the research design and approach is explained. This is followed by describing the data collection method and research approach quality. Lastly, the method of the Cost-Benefit Analysis is further clarified.

2.1 Research Design and Approach

This master thesis has been conducted by an *inductive approach*. Data gathered has led to increased knowledge within the field of study. Thereafter, scientific theories have been used to further increase knowledge about the findings. This has also laid a foundation to the first version of the cost-benefit model. Then, additional reading within the field of study was conducted and the model was developed further. This process was made in several steps, thereby with an inductive approach. Although this approach could be time-consuming, according to Bryman & Bell (2011) and Blomkvist & Hallin (2014), it was still chosen due its advantage for *exploratory* studies, such as this thesis work.

Based on this study's research questions and its purpose, it can be concluded that this study is of an *interpretivist* nature. According to Bryman & Bell (2011), interpretivism is a term for research that focuses on social phenomena rather than natural sciences. This kind of study requires a different research approach that respects the differences between people and the objects of the natural science. An interpretivistic approach does not focus on quantitative data but rather on qualitative data where the research is conducted in close interaction with what is being researched. (Bryman & Bell, 2011)

In order to answer the research questions, a *case study research design* has been chosen. This kind of research method is suitable for previous unexplored areas according to Bryman & Bell (2011) and Blomkvist & Hallin (2014), such as this research area. Data has been gathered by a *qualitative approach* and developed towards two different cases; one for a developed market, Sweden, and one for a developing market, China. A cost-benefit model has been constructed by data gathered and thereafter a Cost-Benefit Analysis (CBA) was made with the purpose to study the cases for each country. The CBA and the cost-benefit model is further examined in section 2.4 and in chapter 5.

The actual research procedure consisted firstly of building an understanding of the issue with a high share of intermittent power generation in the power system. Grid storage and transmission was chosen to be the two technologies in focus and further investigated in this research. Then an understanding for the emerging technology energy storage's market entry barriers, further development and future potential in the energy infrastructure had to be conducted. This applied also for transmission, but since transmission is a mature technology in the energy infrastructure, this part had a different approach with focus on its current driving forces. To create this understanding, an extensive literature survey within the field of study was made. Further, this continuously increased understanding has been connected with scientific theories, such as market entry and market conditions, during the process. Furthermore, a cost-benefit model for the two different countries was conducted with data gathered in the literature survey as its foundation, together with country specific data for grid storage and transmission. The model has been constructed and developed simultaneously as knowledge from the literature survey has increased during the work. This inductive approach applies for both technologies and also for the market analysis.

2.2 Data Collection

The literature survey in this research is essential to understand the context of the problem and find information available in the field of study. Previous research in the area laid a foundation to this thesis, together with information from different governmental and industry organizations and consulting reports. Statistics about electricity generation and consumption in respectively country has been gathered through the Global Wind Energy Council, the U.S. Energy Information Agency and Svenska Kraftnät. Information about the electricity markets, together with information about energy storage and transmission, has been found through multiple sources including academic journals, consultant reports and governmental organizations.

The material is retrieved from the Internet and databases for scientific research, including Google Scholar, Discovery, Diva and IEEE Xplore. Information have also been found at different Swedish governmental organizations, like The Swedish Energy Agency (Energimyndigheten), The Swedish Transmission System Operator (TSO), Svenska Kraftnät and industry organizations such as Svensk Energi and Svensk Vindenergi. They present information about the current electricity market and the transmission grid as well as future plans of expansion. There are also a few consultant reports, from companies such as Sweco, Ramböll, The Boston Consulting Group and Lazard, which are relevant for the study. Information gathered from these consultant reports includes potential future scenarios. Available information about China was limited, in particular from governmental organizations. Most of the collected information comes from previous academic research in the field of study and different news releases from websites.

2.3 Research Approach Quality

Bryman & Bell (2011) argues that reliability and validity are important criteria's to consider when establishing and assessing the quality of a qualitative research. However, some researchers' claims that validity has less relevance in qualitative research since measurements are not a major preoccupation among qualitative researchers. This would mean that validity has little influence on such studies. (Bryman & Bell, 2011)

2.3.1 Validity and Reliability

Validity refers to whether or not the purpose is met and research questions are answered. Validity is achieved by confirming that the literature survey and theory is connected to the purpose and the research questions. (Blomkvist & Hallin, 2014, p. 50) (Bryman & Bell, 2011) The validity in this research has been achieved by reconstructing the research questions to fit the context in the study, since the study has developed during the process and slightly changed direction. Increased knowledge in the field of study has led to interesting findings that have affected the research focus area. However, comparing grid storage and transmission as variation moderators for intermittent power generation is an emerging field, which yields that validity cannot be guaranteed completely. Further, there is a lot of previous research of the variation moderators separately, as well as research on how to enter a new market and differences between developed and developing countries. This enhances the validity in this study. Moreover, Craig & Douglas (2005) acknowledge the challenges of collecting comparative data and analyse results for diverse market environments. Several factors can cause difficulties in achieving comparable results between developed and developing countries. It is generally easier to use the same research approach for similar market environments. (Craig & Douglas, 2005) Nevertheless, Craig & Douglas (2005) argue that the research work can increase validity and support decision making if these challenges are addressed in a reasonable way.

Reliability refers to the consistency of a concept measure; to what extent the results of the study would differ if another researcher repeated the research. (Bryman & Bell, 2011) The limitation of adequate accessible market data affects the reliability of the study. Battery grid storage is an emerging technology and few market studies have been performed where the market conditions for storage is compared with another variation moderator, such as transmission. This makes this thesis a pioneer in the field of study, but it also creates some uncertainties regarding its reliability. Since it is a high topic subject and there is a lot of on-going development within the field of study the market conditions changes all the time, which affects the reliability of the results in the study. The market analysis and the conclusions are based on information available at present time. It is most likely that new information will be available for another researcher in the future.

Further, evaluating costs for energy storage is challenging, as there is limited information about economic performance of the few sites existing today. This research work considers market entry of an emerging technology at an early stage. According to Craig & Douglas (2005), the work should therefore be observed in a long-term perspective and aim to initiate further research within the area. Since many markets move quickly, trends need to be identified at an early stage. Also a long-term perspective is important when perceiving market potential (Craig & Douglas, 2005). Craig & Douglas (2005) also acknowledge the importance of entering a market at an early stage of the market development to avoid competition from other actors. Diverse approaches and methods for cost calculations and estimations are used in the literature. Furthermore, Zakeri & Syri (2014) claims that data for expenses cannot be appropriately scaled for larger or smaller storage sizes. This has been an issue during the design of the model that of course affects the reliability of the results. This has also been the case for data about current transmission projects. Since there have not been many transmission projects in the recent years of the appropriate size in Sweden, data from only one projects has been used. This affects the reliability of the results. In China, there are on-going projects in present time in appropriate size but due to China's restrictions of sharing information limited data was available. However, since an extensive data collection has been performed and no more up-to-date data could be found, reliability can be considered to be achieved. The thesis work was also performed under a limited time frame. The CBA and market analysis could have been performed in more detail with extended time frame.

The aim has also been to create a reasonable and general cost-benefit model including the most relevant benefits for integrating battery grid storage in the current energy infrastructure. The model itself is considered as general, but country-specific costs have been included for Sweden and China, respectively. Due to country-specific conditions, some data are hard to compare but must be included separately for the two countries. Two countries are included to increase quality to the model and understand how diverse market conditions can change the barriers and opportunities for grid storage integration and transmission expansion.

2.4 Cost-Benefit Analysis

The research work investigates two different markets, a developed economy and a developing economy represented by Sweden and China, respectively. Transmission expansion is considered for market specific conditions in these countries, where the focus area is to analyse the market situation from a wide infrastructure perspective. By means of the socioeconomic CBA and market analysis, potential investment decisions can be considered for infrastructure development. However, not all existing benefits for grid storage integration are included in the CBA. Grid storage can be used for several applications when utilizing different properties. The properties chosen for this thesis are applicable for regulating purposes of intermittent renewable power generation.

A CBA can be viewed as a method to determine whether an investment should be realized or not. It is also useful in comparing different projects to see which project that is more beneficial to realize. In a CBA, costs and benefits from a project is considered and expressed in a monetary value. (Layard & Glaister, 1994) Information about a monetary value does not often exist, but must be based on reasonable estimations. It is important to consider the most relevant factors of the project. Regarding infrastructure projects, the project has multiple factors such as impacts within the power system, external effects and macroeconomic effects as presented in Figure 8.

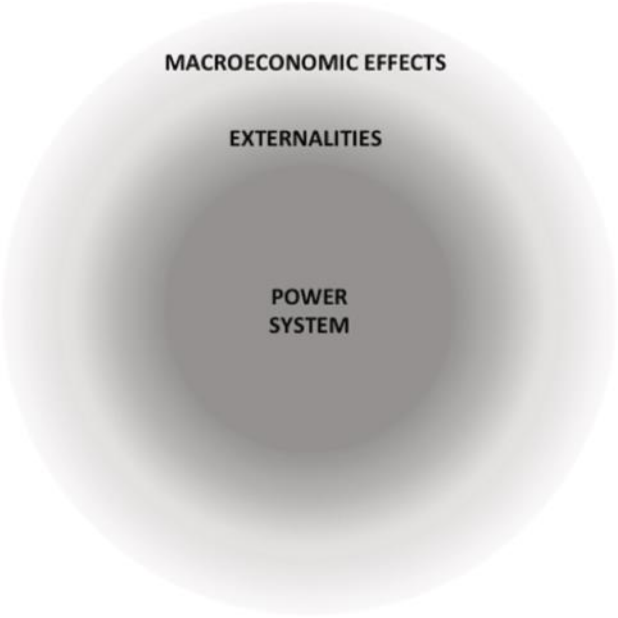

Figure 8: Three layers of factors generated by infrastructure project, Source: (THINK, 2013)

Within the power system, costs and benefits can be considered. Costs can involve infrastructure investment costs over the lifetime and also production cost savings, corresponding to more efficient use of ancillary and balancing reserves. Gross consumer surplus and other market benefits can also be considered within the power system, such as benefits from improved system reliability or price fluctuations on the spot market. (THINK, 2013)

Externalities refer to external effects that the project has on its environment. For instance, it can affect CO_2 emission costs depending on type of energy source used for generation. Another external effect is amount of renewable energy curtailment. Local environmental and social cost should also be considered, for example the impact that the project has on landscape or noise to the surrounding. Early deployment is also important to consider, as the project can lead to increased knowledge about certain types of technologies, such as grid storage. These potential effects are presented in Figure 9. (THINK, 2013)

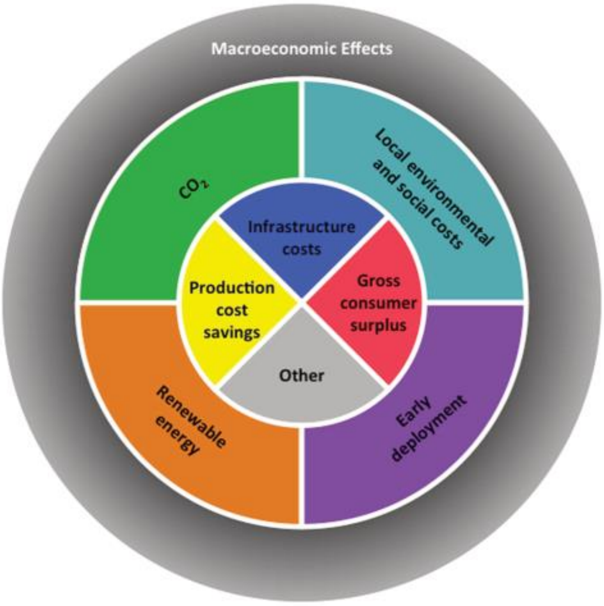

Figure 9: Comprehensive list of effects, Source: (THINK, 2013)

However, some of these effects are not relevant in all projects or overlap with effects already considered. For example, benefits from CO_2 emission reductions can be included in production cost savings, due to the decreased cost for CO_2 emissions. Likewise, benefits from renewable integration can be included in production cost savings. Local and environmental costs can be included in infrastructure costs. For example, costs to meet the current directive regarding local fauna and flora, material assets and cultural heritage can therefore be included in infrastructure costs. This also applies to early deployment costs. Macroeconomic impacts are relatively similar for most projects and can therefore be considered as less important when comparing different projects. (THINK, 2013)

The most important effects on a project can be summed up to infrastructure costs, production cost savings and gross consumer surplus. These reduced effects on a project are presented in Figure 10 below. However, applicability of the CBA relies on consistency and quality of the data wind curtailment that underlines the parameters. (THINK, 2013)

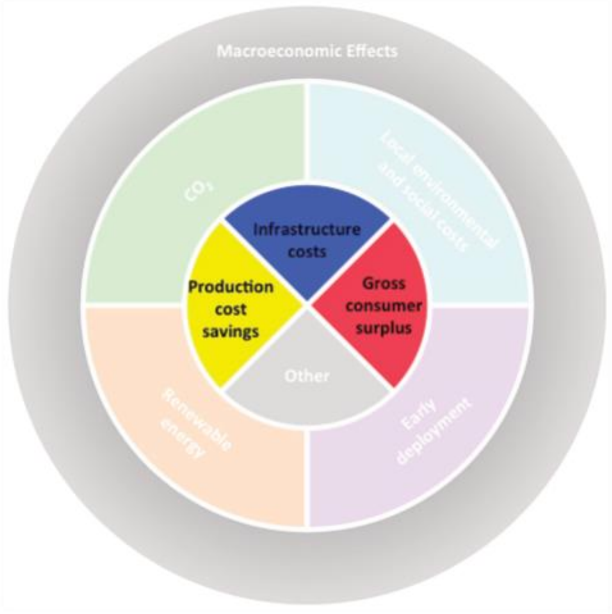

Figure 10: Reduced effect mapping, Source: (THINK, 2013)

All costs and benefits during the project's lifetime are usually included in the CBA and discounted at the same point in time. Thereafter, they are summed up to a net present value (NPV). (Layard & Glaister, 1994) The equations used in the model are showed in section 5.11.

$$\text{NPV} = \sum_{n=0}^{L} \frac{B_n}{(1+i)^n}$$

n = Year

B_n = Sum of costs for year n

i = Interest rate

L = Financial life time in years

2.4.1 Annualized Cost-Benefit Analysis

To compare two investments without income and different life time the annuity for the alternatives can be calculated to make a trustworthy comparison of the costs. The Annualized Cost-Benefit Analysis (ACBA) of an investment in grid storage and transmission is obtained by multiplying the present value with the life annuity of the object.

$$A = NPV * F_A = NPV * \frac{i}{1-(1+i)^{-L}}$$

F_A= Annuity factor

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3. MARKET CONDITIONS

This chapter aims to give a further understanding of the conditions for variation moderators on two diverse markets. The first part of this chapter describes the Swedish electricity market, where upcoming challenges are identified and future scenarios presented. The second part describes market conditions on the Chinese electricity market, together with upcoming challenges and the influence of an emerging market.

3.1 The Swedish Electricity Market

The Swedish electricity market consists of hundreds of actors. However, the market is dominated by a few actors; Vattenfall, Fortum and E.ON, who together have a substantial market share of electricity generation and wholesale. Green & Newbery (1992) claims that it would be more efficient if the market consisted of several actors with smaller market shares in order to avoid deadweight losses. Deadweight losses means the loss a buyer suffer when buying something to a higher price than the competitive level (L in Figure 11) or the loss the buyer suffer when not choosing to buy at all (D in Figure 11) (Posner, 1975). Even though the market in Sweden could be seen as an oligopoly (Brander & Lewis, 1986) the electricity is traded on a joint Nordic market, Nord Pool Spot, which consist of several major actors and hundreds of smaller actors. According to Fridolfsson & Tangerås (2009), this results in a competitive market and no single actor has a dominating share of the market.

The Swedish national grid is controlled by a state monopoly. According to Bushnell (1999), transmission right owners can take advantage of their monopoly position and reduce transmission capacity during hours in which there would otherwise be no congestion. This will lead to social costs, see Figure 11, but not necessarily a loss for the TSO, it could even be beneficial. (Bushnell, 1999) (Posner, 1975)

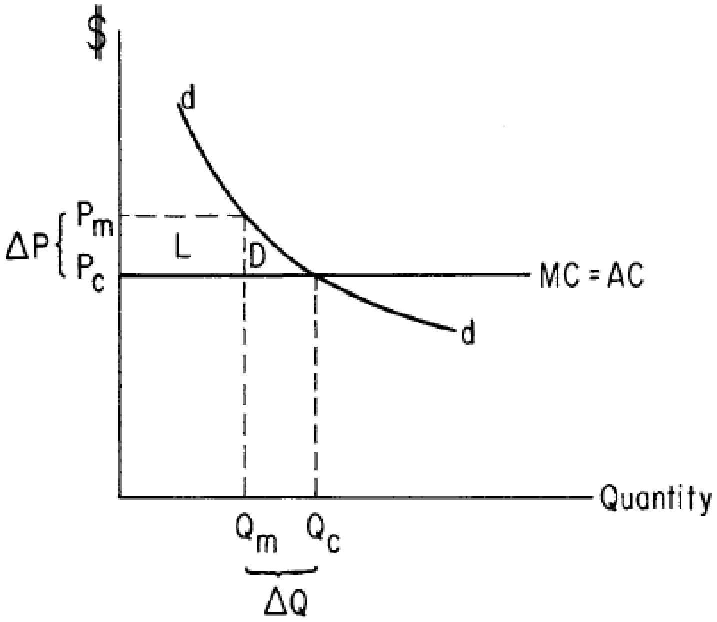


Figure 11: Social costs of non-competitive pricing, Source: (Posner, 1975)

The Swedish national grid is owned by the Swedish government and managed by the Swedish TSO, Svenska Kraftnät. The Swedish TSO is responsible for ensuring that Sweden has a safe, environmentally sound and cost-effective electricity supply. In short term this is achieved by monitoring the electrical system around the clock and in the long term by plan and construct new transmission lines to meet future demand. (Svenska Kraftnät, 2015b) The Swedish national grid consist of 15 000 km high voltage lines with the current of 400 or 220 kV, presented in Figure 13, where the connections to its neighbouring countries also can be seen. (Svensk Energi, 2012d) Large wind plants over 100 MW are connected to the national grid. (Energimyndigheten, 2013b)

Since November 1, 2011 Sweden is divided into four different price bidding areas, as displayed in Figure 12 below. This breakdown is made to show where the grid requires an increase in capacity. The borders are placed where the limitations in capacity are. In general, there is a surplus of generation in north compared to the demand. The opposite occurs in the south where the transmission capacity is not enough during peak hours. This congestion affect market pricing; price decreases in one area and increases in the other area. The decision to split the Swedish market in four areas is also a part of EU's goal of one united electricity market in Europe. (Svenska Kraftnät, 2013b, p. 16)

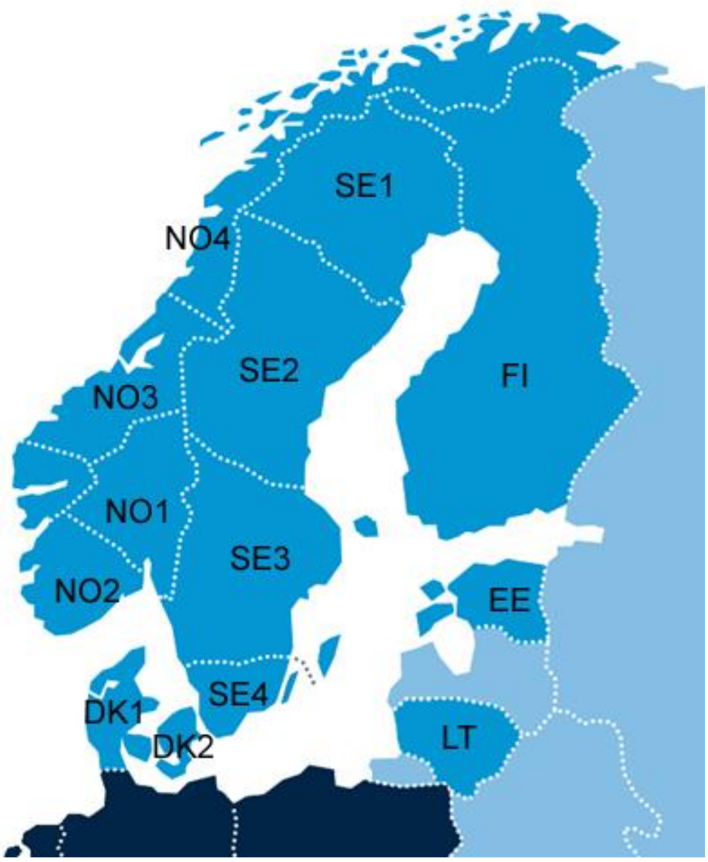
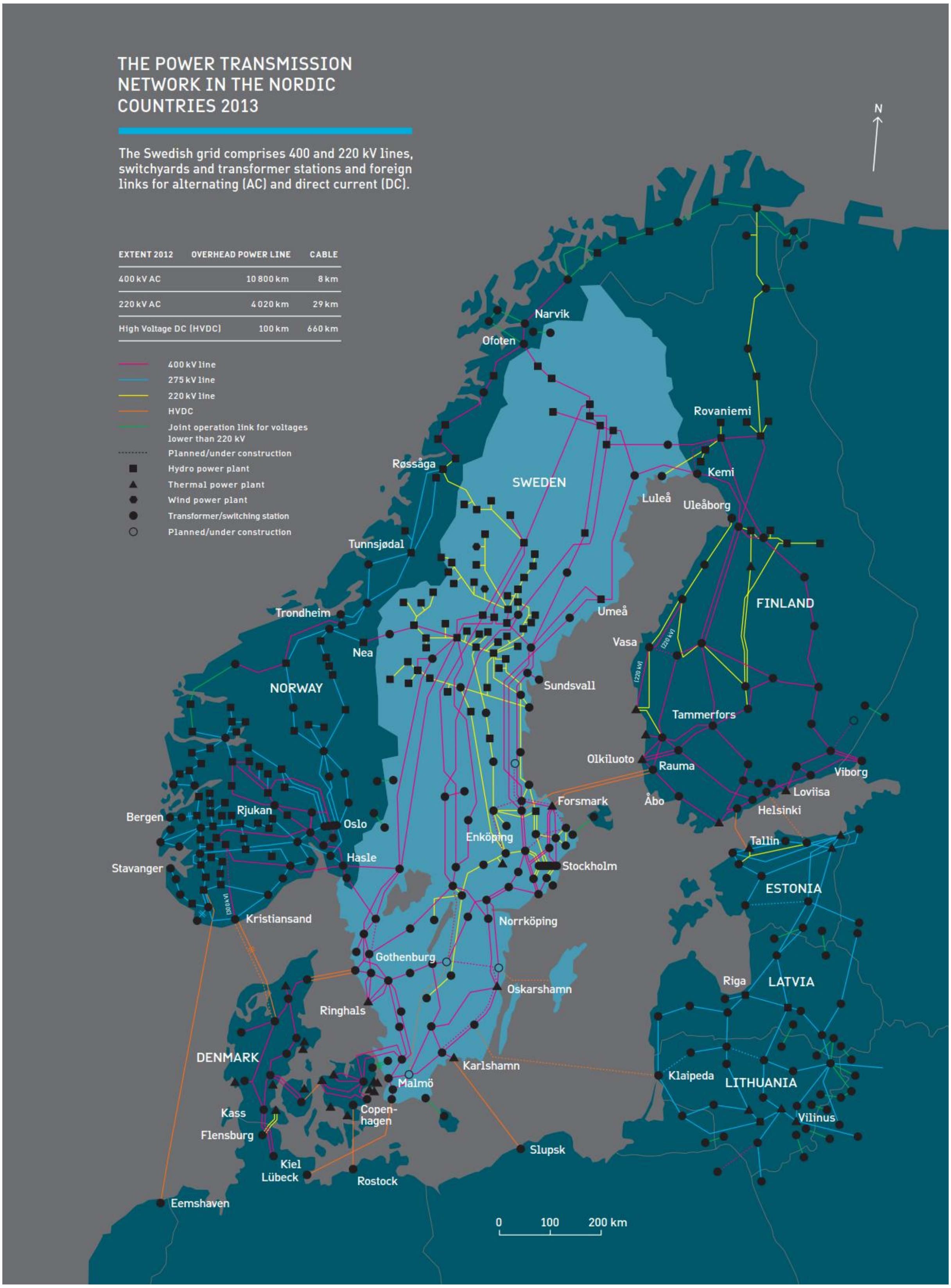


Figure 12: Electricity areas in the Nordic countries, Source: (Svenska Kraftnät, 2013b, p. 16)



THE POWER TRANSMISSION NETWORK IN THE NORDIC COUNTRIES 2013

The Swedish grid comprises 400 and 220 kV lines, switchyards and transformer stations and foreign links for alternating (AC) and direct current (DC).

EXTENT 2012	OVERHEAD POWER LINE	CABLE
400 kV AC	10 800 km	8 km
220 kV AC	4 020 km	29 km
High Voltage DC (HVDC)	100 km	660 km

Figure 13: Swedish Power Grid, Source: (Svenska Kraftnät, 2014a)

3.1.1 Electricity Generation

Sweden has an electricity generation that consist of low CO_2 emitting fuels. The amount of renewables and waste consist of 60 percent of Sweden's total electricity generation, as seen in Figure 14. 38 percent of the generation comes from nuclear which is not renewable but still a low CO_2 emitter. Only two percent comes from fossil fuels and they are mostly used as reserve capacity in peak hours. (Svensk Energi, 2012a)

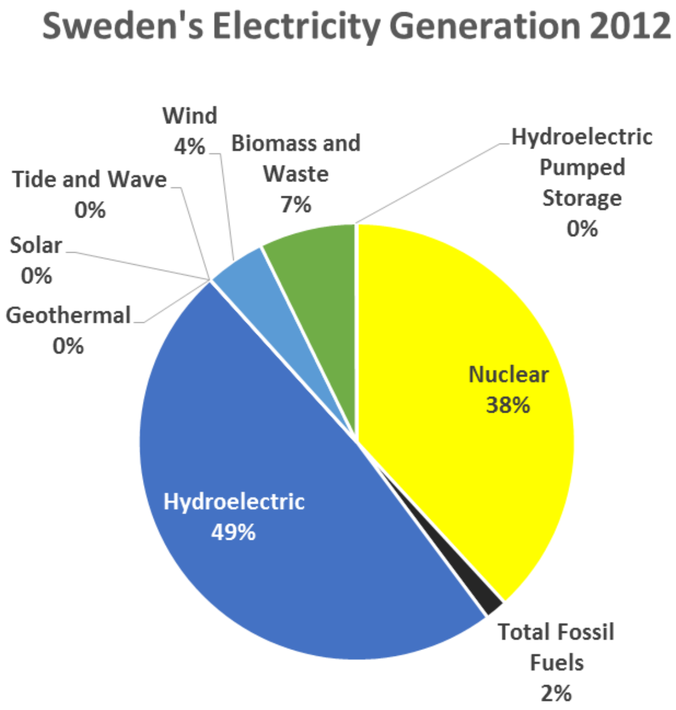


Figure 14: Sweden's Electricity Generation 2012, Source: (U.S. Energy Information Agency, 2012a)

The nuclear power generation is the base load in Sweden's electricity system and consist of ten nuclear power plants on three locations different location in southern half of Sweden (SE3). Hydro power generation is Sweden's largest energy source and like nuclear it acts as a base load. Furthermore, it also acts as a regulating reserve due to its good ability to handle seasonal variation and also variation in shorter intervals. This ability to regulate the electricity generation is very valuable for Sweden's electricity system. The share of wind energy is increasing in Sweden and with this weather dependent production there is a need for regulating reserves. (Svensk Energi, 2012a) However, hydro power as regulating reserve might not be enough in the future. Hydro energy in Sweden is already used near its maximum potential. (Svenska Kraftnät, 2008)

3.1.2 A Competitive Market

Historically the trading in Sweden was controlled by a state monopoly and consumers were forced to buy electricity for a set price. In January 1996 the first step was taken towards a competitive electricity market. The market was partly deregulated and free competition was created in trade and production of electricity. The major step towards a competitive market was made in 1999. The new rules that were applied made it possible for consumer to buy electricity from any electricity trading company on the market. This new competitive market, connected consumers and producers, with the basic principle of demand and supply. (Svensk Energi, 2012c)

Nord Pool Spot market is today the leading power market in Europe and 90 percent of Sweden’s electricity generation is traded there. Nord Pool Spot is owned by the TSOs in Sweden, Norway, Finland and Denmark. (Svensk Energi, 2012b) Nord Pool is divided in two physical parts, Elspot and Elbas.

Elspot is a day-ahead auction market for the Nordic and Baltic region. It is the main market place and the traded power applies for delivery during the next day. The price is set by supply and demand, where a buyer sets the demand and price for the following day. A seller, for example an owner of a wind farm, sets the amount that can be delivered hour by hour and to what price. Each actor uses a strategy to maximize their outcome of the deal. (Nord Pool Spot, 2015a) (Engelbrecht-Wiggans, 1980)

Elbas is an intraday market which is traded on Nord Pool Spot. Elbas is covering the Nordic, Baltic region and Germany. Trading takes place every day until one hour before delivery. Its purpose is to set balance to the market if unexpected events occur, such as higher wind power generation than planned. The price is set by a first come, first served principle. The best prices is prioritized, highest buy price is matched to lowest sell price. (Nord Pool Spot, 2015b)

3.1.3 Upcoming Challenges

According to Global Wind Energy Council (2014) future constructions will be concentrated to northern parts of Sweden where larger wind farms are more feasible, as seen in Figure 15. These problems are most likely to occur in the most southern area (SE4) where transmission capacity from north and regulation is limited. The regulation of intermittent generation could be solved in a better way by investing in transmission capacity towards neighbouring countries as well as domestically between the different bidding areas. However, these kinds of grid investments are very costly. The process of constructing a new transmission line also requires far ahead planning. Constructing a new transmission line, from planning to commissioning, takes about five to ten years (Svenska Kraftnät, 2015). A challenge of geographical transmission is also the monitoring of wind generation and wind forecasts. The forecasts need to be constantly updated to facilitate planning of large wind power generation and balancing power with long start-up time. The actual wind generation can also be used to validate the forecast towards the outcome. (Svenska Kraftnät, 2013b)

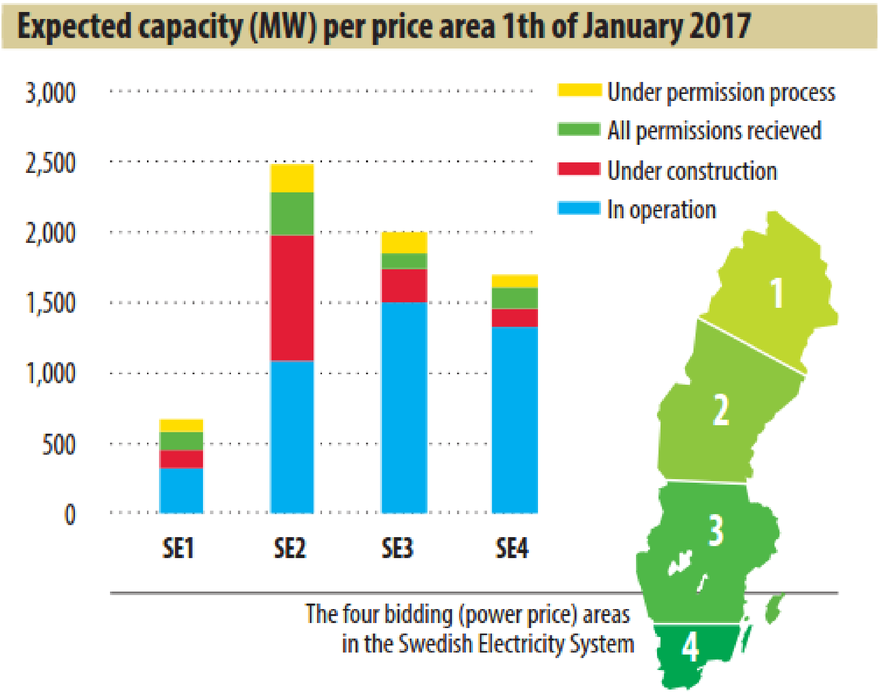


Figure 15: Expected wind capacity 2017, Source: (Global Wind Energy Council, 2014)

The Swedish TSO has received applications for connecting wind power of 20 000 MW, which represents about 75 percent of Sweden's maximum power demand. The expansion of wind power expects to depend on the future design of the electricity certificate system. Slow authorization processes can influence when wind power growth can be realized. Locations of the wind power plants have big impact on the capacity of the transmission grid. Nevertheless, increased transmission capacity in the national grid will be required, no matter of location of the increased wind power generation. If expansions occur in the southern parts, hydro power from the northern parts of the country is expected to balance the grid, requiring enhanced transmission capacity. If expansion occur in the northern parts, improved transmission capacity is also necessary to transmit the power to the rest of the country. (Svenska Kraftnät, 2013b)

3.1.4 Future Scenarios

The system electricity price should increase due to increased marginal costs. This is concluded by both Ramböll (2014) and Sweco (2014). The consultant company Ramböll has evaluated Sweden's future electricity generation where two possible scenarios have been studied. The first scenario, scenario C, consists of 6 nuclear power plants instead of Sweden's 10 plants today. It also consist of 33 TWh wind power per year and to meet peak load, 1 500 MW gas power needs to be installed. In the second scenario, scenario D, nuclear power has been completely phased out and replaced with 82 TWh wind energy per year. Furthermore, 4 700 MW gas power has been installed to meet peak load. Both scenarios involve an increase in the system price to 0.46 SEK/kWh ($0.055/kWh) and 0.53 SEK/kWh ($0.064/kWh), respectively. This can be compared to today's level of 0.30-0.35 SEK/kWh ($0.036/kWh-$0.042/kWh) at Nord Pool Spot market. (Ramböll, 2014) Another consultant company, Sweco, also expects the electricity prices to rise. A scenario analysis for 2030 has been performed to study European Power Market Scenarios with different approaches. A scenario with high economic growth involves higher electricity demand and greater focus on the environment. Consequently, the generation capacity increases and larger investments are necessary for interconnections on the continent. (Sweco, 2014)

High focus on climate change and increased renewable power generation is also expected to lead to volatility prices. Intermittent generation, and consequently volatile prices, is expected to increase in all European countries. As a result of this, Sweco (2014) acknowledges that increased transmission capacity is necessary. By expanding the market integration with continental Europe, the Nordic countries are expected to increase exportation of surplus power. (Sweco, 2014)

More wind power capacity in the future electricity mix can result in increased spill of energy. According to Ramböll (2014), an increased amount of wind energy in the electricity mix will result in an energy surplus, wind curtailment, of 5 percent and 26 percent of the hours of the year. Two scenarios have been studied C and D, respectively. The excess generation will yield a very low system price these hours. (Ramböll, 2014)

The Swedish TSO has analysed a scenario for 2025, with a wind power capacity of 7 000 MW in Sweden. They expects an increase of variation moderators to integrate the expansion of wind power. There is two scenarios shown in Figure 16. Scenario A has the assumptions of an ideal market with continuous plans and forecasts, and with corrected trade on Elbas. Scenario B is the opposite where all trade is made on Elspot and there are no updates of plans and forecasts. However, to decrease the number of variation moderators needed and to increase availability of the existing ones, a few measures have been identified. Two measures are intensified monitoring and increased costs of imbalances. (Svenska Kraftnät, 2013a)

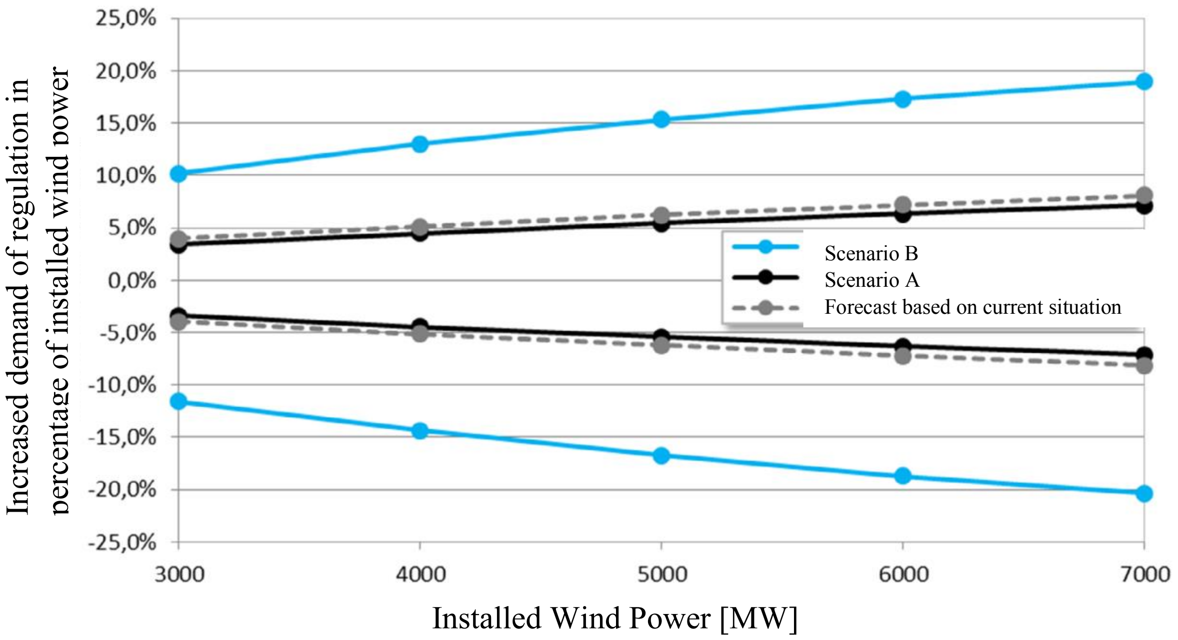


Figure 16: Demand of variation moderators with increased amount of wind power, Source: (Svenska Kraftnät, 2013a)

The Swedish TSO assesses that expansion of wind power in Sweden will not require an adjustment of the present market model in a near future. Thereby, the Swedish TSO does not currently intend to expand their responsibility of balancing the power system, partly because European directives set guidelines for future developments of the market model. (Svenska

Kraftnät, 2013a) However, Aigner (2013) acknowledges that an integrated intraday market in Northern Europe would have major effect on production. This could result in reducing the activation of balancing reserves by about 70 percent in 2020 and $361 million in annual savings. (Aigner, 2013)

One main energy target on the Swedish energy market is to increase the share of renewable energy sources to at least 50 percent by 2020. The Swedish TSO has therefore developed a planning framework ten to fifteen years ahead, including increased wind power generation. In the framework, the Swedish TSO recognizes a few concerns about the future energy market. For instance, planning of the grid is a challenge due to uncertainties regarding future energy sources. Grid expansions are time consuming, which can hold back integration of wind power on the Swedish power market. A big share of wind energy is expected to result in increased value of variation moderators. (Svenska Kraftnät, 2013b)

3.2 The Chinese Electricity Market

In 2002 the state owned State Power Corporation (SPC) monopoly on the power market ended (Posner, 1975). SPC's share of 46 percent of the country's electrical generation and 90 percent of the transmission and distribution were divided into several companies. Two national grid companies were created, State Grid Corporation of China (SGCC) and China Southern Power Grid (CSG). Furthermore, five generation companies were created, each with less than 20 percent market share, along with four power service companies that provides ancillary services. The purpose with the restructuring of SPC was to create a competitive market. (Gee, et al., 2007) This coincide with Green & Newbery (1992), who claims that it would be more efficient if the market consisted of several actors with smaller market shares in order to avoid deadweight losses. However, the market structure can still be viewed as an oligopoly (Brander & Lewis, 1986).

Earlier, private investors have been lured into the Chinese power market with very beneficial agreements, due to China's lack of sufficient power generation during the late 80's and 90's. After the reconstruction in 2002, these private owned generator companies started to compete for market shares under a "single buyer" system and the previous lucrative agreements were dissolved. As a consequence of the power market reform, private actors sold most of their business due to lack of returns. (Gee, et al., 2007)

State Electricity Power Regulatory Commission (SERC) was created in 2003 to work as a regulatory agency under the State Council. However, the agency does not have the same authority that similarly agencies in other countries have. SERC is in charge of overseeing market reforms, for example tariff model proposals and competitive bidding rules, and of protecting fair competition. SERC share the authority of tariff settings with the much larger and more authoritatively, National Development and Planning Commission (NDRC), who is in charge of central planning. NDRC opposed the market reform since it now has to compete with the more recently created SERC. (Gee, et al., 2007) However, China plans to restructure the National Energy Administration (NEA), which is under the jurisdiction of NRDC, and incorporate the functions of the SERC that is to be dissolved. The reason for this is the overlapping of functions and responsibilities between the NEA and the SERC. (English.news.cn, 2013)

This new oligopoly situation on the Chinese power market has moved the sector toward structural unbundling and corporatization. However, pricing is still not truly set by an open market and controlled by political and societal goals. (Gee, et al., 2007) (Brander & Lewis, 1986) (Posner, 1975) Mou (2014) also claims that the electricity market is still regulated by the government. Furthermore, to create a united electricity market is more effective than the current regional and provincial market. (Mou, 2014)

3.2.1 Electricity Generation

China is the largest global energy consumer and their electricity generation comes mainly from fossil fuels where coal is dominating with 77 percent, as seen in Figure 17. China's rapidly growing economy together with being the world's most populous country drives the urge to secure energy resources. In 2013, new leadership emerged in China and the new administration has a more long-term and sustainable focus.

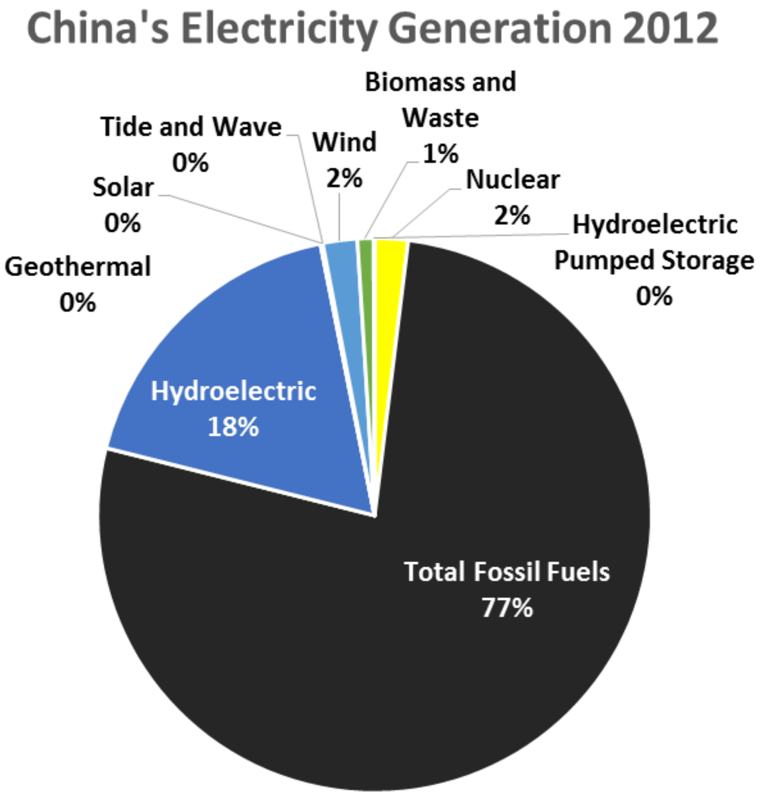


Figure 17: China's Electricity Generation 2012, Source: (U.S. Energy Information Agency, 2012a)

3.2.2 A Controlled Market

In comparison to Sweden's current competitive electricity market, the electricity market in China is controlled by the State Council. The State Council has ultimate control over the power sector and its development and operation. NDRC, who is under the control of the State Council, reviews and approves electricity tariff settings and adjustments. Regarding new power projects, the tariff is often proposed by the provincial government, reviewed by SERC and approved by NDRC. New power projects also needs approval from NDRC before being established. (Ma, 2011)

In 2009, a four category fixed feed-in tariff for new onshore wind power projects was announced by NDRC. This was implemented to benefit the wind power industry and abolish the earlier complex and time consuming tariff setting process. The new feed-in tariff has been divided into four categories to reflect the wind resources in the different areas. The regions with most beneficial wind conditions in north and west has been given a tariff of 0.51 RMB/kWh ($0.082/kWh). The regions with less beneficial wind conditions have been given tariffs of 0.54 RMB/kWh ($0.086/kWh) and 0.58 RMB/kWh ($0.093/kWh), respectively. Regions with even less wind resources have been given a tariff of 0.61 RMB/kWh ($0.098/kWh). Figure 18 shows the different tariff regions. These new feed-in tariffs are the minimal on-grid tariffs in each region. The developer of each project has the possibility to negotiate with the grid company for a better tariff. However, it is unlikely that the grid companies will offer higher tariffs than minimal tariff defined. (Ma, 2011)

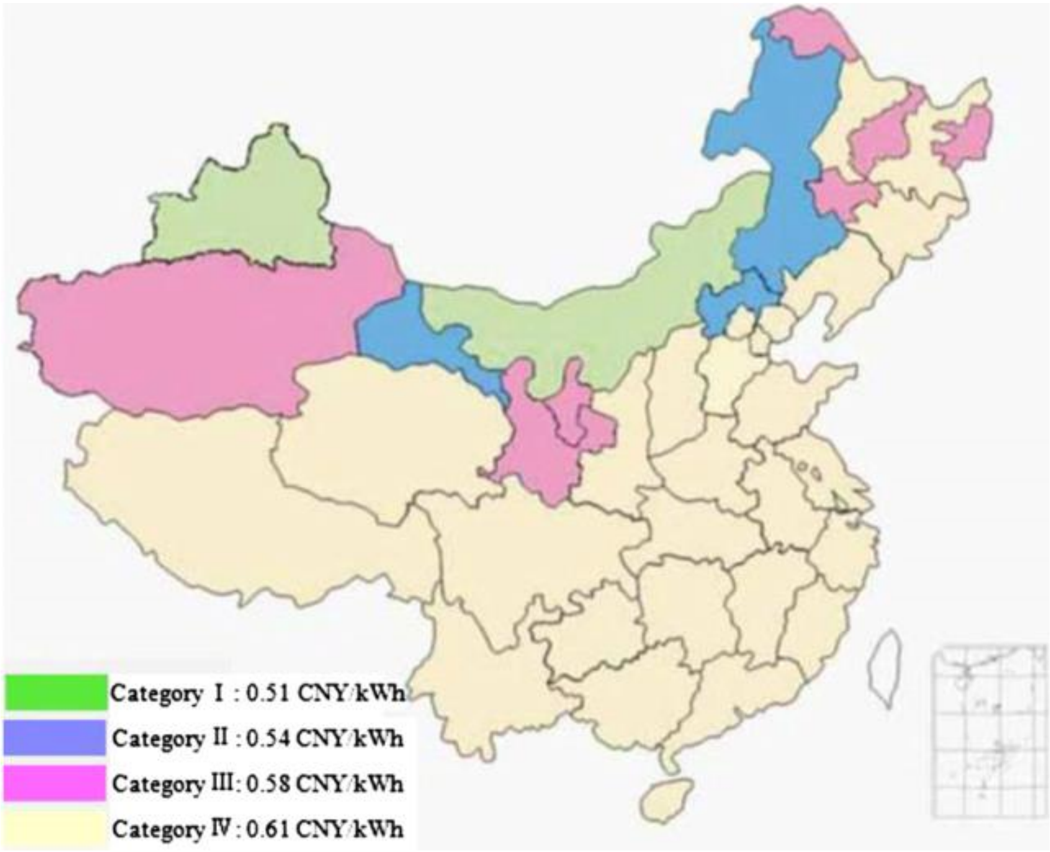


Figure 18: Feed-in-tariffs for onshore wind power, Source: (Hu, et al., 2013)

3.2.3 Upcoming Challenges

China’s ambitious renewable energy goals will continue to bring challenges to the grid. The country aims to reach 200 GW of installed wind capacity and 50 GW installed solar capacity by 2020. (The Electrical Energy Storage Magazine, 2014) The rapidly growing wind power in China over the last decade, and especially after the first Renewable Energy Law was issued in 2006, had already brought substantial challenges for the county’s grid infrastructure. The majority of wind farms in China are built in northern or north-western parts of the country due to suitable weather conditions. The demand of electricity however, is mostly situated in the eastern parts of the country. This means that electricity has to be transmitted through large distances to reach the demand centres, as seen in Figure 19. For example, the distance from Xinjiang province to Central China Grid is 2 500 km and to Eastern China Grid the distance is 4 000 km. (Li, et al., 2012)

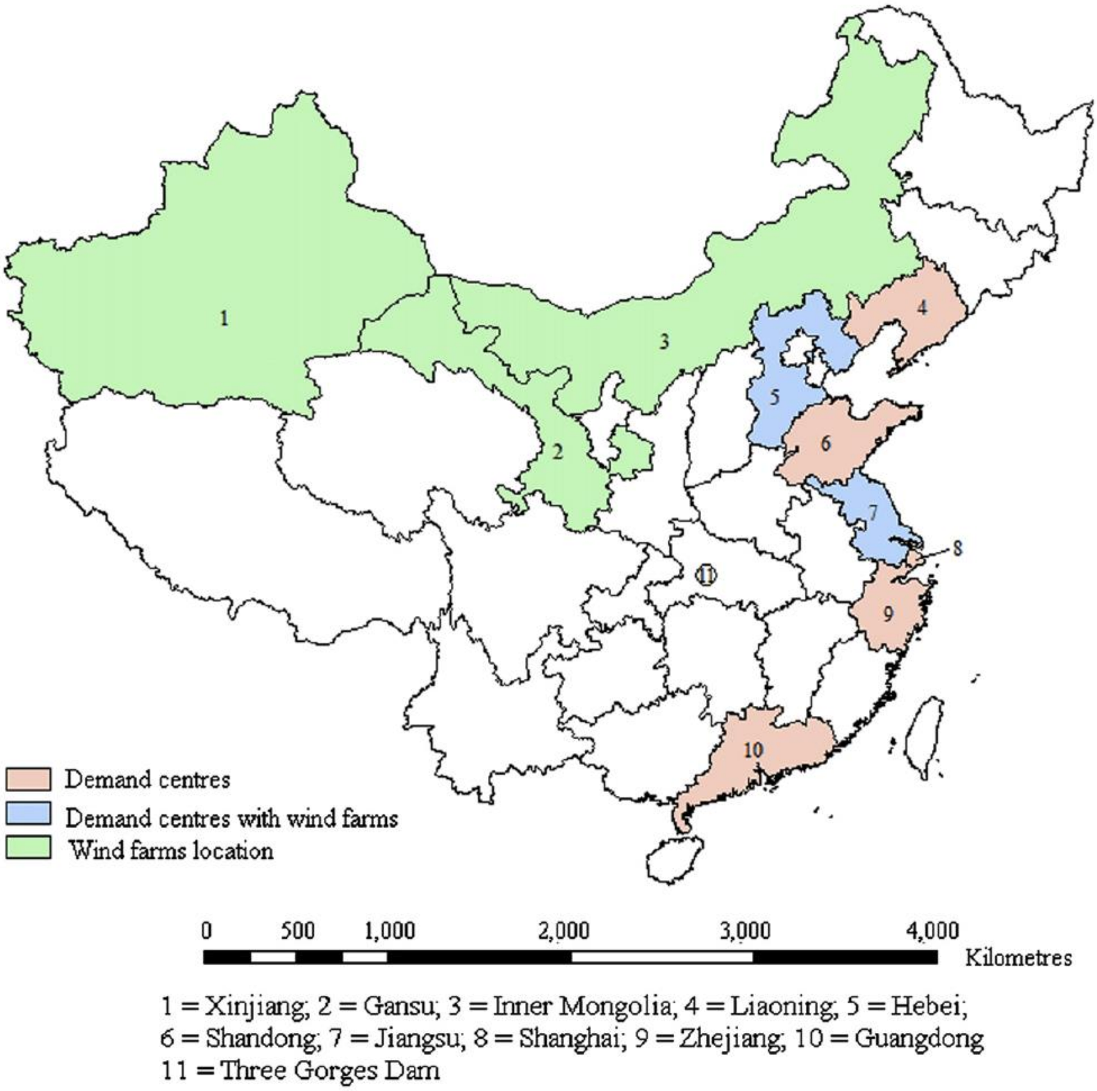


Figure 19: Locations of wind farms and electricity demand centres, Source: (Li, et al., 2012)

The geographic disparity between power demand and the geographic distribution of installed wind power capacity put pressure on grid connectivity. Demand centres are far away from the large wind resources in the northern parts of the country, where grids are fairly weak with insufficient capacity or technology to feed in the wind power. Grid balance can be disrupted by low-quality generation, resulting in further wind capacity surplus. Given that technology remains unchanged, the allowable grid-connected wind power capacity will be limited to a relatively low level, otherwise the grid cannot work. Wind power generation exceeding allowable grid-connected capacity will therefore be curtailed, even though wind power has access priority to the grid. (Wu, et al., 2014)

Wind power curtailment along with the lack of transmission capacity from wind power plants is a large problem in China. As seen in Figure 20, the curtailment for some provinces is substantial. The total wind curtailment in China reached 12.3 TWh in 2011, representing 16 percent of China's total generation from wind power. This result in an economic loss of over 1 billion US dollars, leading to 7.6 million tons of carbon emissions from coal power plants that could have been saved. (Clavenna, 2012)

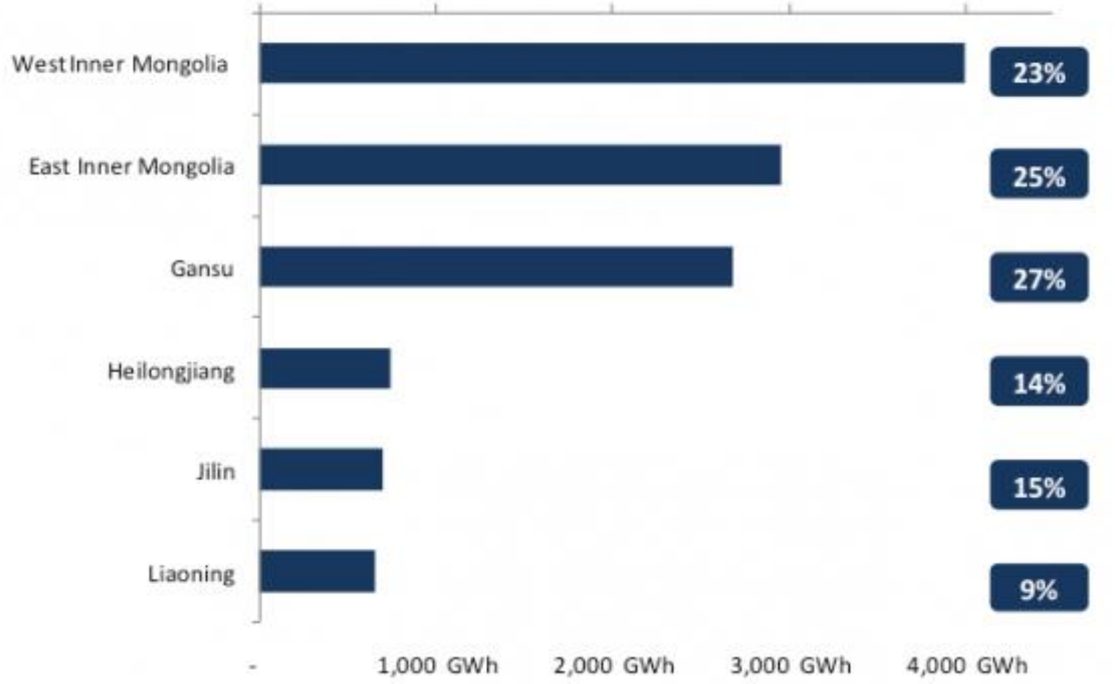


Figure 20: Percentage of curtailed wind generation by province in 2011, Source: (Clavenna, 2012)

A few factors represent the major challenges in the country and contribute to wind curtailment. Infrastructure is influenced by a weak transmission grid, long distances between wind resources and load centres, coal-fired power plants and insufficient market mechanisms. According to Li et al. (2015) feed-in tariffs are unfavourable and dispatch priorities are unreasonable. In addition, wind power grid integration is insufficient. (Li, et al., 2015) Also Wu et al. (2014) recognizes that present policies hinder improvement of wind power integration technology. Wind power integration can be developed by increasing wind power generation quality (by stabilizing the output) and by improving grid technology. However, wind power companies have no incentive to invest in solutions to increase generation quality (including system control, dispatch and transmission), since the area pricing of wind power is based on fixed benchmark prices unrelated to generation quality. The income depends on wind power capacity, which technological enhancement cannot increase in a short time perspective. (Wu, et al., 2014)

Moreover, Chinese power grid companies have no incentives to improve wind power connection technology. The companies pay a fixed price for wind power, regardless whether grid technology is improved or not. Low-quality wind power generation can be curtailed to ensure system security, since there is no obligation to connect wind power into the grid if the grid connection requirements are not satisfied. Thereby, instability from low-quality wind power generation can require large investment costs for grid companies to improve infrastructure and regulating technology. In addition, wind power has higher price than traditional energy sources and increases consumer costs. Thereby, electricity demand decreases following an income reduction for power grid companies. Consequently, power grid companies do not profit from improving wind power integration technology. (Wu, et al., 2014)

Chinese wind power policies has created reverse wind power incentives for generators and transmitters. Consequently, the ability to manage wind power is currently far behind installation development. Wu et al. (2014) suggest a reformation of the wind power pricing system in order to remove imbalanced benefit distribution and encourage coordination on the wind power market. Also, economic incentives and regulations for wind plants could result in that grid connection requirements can be reached. By introducing risk-sharing instruments, stakeholders can become aware of and carry out required obligations, such as system balance. By policy and instrument improvements wind surplus can be reduced, wind power development promoted and the environment protected. (Wu, et al., 2014)

3.2.4 Emerging Market

China is a developing country with an emerging market. This is supported by MSCI (2015), which classifies China as an emerging market. This classification is set by several criteria's such as; economic development, size and liquidity requirements and the market accessibility (MSCI, 2014).

Many emerging markets have larger instability and stronger regulations compared to developed markets. Lou (2003) state that the growth rate in emerging markets is fast and instable, with many businesses existing at growing stages. Businesses in rapid growing industries are more likely to challenge unpredictable market fluctuations than in slow-growing industries. (Luo, 2003) Moreover, Wang et al. (2014) recognize that China is influenced by fast urbanization, which tend to increase energy consumption and carbon emissions. The energy sector, containing a large share of water-intensive coal production, put large constraints on water resources (International Energy Agency, 2012). To become a low-carbon economy, Wang et al. (2014) stress the importance to increase renewable energy technologies and develop energy policies.

Renewable energy technologies are today expanding in developing countries. According to the International Energy Agency (2014), global energy trends indicate that several developing economies have intensified ambitions to become frontrunners in the development of low-carbon energy technologies. As an example, more than half of the world's solar PV installations were located in Asia in 2013. Furthermore, China's electrification of the transportation sector has increased in order to reduce carbon emissions and improve air quality. (International Energy Agency, 2014)

Technology development has also advanced over the last decade, to reach economic and climate targets. The International Energy Agency (2015) recognizes that China aims to gain economic advantage from implementing more sustainable energy policies and technology reforms. This could accelerate innovation of low-carbon technologies and promote additional climate goals. While expanding infrastructure, developing economies can be early movers in applying a system transition to low-carbon technologies. Dynamic power systems require major investments or have a major increase of demand. In such power system, a complete system transition can be beneficial to balance demand and response more efficiently. In a more stable power system, such transition would result in higher economic pressure. (International Energy Agency, 2015)

As developed economies become more devoted to decrease carbon emissions, national climate targets promote increased share of intermittent power generation. Further, to reach targets of reducing global emissions climate actions in emerging economies will be critical. Thereby, the International Energy Agency (2015) recognizes that developed economies' market and energy policy experience can support energy actions in developing countries. By transferring knowledge and technology support to developing economies, research and strategies for technology advantages can be designed and air pollution reduced.

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4. MARKET ANALYSIS OF VARIATION MODERATORS

This chapter investigates the market for grid battery storage and transmission as variation moderators for intermittent renewable power generation. Since grid battery storage is an emerging technology without an established market, potential market entry barriers are first considered. Thereafter, market driving forces that influence and drive the development of grid storage integration, are identified and analysed. This is followed by an analysis of market driving forces for transmission expansion. These forces depend on country-specific conditions and are thereby analysed for Sweden and China separately.

4.1 Grid Storage

Battery storage can change the power system and become one of the market leading storage technologies for grid applications. This is supported by The Boston Consulting Group (2010) and Insight_E (2014). Insight_E (2014) expects Li-ion batteries to be a foremost battery storage technology in the future. The technology development is driven forward by increasing demand of electric vehicles and home storage batteries. Today there is also an increased interest in Li-ion battery technology for large-scale grid applications. (Insight_E, 2014) Further use of storage is expected to make prices and efficiencies more favourable and therefore more economical. (The Boston Consulting Group, 2010) Because of the recent appearance of large-scale Li-ion battery storage, there are still limited data available and substantial market entry barriers to overcome.

4.1.1 Market Entry Barriers

Implementation of grid storage in the electrical power system is associated with several market entry barriers. The most significant have been identified as ownership and operation uncertainties, recognition by policy makers, product diversity, competition, capital requirements, market experience, technical performance and changing market conditions.

4.1.1.1 Ownership Uncertainties

One barrier of entry for grid storage establishment is to clarify which market actors that should own and operate the storage. Since the national grid in both Sweden and China is owned and operated by the government in respectively countries it puts constraints on the ownership question for grid storage.

Current monopoly situation can hinder grid storage integration. The transmission grid in Sweden is owned and operated by a state-owned monopoly that decide whether to invest in new technology or not. Similarly, China's transmission grid is owned by two state-owned companies, creating an oligopoly. Grid operators would benefit from grid storage, but the technology would also bring high investment costs. Anuta et al. (2014) argue that grid operators can cover the high capital cost associated with grid storage integration better than other potential market actors. The storage system could provide continuous power regulation and be owned and operated by grid operators, as a part of the transmission system. Transmission grids that receive intermittent power is suggested to consider energy storage in accordance with established regulation. (Anuta, et al., 2014)

Potential owners involve market actors from the energy sector, which have the right knowledge to make an impact on the market situation. This is supported by The Boston Consulting Group (2010) that has identified power producers as possible third party owners of grid storage facilities. It is however uncertain whether these actors will be allowed into the current energy infrastructure or not, since the transmission grid is controlled by monopolies. Ownership by small power producers could involve investment issues because of high capital costs and partnerships between market actors might be necessary. (The Boston Consulting Group, 2010) In this manner, grid operators are more likely to carry the large investments better than small power producers.

Conversely, European legislation can be a major barrier for storage ownership by grid operators. This theory is supported by several research findings within the area. There is a risk that storage can be classified as a generation tool that would intrude the market rules for unbundling ownership, included in a directive created by the EU. If grid operators acted on the generation market, the system wide responsibility could be hindered. Furthermore, neither a clear definition of storage nor a framework is provided by the EU. However, the benefits of deploying energy storage to the grid are recognized. (Insight_E, 2014) (The Boston Consulting Group, 2010) The uncertainty about how to interpret EU's unbundling directive sets central barriers for grid storage integration and storage development in EU membership countries. Vague ownership regulations constitute obstacles for grid operators and potential stakeholders and hinder the development of power system enhancement.

Because of the unbundling directive, power producers might be the only possible owners of grid storage in the EU today. Power producers can also benefit from grid storage facilities by taking advantage of spot price fluctuations on the competitive market and increase income. In addition, more energy can be utilized since less energy would be curtailed. It is however uncertain whether these actors will be allowed into the current grid infrastructure or not, since the grid is controlled by monopolies.

China's controlled market does not bring power producers incentives to invest in grid storage technologies, since no profit can be received from spot market fluctuations. Neither power grid companies nor power producers, such as wind power companies, have economic incentives to invest in regulating technologies like grid storage, as described in section 3.2.3. There is no further profit to be received by improving wind power integration technology or by increasing generation quality. Instead, wind power generation is curtailed to ensure system security.

4.1.1.2 Operation Uncertainties

Uncertainties about storage ownership also involve challenges about how the grid storage should be operated. There is a potential risk of conflicting interests between the owner and the operator of a storage facility. Insight_E (2014) acknowledge that the owner would want to take fully financial advantage of the storage by dispatching electricity according to market data and price anticipations. Operators of the grid storage would on the other hand want to dispatch electricity depending on grid requirements. (Insight_E, 2014) This potential conflict could be reduced by introducing a clear regulated framework.

The risk of conflicting interests could also be limited if the same market player owns and operates the grid storage. At an early stage of market entry, small power producers can be the best possible operators of energy storage systems. In comparison to large established utilities, small utilities can be more adjustable and open for new business opportunities that can strengthen the market position. Small-scale community storages might be more convenient at first, while large-scale energy storage systems might require partnerships between several market actors. Once the market for energy storage is established, new actors can appear and larger storage facilities integrated. This is supported by The Boston Consulting Group (2010), which also expects regulators to increase power producers' responsibility of balancing power at peak and off-peak hours. Furthermore, present PV suppliers already offer battery storage solutions in small scale. Energy storage could also be provided in a large scale, and assist power producers in providing balance regulation. (The Boston Consulting Group, 2010)

4.1.1.3 Government Policies

One of the largest barriers of successful market penetration is found to be absence of *recognition by policymakers*. There is not a developed framework for energy storage for grid use, which causes uncertainty for stakeholders that hold back potential investments in the business. The lack of standards can cause stakeholders to invest in other areas where the market is more mature. This is supported by Anuta et al. (2014), who point out that technologies of renewable energy sources can benefit from inclusion within the renewable energy targets and therefore be perceived as cheaper compared to grid storage. Inclusion of energy storage into the renewable energy targets would however be problematic, since the energy stored can originate from any kind of energy source. (Anuta, et al., 2014) Also the Electric Power Research Institute (2013) recognizes challenges for regulators and policy-makers to valuate energy storages, since comparison with other conventional solutions is problematic. Operation can be viewed both for generation and for loading, but with limited energy duration. There is also a lack of commercial track record of energy storage, which can cause uncertainties about costs and performance related to energy storage utilization. (Electric Power Research Institute, 2013) Because grid battery storage is an emerging technology, government action is necessary to initiate the market development.

Government policies have large effect on market entry, where standards, regulations and restrictions affects the barrier of entering a market. This is supported by Porter's (1979) theory about market entry barriers. There is an absence of business models and regulatory framework for integrating grid storage in the present power system. The lack of standards and measures of connecting, operating and maintaining grid storage is also recognised by previous research (Anuta, et al., 2014) (Eyer & Corey, 2010). Governmental support can provide economic incitements for energy storages and be of great importance in order to promote improved balance in the energy infrastructure system.

Reasonable compensation set by authorities and regulators can be significant important to further promote grid storage development, especially since energy storages do not yield income that investors normally require. This is confirmed by Eyer & Corey (2010) and Anuta et al. (2014), who recognize the importance of authorities and policymakers recognition of the advantages that energy storage systems can carry. Subsidies could help reduce the large capital cost to lure investors into this new business area with high risks and lack of clear regulations. Compensation for energy storage can impede stakeholders' current cautiousness in taking high risks on new technologies because of large investment costs and conventional regulations. (Anuta, et al., 2014), (The Boston Consulting Group, 2010) When a few actors initiate market investments, the market development is driven forward. Recognition of the value of grid storage by policymakers could thereby reduce the entry barriers for the technology.

To implement an effective and robust *business model* is important for grid storage penetration on the power market. In order to do so, governments should consider grid storages as variation moderators and provide a *regulated framework* to reduce uncertainties in investment decision making. Robust business models for integrating energy storage would drive and increase the market potential of integration into the electricity grid. In consistency to Anuta et al. (2014) findings, stable electricity markets and policies are driving forces which can decrease capital costs by reducing uncertainty in energy storage investments and at the same time stimulate the technology development. Anuta et al. (2014) identify the need for modernisation of the current market structure, by establishing suitable regulation for grid storage and policies to provide opportunities for stakeholders and third party owners of grid storage systems to build sustainable business models. According to Anuta et al. (2014), the design of applied business models should depend on grid location, regulations, ownership and market structure, in order to implement grid storage successfully.

4.1.1.4 Product Diversity

A potential market barrier is the diverse types of energy storage technologies. There are many potential technologies and applications for grid storage, but no single technology available has the appropriate characteristics for all applications. This is confirmed by previous research findings by Karlsson & Dahlqvist (2014). This can result in competition over funds for research and development of several grid storage technologies. The development of different types of energy storage technologies can be a potential barrier, since product differentiation can form a source of market competition at the market entry stage. This is supported by Porter (1979), who also claims that product differentiation can decline as the business mature and then lower barriers of entry and increase buyer-power. (Porter, 1979) As one or a few grid storage technologies establish the number of applicable grid storage technologies might decrease.

4.1.1.5 Competition

Apart from the product diversity within energy storage technologies, there is also competition from other technologies which also have the potential to provide flexibility on the energy market. Competition is expected from flexible generation[1], integration of demand response[2] solutions, Smart Grids[3], distributed generation[4] and renewable technologies. (Eyer & Corey, 2010) (International Energy Agency, 2014) Adjustable wind generation and increased transmission capacity are two other examples of competition. (Johnson, et al., 2014) These competitive technologies and solutions compete for funding and a place in the future electricity market (Eyer & Corey, 2010). The economical aspect, with high capital costs for grid storage technologies, can hinder grid storage to compete with other, more cost-effective technologies.

Previous research findings has compared the cost of expanding the transmission grid and the cost of integrating grid storage, resulting in diverse conclusions. According to findings by Döring et al. (2014), options like grid expansion can today be more cost-effective than energy storage. This is however a controversial and depends how cost estimations are performed. As the cost for grid storage technology decreases, storage can in some situations provide a more flexible solution. According to the International Energy Agency (2014), the demand of energy storage is expected to increase as intermittent power generation increases, due to the system flexibility that energy storage can provide.

It is likely that energy storage will be a part of the infrastructure development, in combination with other flexible technologies and solutions. Even though grid storage will not be the only key technology in the future energy infrastructure, it can provide an important asset in a system-wide development. Both the International Energy Agency (2014) and Anuta et al. (2014) confirms this theory and recognize that energy storage can be combined with other interconnecting and demand-response solutions. Research and development for grid storage should therefore be integrated with the present infrastructure, in order to optimize investments and management in the future electricity system. This is confirmed by the International

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[1] Generation that is easy to regulate, such as hydro power and gas power plants.

[2] Federal Energy Regulatory Commission defines Demand Response as: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." (Balijepalli, et al., 2011)

[3] Smart Grids is an international concept of a future efficient electrical system. By using new technology the current system can be developed to meet the demand of a sustainable energy supply in the most cost-effective way possible. (Svenska Kraftnät, 2013b, p. 58) Communication, control and computer technologies are expected to be important for reduced costs and increased reliability. Smart Grids is expected to enable efficiency and new products, services and markets. (Eyer & Corey, 2010, p. XXVII)

[4] Distributed generation refers to power generation that takes place close to the consumption. Generation occur on- site which reduces the costs of transmission and distribution. Historically this kind of generation came from combustion generator like diesel generators. Today, solar power has become a popular distribution generator. (Bloom Energy, 2014)

Energy Agency (2014), which promotes a wide system thinking. Nevertheless, for energy storage to compete with other options cost-effectiveness is a key aspect.

4.1.1.6 Capital Requirements

Large capital cost is a major financial barrier for market integration of grid storage. This statement is supported by many sources, including Johnson et al. (2014), Hittinger et al. (2012), Anuta et al. (2014), International Energy Agency (2014) and Eyer & Corey (2010). Moreover, Porter (1979) identifies large capital requirements as a barrier of market entry. This applies especially if the required capital is used for costs that cannot be recovered, such as for Research and development (Porter, 1979). Such costs are likely to be required for market integration of grid storage technologies that have not yet been introduced for large-scale usage. This is confirmed by The Boston Consulting Group (2010), that recognize that the technology for large-scale application of electricity storage is not fully formed and inadequately operational tested, with the exception of hydro pump storage. Historically, energy storage research has focused on improving performance. Improving the manufacturing process to be able to decrease the capital cost will be far more valuable in the near term, which is confirmed by Hittinger et al. (2012). The real costs and worth of energy storage can, according to Anuta et al. (2014), change if the technology improves, investment costs decrease and knowledge among users increase.

4.1.1.7 Market Experience

One market entry barrier for grid storage is the lack of market experience. According to Porter (1979), market experience involves several advantages which stimulate cost reduction, including economies of scale, capital-labour replacement and efficiency among workers. Eyer & Corey (2010) acknowledge that limited understanding, knowledge and experience of energy storage together with limited risk-reward sharing mechanisms are major challenges which energy storage involve today.

However, as technology improves and the technology cost reduces, the entry barrier may no longer exist. According to Porter (1979), new competitors can even experience a cost advantage when exempted from large investment costs. In this matter, grid storage might require less investment cost in the future after integration on the energy market. Although the first market actors may experience high technology costs, the costs might decrease for following actors entering the market. In this manner, the technology of Li-ion battery is advantageous for market integration of grid use. As the battery technology is developed for electric vehicles, the market experience increases.

4.1.1.8 Technical Performance

A key challenge for all electrical storage technologies is limitations in technical performance. There is a loss of energy in all systems and the efficiency can be as low as 80 percent for battery storage. The low efficiency can cause a disadvantageous business situation and entails costs for the lost electricity. (The Boston Consulting Group, 2010) This, together with high capital cost, can hinder grid battery storage to be economical profitable.

Technical performance can also hinder storage integration with large wind farms that require large storage capacity. A technical limitation is the amount of energy that can be stored, which Karlsson & Dahlqvist (2014) confirm. Li et al. (2012) claims that the energy storage capacity for electrochemical energy storage systems cannot provide satisfactory support to wind farms, with an installed capacity of 50 MW. This could, according to Li et al. (2012) make electrochemical energy storage inappropriate in China, where the majority of wind farms exceed 50 MW installed capacity and it could therefore be hard to find a suitable reserve capacity system to obtain security of supply. (Li, et al., 2012) However, from a system perspective as this thesis focus on, grid storages can be scaled by building numerous storage units connected in the system to obtain desired power capacity.

4.1.1.9 Changing Market Conditions

The disability to look several years ahead can be a market entry barrier for an emerging technology as grid battery storage. Today the electricity mix does not comprise a large share of intermittent power sources, but the problems related to intermittent power generation is expected to escalate as the share increases. The barriers of entry changes as market condition changes (Porter, 1979). This is consistent with Craig & Douglas (2005), who identify *change* as a market challenge. The fast movement of market conditions force research to adapt and monitor financial, political and technological changes (Craig & Douglas, 2005).

The strong need for grid storage might not exist today or in a near-term future, but several years ahead. According to Holttinen et al. (2011), the share of wind generation is crucial for a cost efficient balancing of energy storage. Wind penetration levels of 10-20 percent of gross demand is not enough for cost-effectiveness regarding grid storage (Holttinen, et al., 2011). Göransson (2014) has found that sufficient variation management can be reached by load shifting from daytime to night-time when 20 percent of the power demand originates from wind power generation. When wind power generation cover 40 percent of the power demand, load shifting will not be enough as variation management (Göransson, 2014). Holttinen et al. (2011) claims that wind penetration levels exceeding 10-20 percent requires extra flexibility, which energy storage can provide. As the share of wind energy grow, the demand for grid storage increases. To recognize the future value of grid storage integration actions must be taken in advance.

4.1.2 Market Forces

Following the market entry barriers for grid storage, several market forces can be concluded. The development of energy storage is driven by several forces which can create opportunities for integrating energy storage into the grid. This section will present the drivers on the market for grid storage.

4.1.2.1 Technology Development

The ongoing technology development increases the potential of energy storage for grid integration. Because of similar technical properties for battery technologies, other research areas such as *Smart Grids*, *electric vehicles* and *home batteries* drive the technology development forward also for grid storages. These developments can have significant role for implementing the storage technology in the energy infrastructure in a large scale. The development for grid storage is also driven by economies of scale from increased use of batteries. (Eyer & Corey, 2010) (Anuta, et al., 2014) (IEC, 2011) (Ny Teknik, 2015)

Li-ion batteries predict to decrease radically in price along with technological improvements due to the electrification of the automotive industry. The growing market for electrical vehicles and for electrical portable devices pushes the battery development forward and drives the costs down (Eyer & Corey, 2010). As seen in Figure 21, large cost reductions have been made in the last few years. The cost reductions can be expected to continue as technology improves in the future. These factors are crucial for grid storage's entry in the energy infrastructure market. As earlier stated, technical and economical restrictions still limits grid storage ability for large scale impact. However, since these issues continuously reduce with the on-going technological development, it could be believed that grid storage will have a bright future in a future energy infrastructure system.

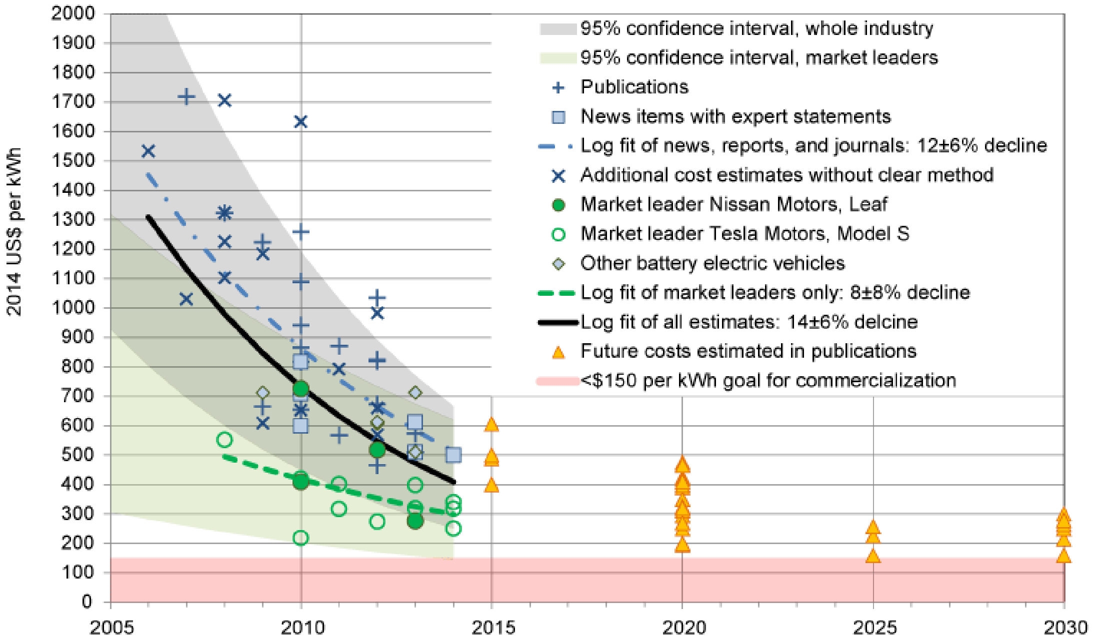

Figure 21: Historical cost of Li-ion battery packs, Source: (Nykvist & Nilsson, 2015)

Also the development of other flexible solutions in the power grid can provide opportunities for grid storage. Energy storage is expected to be a balancing instrument in the future Smart Grid (Anuta, et al., 2014), (IEC, 2011). Smart Grids involves distributed energy resources and load aggregation, which contributes to increasing market demand for energy storage. (Eyer &

Corey, 2010) This follows the growing need for improved electric service power quality and reliability.

Furthermore, batteries for home applications are likely to contribute to a faster development for grid storages as well. According to Ny Teknik (2015), Tesla[5] has announced a battery for home and office applications to expedite the transition to an efficient renewable energy system. Tesla Motors (2015) claims that the price for this home battery of 7 kWh is $3000 which is approximately $430/kWh. This was announced during this study's final moments and it is another example of the fast development within the energy storage field.

4.1.2.2 Congestion and Security

Grid storage has also been recognized as an alternative to expand the current transmission grid, or at least postpone the very costly investment of a new transmission lines, so called *transmission deferral*. This is illustrated in Figure 22. This is verified by Zakeri & Syri (2014) who states that transmission grids are oversized in order to handle temporary peak hours. If the grid capacity needs to be increased, grid storage can be an alternative instead of reinforcing the transmission grid. (Zakeri & Syri, 2014) Likewise, Insight_E (2014) claims that one of the highest value of energy storage is received when investments in new transmission grids can be postponed.

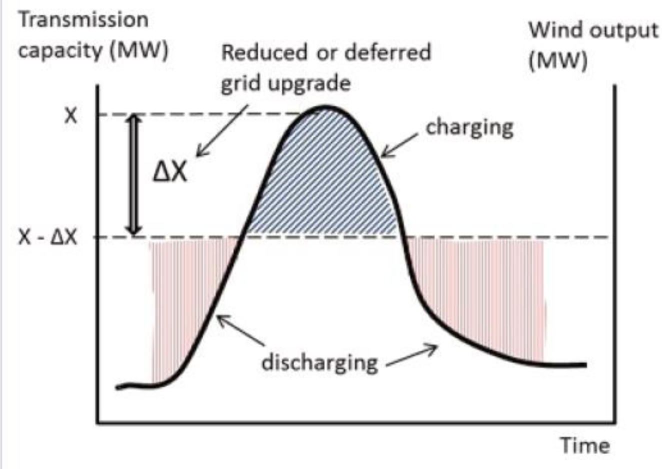

Figure 22: Transmission Deferral, Source: (THINK, 2013)

Problems related to *congestion* in the transmission grid can push the introduction of energy storage into the grid, in order to improve *reliability and security*. According to Eyer & Corey (2010), managing peak demand and reducing congestion on current transmission lines can thereby drive the storage development. This coincide with transmission deferral, as mentioned

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[5] Tesla is an American company, founded in 2003, who designs and manufactures electric vehicles and electric powertrains. (Tesla Motors, 2015)

above, since transmission upgrades also is a solution of the reliability and security issues related to congestion. Postponing costly transmission upgrades by investing in grid storage can reduce issues associated with congestion and contribute to increased economic benefit. Zakeri & Syri (2014) claims that service costs for power supply reliability and grid management can be reduced when implementing grid storage in the energy infrastructure. Avoiding oversized transmission capacity can also lead to decreased losses in the grid (Brakelmann, 2003) (Negra, et al., 2006).

Furthermore, grid storage can provide new opportunities for operating the transmission system in case of incidents and major disturbances. Döring et al. (2014) claims that the increase of intermittent renewable energy in Europe has decreased existing security margins. Moreover, integration of grid storages can contribute to an even higher reliability than grid reinforcements can. In addition, the economic cost associated with reliability cannot be assigned by market instruments. The reliability and system security aspect has a social value and belongs in a regulated framework for energy storage. (Döring, et al., 2014) The development of grid storage would not only lead to improved system reliability and security, but also reduce wind curtailment.

4.1.2.3 Wind Curtailment

Wind curtailment can be a future concern in Sweden and is already a major problem in China. By operating grid storage for renewable time shifting, more wind power available can be used and wind curtailment reduced. By utilizing more energy from the wind, wind farm investments are used in an efficient manner. Thereby, storage can contribute to increased economic benefit, which also coincides with an environmental friendly and sustainable thinking. Figure 23 shows how grid storage can influence the amount of curtailed wind energy based on a simulation modelled by Silva-Monroy & Watson (2014). The result of integrating a 500 MW storage shows a clear reduction of spilled wind energy by about 2 percent. (Silva-Monroy & Watson, 2014)

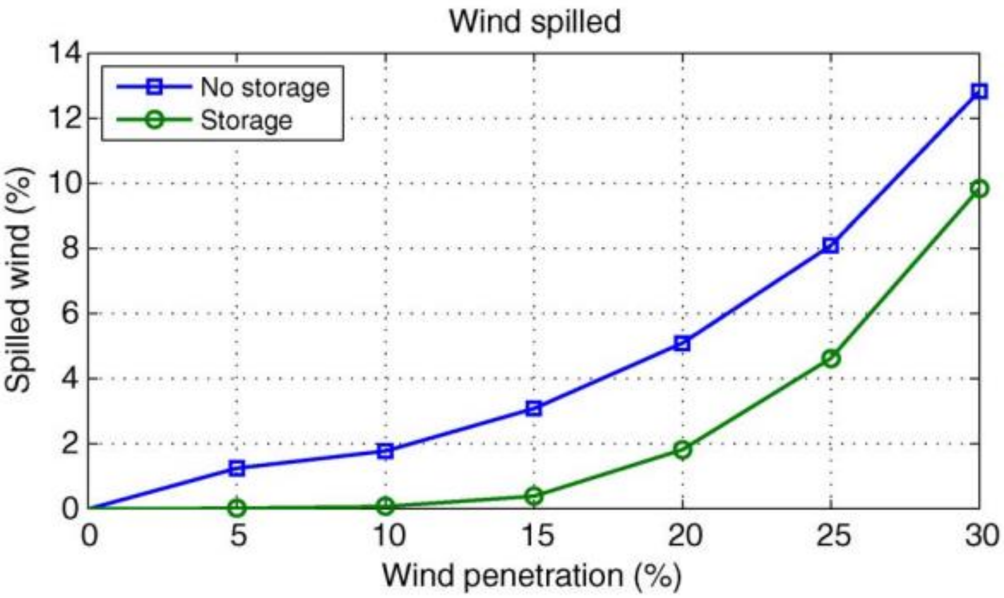

Figure 23: Wind curtailment as a function of wind energy penetration, with and without a 500 MW storage device. Source: (Silva-Monroy & Watson, 2014)

However, other studies have shown that it might not be cost efficient to invest in grid storage for only a few MWh of curtailed energy. Holttinen et al. (2011) claims that it can be preferable to spill a few percent of the annual wind power generation due to economic reasons. This is supported by Johnson et al. (2014), who claim that batteries available today and in the near-term future are found to be too costly to reduce curtailment in an economical viable way. Yet, the share of intermittent energy sources is increasing, meaning that curtailed energy can increase. In a long term perspective, it is reasonable to believe that integration of grid storage, with the purpose to reduce curtailed energy, will be more economically reasonable.

Furthermore, problems related to spill could be solved by investing in flexible energy systems as storage rather than investment in new transmission grids to export generation surplus. Lund & Münster (2003) claims that investment costs for new transmission lines are significant higher than costs related to avoid surplus generation. The recommendation is thereby to invest in a flexible energy system, including heat pumps, regulation of CHP plants and heat storages to limit surplus generation. The solution of a flexible energy system is found to be the best option independently if the market price is high or low, but dependently on market reactions on surplus generation. If the market reacts, substantial profits can be made. (Lund & Münster, 2003) These findings are of great interest for this master thesis, since it is found to be more economical to avoid generation surplus, by for example including energy storage, than to transmit excess energy to another areas.

4.1.2.4 Economic Incitements

Renewable time shifting can not only reduce wind curtailment and congestion problems but also profit from the spot market. Since there are large gaps between peak and off-peak prices, the storage unit can be charged when the electricity price is low and discharged when the electricity price is high. The off-peak prices are most likely to occur when congestion occurs and there is an excess of energy in a certain bidding area. This is verified by Anuta et al. (2014) who claims that high electricity prices as well as large gaps between peak and off-peak prices are two driving forces for energy storage. Further, Zakeri & Syri (2014) also argues that grid storage can be operated to receive higher electricity prices on open spot markets for electricity trading. The profitability of energy storage can thereby increase due to deregulation of electricity markets and price arbitrage. The level of economic benefit depends on how much the spot prices fluctuate.

These increased revenues can be retrieved by price forecasting along with optimized scheduling for charging and discharging time. This is also concluded by Zakeri & Syri (2014) who claims that improved price forecasting and optimized scheduling for charging and discharging energy will lead to increased revenue from energy storage systems. However, if congestion is reduced due to increased integration of variation moderators such as grid storage and transmission, also the incitement of spot market benefits reduces since the fluctuation in prices would not be as high. In a long-term perspective, the electricity prices at peak hours would decrease as there is no longer a lack of supply. Similarly, low dips in electricity prices will be reduced as excess energy supply can be either stored or transferred to another location where the demand is higher. This does not apply for the Chinese market where they have a predetermined feed-in tariff. Furthermore, there are sources that claim that the average electricity price in Sweden will increase in the future. (Ramböll, 2014) (Sweco, 2014)

High generation costs to stabilize intermittent power generation can be reduced. To adjust frequency from instable generation thermal generators are normally used. As the share of intermittent energy sources increases the output margin from thermal generators must intensify, which reduces efficiency. If grid storage can alleviate output fluctuations from intermittent power generation, the thermal generators can operate at a higher efficiency. (IEC, 2011) Thereby, high generation costs can be reduced and efficiency improved.

4.1.2.5 Energy Targets

The growing sustainable thinking in the world in recent years has made wind power to one the most emerging energy sources on the planet. The EU has set certain *energy targets* for 2020 and 2030 where wind power plays an important role since the targets involves increasing the share of renewable generation to decrease *greenhouse gas emissions*. (European Commission, 2015) Insight_E (2014) recognizes that energy storage can bring an important advantage for the EU to reach these energy targets. This is assumed to be one of the most important driving forces for grid storage success of entry in the future energy infrastructure. However, it depends of course of a lot of other factors such as political, technical and economical properties.

China faces major *pollution* issues along with a rapidly growing economy which also contributes to wind power development. However, this leads to issues in the energy infrastructure due to the intermittent electricity generation from wind power. Furthermore, Littlewood (2013) claims that over 80 percent of applications for energy storage projects have the purpose of integrating renewable energy in China. As displayed in Figure 24, Li-ion is the foremost technology with over 100 MW installed capacity (Littlewood, 2013). Also globally, several targets are associated with a cumulative share of intermittent energy sources. The growing amount of intermittent renewables that requires regulation gives opportunities for energy storage (Eyer & Corey, 2010).

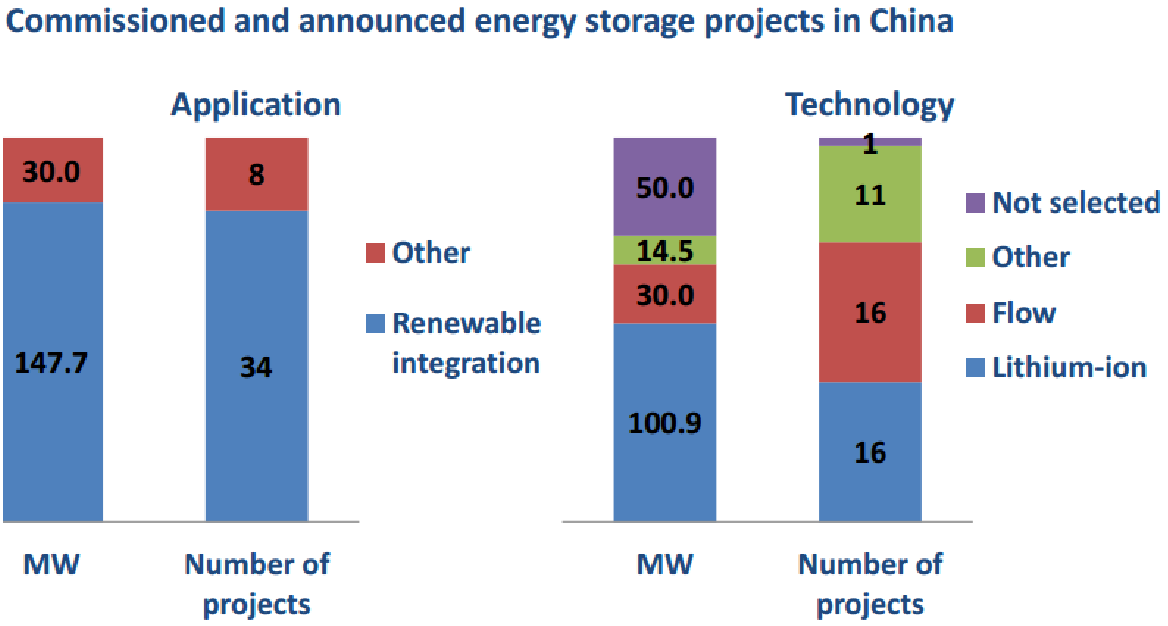

Figure 24: Energy storage projects in China. Source: (Littlewood, 2013)

4.2 Transmission

The increasing share of intermittent power generation yields that increased transmission capacity is necessary in order to secure the supply and maintain a stable and suitable voltage profile. Holttinen et al. (2011) claims that integration cost from transmission investments may be required for handling larger power flows and maintaining a stable and adequate voltage profile. It is also needed if congestion occur on the grid, due to new wind generation far from load centres. However, grid reinforcements have other benefits to consumers and producers such as reliability and/or increased trade. The level of investments needed is very dependent on where the wind power plants are located relative to current grid infrastructure and load. Furthermore, they are not continuous and can differ and be very high in some cases. (Holttinen, et al., 2011) Holttinen et al. (2011) also claims that the amount of grid reinforcements should be customized to final amount of wind power instead of investing in several different phases. However, it is not efficient to invest in grid reinforcements to avoid bottlenecks on the grid completely. It can be preferable to spill a few percent of the annual wind power generation due to economic reasons. Furthermore, a system without bottlenecks can be classed as over-sized and not economic optimal, of course should severe bottlenecks be avoided. (Holttinen, et al., 2011)

4.2.1 Market Forces Sweden

Congestion is a major driving force for transmission expansion and leads to imperfect market competition. According to Shrestha & Fonseka (2004), constraints or bottlenecks, in any form, will prevent perfect competition between market participants in the transmission grid. The consequence of this is price hikes above the marginal costs. To maximize the social welfare it is important that supplier surplus (SS) and consumer surplus (CS) is maximized. The SS curve and CS curve, respectively, can be seen in Figure 25. Furthermore, to maximize social welfare an effective transmission system operation and planning becomes important. (Shrestha & Fonseka, 2004)

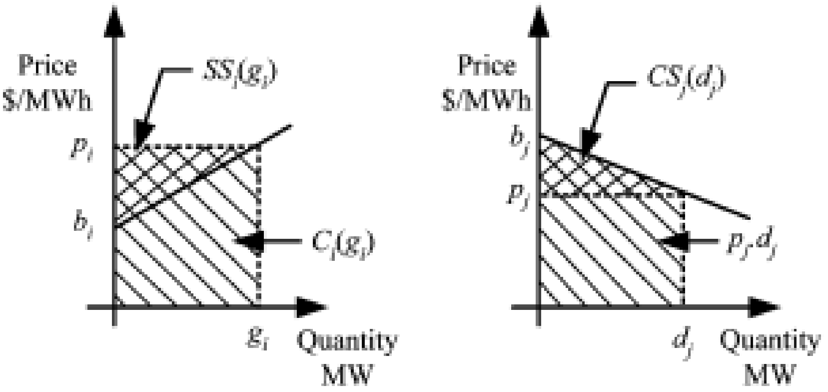

Figure 25: Supply and demand side bid representation

The development of transmission in the Nordic countries is driven by market factors such as *price differences* in different bidding areas, due to congestion. According to Göransson (2014), an increase in exchange capacity between the Nordic countries would make it possible to transfer electricity from one trading partner with low marginal cost to another one with higher marginal cost. Low marginal cost is attractive to electricity intensive industries and other electricity consumers, but is less attractive to the power industry. However, large investments in transmission create marginal costs corresponding to marginal costs during low-load hours in the United Kingdom and Germany. Thereby, it is possible to take advantage of importing at a low price and exporting at a high price. (Göransson, 2014) This could create economic incentive for the power market in the Nordics to invest in further transmission expansion.

Furthermore, *spot price fluctuations* on the market also create an incitement to invest in increased capacity. Electricity can be bought at a low price and sold at a higher price. However, this incitement might be reduced over time, as installed capacity of variation moderators increases, and the price differences between peak and off-peak hours reduce. This also applies for increased grid storage integration, as discussed earlier in section 4.1.2.4.

Also at European level, transmission development is driven by removal of bottlenecks. Internal grid expansion in Sweden and other countries in Europe is necessary to stabilize the generation in Sweden. Removal of bottlenecks between European countries as well as domestically yields stabilized generation patterns of conventional generators according to Aigner (2013). This might lead to an overall price reduction of 5 percent and in some areas a reduction of about 40 percent, in comparison to the case without grid expansion. A cost-optimal grid expansion requires investments of $39.3 billion in 2030 but result in decreased production costs of $20.1 billion. The resulting payback time is a period of about 6 years. (Aigner, 2013) This highlights the importance of a favourable investment situation as a condition for making large investments in the infrastructure.

Another driver for transmissions development is EU's target of a *United European Electricity Market*. This target creates incentive to strengthen transmission capacities inside of Sweden and to connect to the rest of Europe to increase *reliability* and *security*. To create a united market in Europe it is necessary to develop the transmission grid. Some of the existing work within this field promotes cross-national methods for a joint energy market in Europe in a system with more large scale wind power. According to Aigner (2013), an energy market without integration require more regulation power because of increased need to balance the system. Costs can be reduced by exchanging regulating reserves in an integrated power market in Northern Europe, involving grid expansion. (Aigner, 2013) This is seen as a strong driver for transmission expansion.

National and international energy and climate politics drives reinvestments in Sweden's *aged transmission grid*. Grid constraints can otherwise hinder the societal development. A large part of the Swedish national grid is more than 50 years old, as shown in Figure 26. According to Svenska Kraftnät (2013b), reinvestments in the grid are necessary to reach energy targets to increase the share of *renewable energy*. Reinvestments are necessary to replace aged parts in the system to increase *reliability and security*. Benefits from this can be taking by investing in new and more efficient equipment that will lead to an upgrade of installed capacity. Since reinvestments generally are not as costly as building a completely new transmission line this could be beneficial for transmission development.

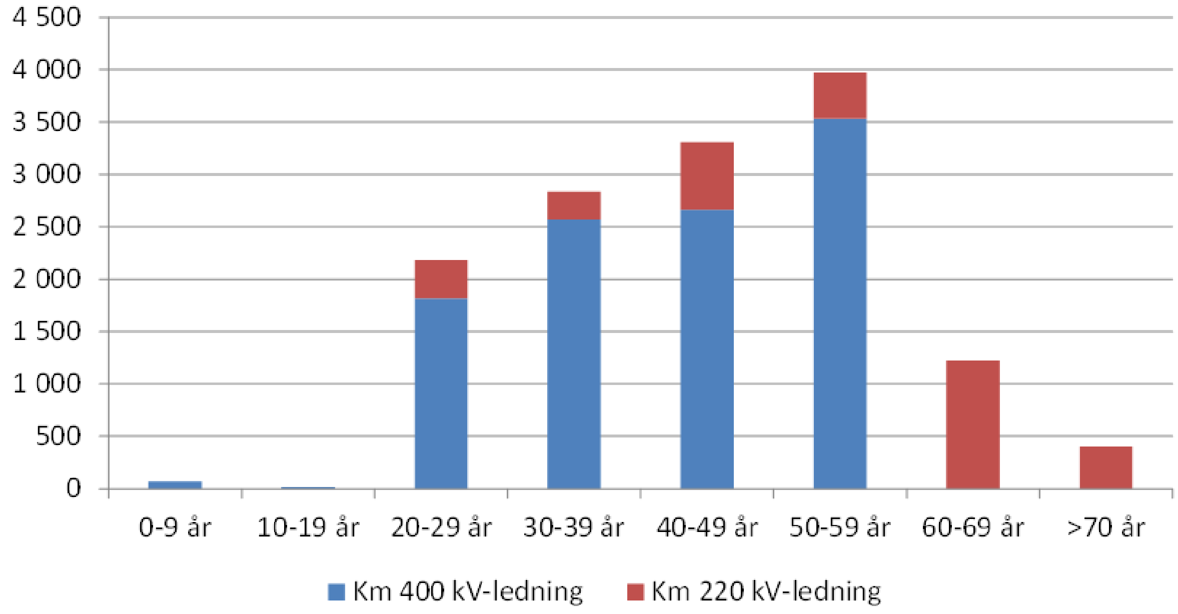

Figure 26: Age of 400 kV and 220 kV grids in the Swedish national grid, Source: (Svenska Kraftnät, 2013b, p. 90)

4.2.2 Market Forces China

Energy targets to reduce the air *pollution*, relieve *water constraints* and the increase of *intermittent renewable energy generation* drive the expansion of China's transmission grid. However, the development of the transmission grid is also driven by *congestion*. China has major issues in their transmission system, consisting of insufficient capacity in some areas. China's rapid growth in the country in recent year drives the development of transmission grids in the country. China's electricity infrastructure requires extensive improvements to avoid bottlenecks and maintain a security of energy supply, according to Li et al. (2012). The existing power grid system is insufficient and cannot manage the increase of wind power generation in recent years. The independently acting, but state owned, energy companies are responsible for optimizing only their part of the system. This can hinder the target to build a robust system and support renewable energy technologies, as it is important to consider the entire system as a whole in order to reduce bottlenecks. (Li, et al., 2012) (Wu, et al., 2014)

The energy infrastructure is also challenged by a large amount of *wind curtailment* in the northern parts of China, as earlier described in section 3.2.3. The lack of sufficient transmission capacity is a result of the rapidly *growing economy* with fast expansion of installed generation capacity in remote locations, far away from load centres. The need to transmit *large capacitie*s over *long distances* puts high pressure on the transmission grid and drives the grid expansion in the country. These forces, together with *reliability and security* aspects, drive the development of long-distance transmission grids with high capacity to decrease wind curtailment. This is also stated by Clavenna (2012) who claims that wind capacity is expected to continue to increase in the northeast and west provinces. These provinces are far away from China’s natural gas infrastructure, which can reduce curtailment by quickly responding to variations from wind power. Problems related to wind curtailment is expected to remain the next few years. (Clavenna, 2012)

The high amount of wind curtailment is a result of China’s relatively low investment ratio in the grid infrastructure, compared to investments in power generation. Li et al. (2012) claims that the two state grid companies, SGCC and CSG have made heavy investments in the grid construction, which corresponded to 48.94 percent of investments in the electricity sector in 2008. However, the accumulated investments in the power grid are still lower than the investments in power generation. Figure 27 shows a comparison between investments in power grids and power generation that has been made in U.S., Japan, UK and France since 1978. The accumulated investments in Chinese grid infrastructure corresponds to less than 40 percent, which can be compared to the other countries where the share is 50 percent or more. (Li, et al., 2012) The increased need for investment in transmission is seen as a driver for its future development. There is no need to invest in large generation capacities if the energy generated cannot be transmitted to the consumers.

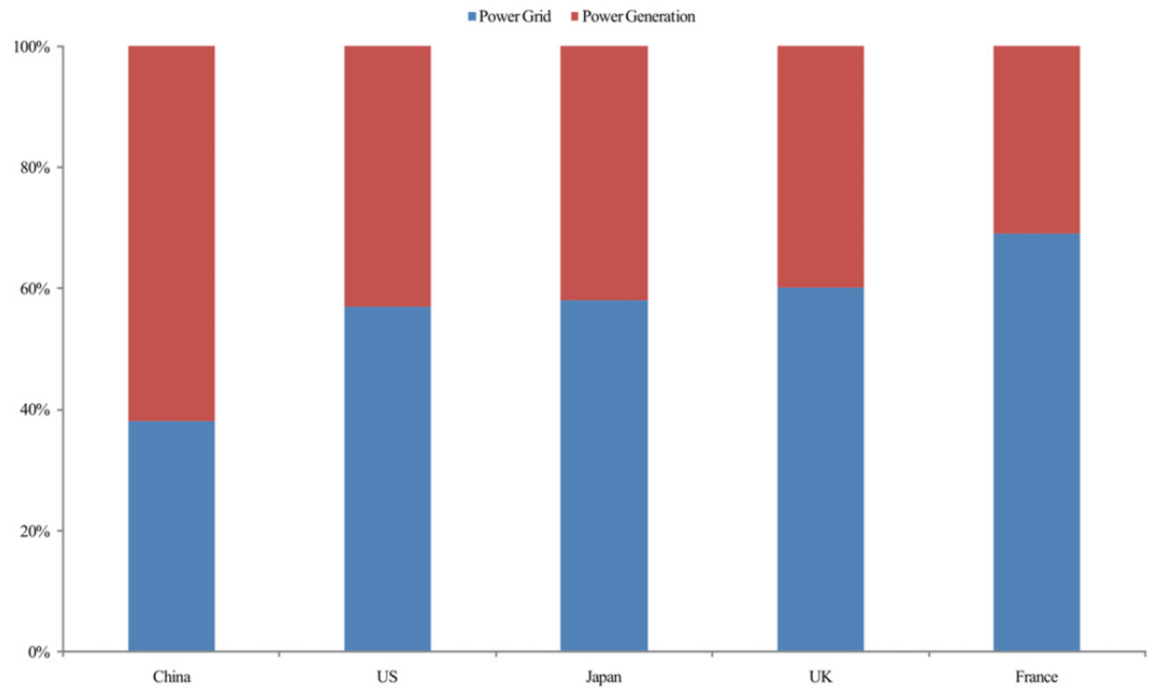

Figure 27: Ratio of accumulated investment in power grid and power generation since 1978, Source: (Li, et al., 2012)

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5. COST-BENEFIT MODEL

In this chapter, the cost-benefit model is described. The cost-benefit model is created to find a cost-effective balance between future investments in transmission expansion and grid storage integration. The model is influenced by market forces and barriers identified in the previous chapter. Initially, the case studies for Sweden and China are described followed by clarifications of costs, benefits, constraints, input data and equations used in the model. Thereafter, results from the cost-benefit model are presented for different cases in the model. The Matlab code of the model is presented in Appendices.

5.1 Case Descriptions

The projected case for the model is based on the assumption that the share of intermittent power generation increases. In Sweden, this is a probable consequence from closing down three of the oldest nuclear plants situated in SE3. The replacing power generation from wind power is expected to be transmitted from other parts of the country, most likely SE2 as presented in section 3.1.3. This can cause problems due to uneven power supply to the grid. As mentioned in section 3.2.3, wind curtailment is already a major problem in China. Large capacity of wind power is installed but not fully utilized. Sweden might also experience problem with curtailment, along with congestion, as power generation from wind increases, as presented in section 3.1.3. When the power generation is higher than the demand in a certain area, power can be transmitted to another area further away with higher demand. Another option is to store energy to supply power to the grid when the supply is lower than the demand in the current area.

Both of these options require high investment costs. If wind power generation in the northern parts of Sweden is going to satisfy energy demand in the southern parts of the country, greater transmission capacity is needed. This is also the case in China, where the wind power generation in the north needs to be transferred to remote load centres in the eastern parts of the country, as presented in section 3.2.3. Increased transmission capacity over long distances involves large capital costs. These costs can possibly be reduced if grid storage is integrated. Grid storage can also reduce the amount of wind curtailment and supply power to the grid when there is a lack of supply from wind energy, but this alternative also involves high capital costs. To consider both these alternatives when making an investment decision in order to avoid wind curtailment, a cost-benefit model is created. In that way, transmission and grid storage can be compared in a reasonable manner. The cost and benefits from grid storage integration have been evaluated and considered in the model.

5.2 Cost Descriptions

A CBA for transmission and grid storage is estimated from costs of real projects. Both investment costs and future costs, including maintenance, operation and replacement costs, are taken into account.

5.2.1 Investment Cost Transmission

The investment cost for a power transmission line is based on actual investment cost of projects in Sweden and China, respectively. In reality, the cost for building a new line is very project specific and depends on many factors. According to Blomqvist & Gabrielsson (2014) the cost for moving a transmission line of voltage level 400 kV is about $570,000 per kilometre, while the cost for building a new line range between $950,000 and $5,695,000. The large variation in cost depends on whether the line is overhead or underground, as well as type of terrain. Type of terrain affects both scope and construction time. (Blomqvist & Gabrielsson, 2014) An underground cable can be up to 5-15 times more expensive compared to overhead lines with the same transmission capacity. However, underground cables are more protected from weather variations and the costs of maintenance can be reduced compared to overhead lines. (Svenska Kraftnät, 2014a) According to Blomqvist & Gabrielsson (2014) economies of scale also affects the transmission cost, since the cost per kilometre reduces as the distance increases.

The CBA is based on AC transmission lines, which in general are built stepwise in large intervals. In Sweden, AC lines are the most common alternative, with a voltage of 400 kV (Svenska Kraftnät, 2014a). The transmission investment cost for Sweden is based on a recent transmission project with AC and DC lines combined. This combination is valuated as relevant in Sweden, partly due to increased urbanization. According to Svenska Kraftnät (2012), underground cables are applied in urban areas where DC is preferred due to fewer losses. Also Khandelwal & Pachori (2013) acknowledge that underground cables are preferred for situations where land is inhabited or has a high development potential, because of less environmental impacts. For land with lower value, overhead lines are generally preferred, because of less capital costs. (Khandelwal & Pachori, 2013) To simplify, the cost-benefit model considers the entire investment to have AC properties.

To compare China and Sweden in a reasonable manner, 500 kV AC has been used in the model for China since it is a more common current level than 400 kV (Global Energy Network Institute, 2007). The cost from a recent long distance transmission project in China was used as a base for transmission cost estimation for the Chinese case. The project only contains AC lines, which is considered reasonable because of the longer distances of power transmission in China and the common use of AC lines. The fact that DC lines generally are more expensive than AC lines can however contribute to the large difference in transmission investment cost for Sweden and China.

Cost development is considered to take the extensive lifetime into account. Cost trends for both DC and AC transmission lines have been rather continuous for decades. Historical data for cost per powered distance of AC lines is displayed in Figure 28, where significant deviations have been excluded. All costs has been calculated to year 2005 $. The cost trend for AC lines is fairly consistent during the last hundred years. DC lines indicate a slight cost increase since 1960's (Performance Curve Database, 2008). Based on the historical trends the cost for power transmission can be presumed to remain on the same level as today. The losses in the transmission grid have been considered by using a value for the efficiency of the grid.

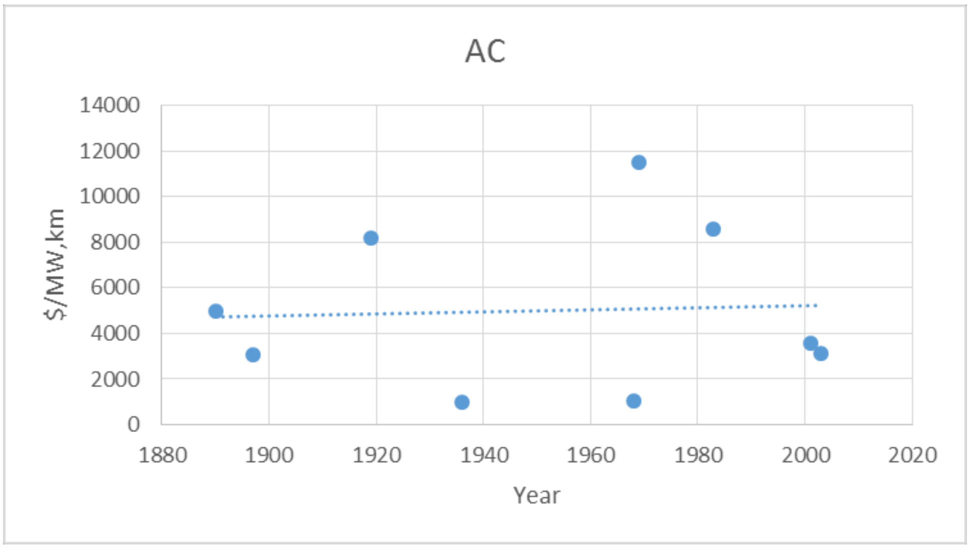

Figure 28: Cost trend AC, Source: (Performance Curve Database, 2008)

5.2.2 Investment Cost Grid Storage

Large capital costs is the major challenge for storage technologies, but the cost development for Li-ion batteries is expected to decrease drastically in upcoming years, as earlier presented in Figure 7 and Figure 21. The main reason for the expected cost reduction is because of the fast development of Li-ion batteries used in electric vehicles, driven by the transportation sector. As technology improves and becomes more available costs are cut down. To take the expected cost reductions into account, the model is simulated for four different battery cost; 25, 50, 75 and 100 percent of the present battery cost.

Regarding the grid storage system as a whole, the cost for the batteries is not the only cost that has to be considered in the model, see Figure 29. The model includes cost for the energy storage unit which means cost related to the batteries. The costs for the power conversion system and balance of plant are also included in the model. Power conversion system contains costs such as power interconnections and cabling. Balance of plant costs includes cost such as project engineering, grid interconnection, system integration, building and foundation, monitoring and control systems as well as shipment and installation costs. The losses have been considered by using a value for the efficiency in the model.

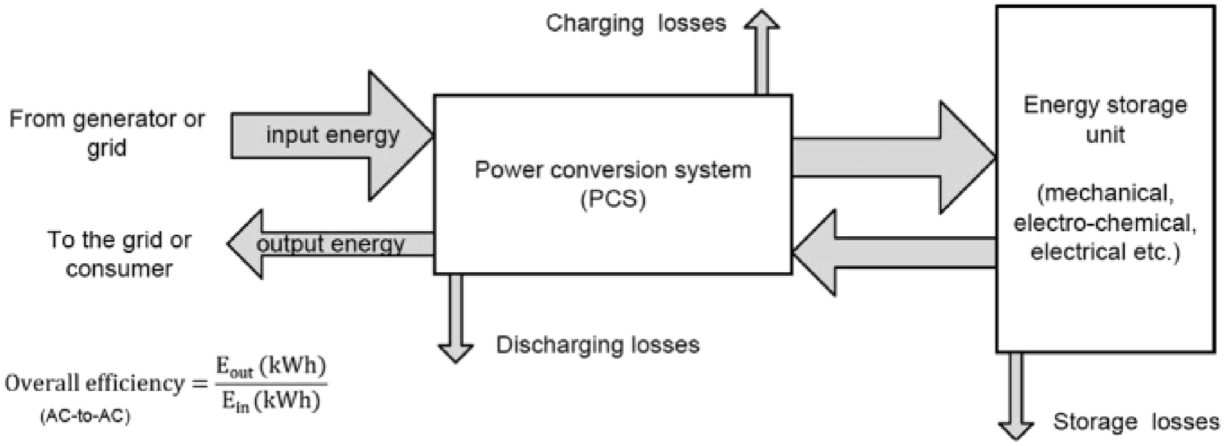

Figure 29: Main sections of EES systems and energy losses, Source (Zakeri & Syri, 2014)

5.2.3 Reinvestment Costs

Transmission usually has a longer life time than grid storage. However, if reinvestments (RI) are made in the grid storage system such as replacing the batteries, the projected lifetime can be extended. In the analysis the batteries are assumed to dispatch every day for the projected lifetime, which affects the battery durability. According to the Electric Power Research Institute (2013) the replacement frequency of the batteries can be presumed to be every ten years. Other parts of the grid storage facility can have longer life time, extending over the entire projected lifetime of the storage system. Therefore, an annual reinvestment cost, containing the expenses for replacing batteries, is included to increase the lifetime of the entire storage system.

Transmission has also some parts in the system that requires reinvestment to obtain the intended life time for the whole system. These costs are also included in the model. However, sources of accurate data were limited and an approximate value was calculated. In Sweden, data from the Swedish TSO was available for their whole system ($RI_{TotalSwe}$). This value was divided by the total length of transmission grid in Sweden and the power capacity during a cold day in a normal winter. This resulted in a value with the unit [\$/MW, km, year] which could be used in the model. For China, see section 5.2.4.

$RI_T = \frac{RI_{TotalSwe}}{P_{Swe} * L_{Swe}}$ RI cost transmission Sweden [\$/MW, km, year]

5.2.4 Operation and Maintenance Costs

Operation and maintenance (O&M) cost is also included in the model. Regarding transmission, sources of accurate data were limited and an approximate value was calculated for both countries. In Sweden, data from the Swedish TSO was available for their whole system ($OM_{TotalSwe}$). This value was divided by the total length of transmission grid in Sweden and the power capacity during a cold day in a normal winter. This resulted in a value with the unit [\$/MW, km, year] which could be used in the model.

$OM_T = \frac{OM_{TotalSwe}}{P_{Swe} * L_{Swe}}$ O&M cost transmission Sweden [$/MW, km, year]

Data of O&M and RI costs in China were very limited. Estimations based on Sweden's O&M and RI cost had to be made. O&M and RI has been calculated as a percentage of installed capacity in Sweden and then approximated to be the same for China.

$OMRI_T = \frac{(RI_T + OM_T)}{IC_T} * L$ O&M and RI cost transmission China [% of investment cost]

OM cost for grid storage included in the model is both fixed and variable annual costs. The variable costs are increasing with increased use of the storage. There is always a minimum cost that is represented by the fixed cost.

5.2.5 Planning and Construction Cost

The cost model includes additional costs for time of construction of energy storage and transmission due to loss of income during planning and construction time. These estimations are based on project length of real projects, from planning of the project to commissioning. The purpose of including this, is to consider a cost associated with hours of curtailment. The alternative that can be realized in shortest time can benefit from the avoided curtailment. The market price for electricity has been multiplied with the yearly hours of wind curtailment during the planning and construction time. For Sweden, the mean spot price has been applied and for China, a feed-in tariff represents market price for electricity. For every year of planning and construction, this cost appears.

5.2.6 Residual Value

Battery storage units have valuable metals that could be sold and reused in future batteries or other products. This yields an income which is included in the model every time the batteries have to be replaced during the total system life time. There are limited available data on residual value of energy storage. Enerdel (2013), a manufacturer of Li-ion batteries, offers a residual value of up to 25 percent. This applies to cost reduction of a replacing system and brings a lower cost over the system lifetime. (Enerdel, 2013)

Transmission however, is assumed to have zero residual value. The cost for demolition is assumed to be equal to the income from the valuable metals that could be obtained in the transmission lines and then reused in other products.

5.3 Benefit Descriptions

There is a difficulty in performing a typical CBA of grid storage, since the benefits that can be received involve several applications. To recognize the entire worth of grid storage, all the benefits for different applications should be measured and included in the analysis (Insight_E, 2014). It is however challenging to determine an accurate value of all the benefits that grid storage can provide. Thus, the benefits considered most relevant for grid storage in the model are long duration benefits for renewable integration applications. There are other benefits, being excluded in this model, which can be considered relevant in other applications of grid storage.

There are several ways to employ energy storage systems with the purpose of regulating intermittent power generation. By storing energy, wind curtailment can be reduced and oversized construction of power capacity eliminated. In addition, wind power output can be smothered by relieving variation suppression and support voltage control. (Zakeri & Syri, 2014) Evaluations of benefits associated with renewable integration applications of grid storage has been performed in other research work and is not be the focus in this thesis. Instead, the most relevant benefits already evaluated in a previous research work by Narula et al. (2011) have been included in the cost-benefit model. It should be observed that some of the benefits based on previous research are evaluated based on other market situations. In most cases, the benefit value have been rounded down for the purpose of not exaggerating the worth of the benefit. Furthermore, benefits included in the cost-benefit model are chosen based on relevance when integrating grid storage. Other benefits that can be received both by increasing transmission capacity and by implementing grid storage are excluded. Consequently, no benefits for transmission are included, since these would also be included as benefits for grid storage.

5.3.1 Renewable Energy Time Shifting

One advantage of grid storage integration in Sweden, is to benefit from electricity price fluctuations on the spot market. Energy can be stored at excess supply, when the electricity price is low, and discharged at excess demand, when the electricity price is high. The benefit from renewable energy time shifting is applied in the model for Sweden only. In China this is not applicable due to predetermined feed-in tariffs, as presented in section 3.2.2.

The benefit has been evaluated by calculating the difference between average daily maximum spot price[6] during the years 2013 and 2014 for SE3 and the average daily minimum spot price[7] during the years 2013 and 2014 for SE3 and then multiplied with days per year.

5.3.2 Renewable Load Following

Grid storage can provide load-following service that would otherwise be provided by power generation. As discussed in section 4.1.2.4, thermal generation is today often used to stabilize output fluctuation from intermittent energy sources. The benefit of load following is based on market prices of generation costs, including costs for fuel, generation and emissions. These costs can be reduced or avoided when grid storage is integrated. The demand of the added

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[6] (Nord Pool Spot, 2014)

[7] Ibid.

generation capacity is highly market specific, depending on area and time. According to Narula et al. (2011) the wind generation output variability involves changes that occur over minutes to hours. The annual benefit from grid storage integration is estimated to \$54 600/MW (Narula, et al., 2011). This value have has been used as an approximate value for both markets in the model. It should be noted that this value estimation differs from the market situation in Sweden and China. Because of lack of information from these specific markets, the values are assumed to be roughly the same.

5.3.3 Electric Service Reliability

Grid storage can provide backup for unexpected wind generation shortfalls that can cause electric service outages. The value for avoiding electric service outages has been included as a benefit for grid storage in the model. Narula et al. (2011) have evaluated the value to \$10/kWh. To validate this value, the loss of GDP in Sweden and China is calculated during 1 hour of power outage per year, see Table 3.

$$SR = \frac{BNP}{Working\ hours\ per\ year * Average\ load}$$

Table 3: Electric Service Reliability Validation

	Sweden	China
GDP [\$]	447 264 000 000[8]	8 230 000 000 000[9]
Approx. Working hours per year [h]	2 500	2 500
Average load [MW]	18 379[10]	544 292[11]
Benefit [\$/kWh]	10	6

The validation shows that the value for electric service reliability is equivalent for Sweden but a bit lower for China. The benefit value for China is therefore adjusted in the model.

5.4 Capacity Limitations

Transmission power capacity is assumed to be installed in fixed large steps in the model. One transmission line has a fixed value and the amount of transmission lines, in positive integers, is calculated to obtain the optimal solution. This is to model the complexity in expansion of new transmission lines because of the long planning and construction time. As presented in section 4.2, transmission capacity should be customized to fit the final amount of wind energy

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[8] (Ekonomifakta, 2014)
[9] (Trading Economics, 2013)
[10] (U.S. Energy Information Agency, 2012b)
[11] (U.S. Energy Information Agency, 2012c)

instead of making large investments in several stages. Therefore, a reasonable value of each step of transmission capacity has been included in the model.

As validation for the value used in the model, the Swedish national grid has been studied. Between SE1 and SE2, there is a transmission capacity of 4210 MW (Svenska Kraftnät, 2014c) divided on four 400 kV lines (Svenska Kraftnät, 2014a). This corresponds to a capacity of approximately 1050 MW per line. However, these sections are about 300 km which is shorter than the distance modelled. As can be seen in Figure 30 below, the transmission capacity in an AC line decreases with length. Therefore, a lower capacity than 1050 MW, stated above, has been used in the model. A value of 700 MW has been estimated for a line with the given distance for the case of Sweden.

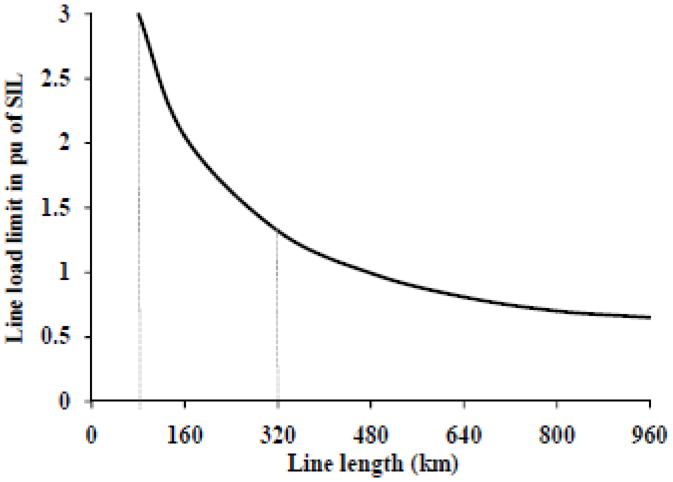

Figure 30: St. Clair Curve, Source: (Hao & Xu, 2008)

For China, the input data is based on a project with 500 kV AC line which makes it possible to transfer more power than in a 400 kV AC line. Thereby, the value has been estimated to 1000 MW for the case of China.

Grid storage however, is a more flexible system with shorter development times. “Grid storage” is referred to several storage units included in the total system and not a single unit. Therefore, the power restrictions are assumed from low power demands (100 MW) and then with the possibility to be scaled to higher power demands, no upper limit. Power efficiencies for both technologies have been considered.

5.5 Distance Limitations

The length of transmission line is set to a constant value and is based on reasonable assumptions and estimations of the distance between expected wind farms and demand sources. Electricity is assumed to be transmitted over large distances, for example from northern Sweden (SE2) to southern parts of the country (SE3) as presented in section 3.1.3. This gives approximately a distance of 500 km which is used in the model. This length also coincide with the project that the investment cost is based on, which is a project between Sweden’s southern and central parts with a long distance of about 440 km (Svenska Kraftnät, 2013c). For China, the large geographical distance is a major challenge for power transmission, as discussed in section 3.2.3. Because of the large distances and the geographical disparity of wind power generation and power demand, the distance is doubled compared to Sweden. The approximated distance used in the model is set to 1000 km.

5.6 Input Data Sweden

In Table 4, general input data for the model of Sweden is presented, followed by input data for grid storage and transmission in Table 5 and Table 6, respectively.

Table 4: General Input Data Model, Sweden

General Input Data Sweden				
Name	**Short**	**Value**	**Unit**	**Source**
Length of transmission	L	500	km	[12]
Average spot price Sweden SE3 benefits storage	EP	40.1	$/MWh	[13]
Hours per year	t	8760	h	
Interest rate including inflation rate	ir	5.5	%	[14]
Factor to convert SEK to U.S. Dollar	sd	12	%	[15]
Factor to convert Euro to U.S. Dollar	ed	106	%	[16]
Factor to convert CNY to U.S. Dollar	yd	16	%	[17]

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[12] See section 5.5.
[13] (Nord Pool Spot, 2014)
[14] (Zakeri & Syri, 2014) (Energimarknadsinspektionen, 2011)
[15] (Microsoft, 2015)
[16] Ibid.
[17] Ibid.

Table 5: Input Data Grid Storage Model, Sweden

Input Data Grid Storage Sweden				
Name	**Short**	**Value**	**Unit**	**Source**
Li-ion battery cost (100 %)	BC_GS	795000	$/MWh	18
Power conversion systems cost	PCS_GS	405980	$/MW	19
Balance of plant cost	BOP_GS	84800	$/MW	20
Benefits from spot market	sp_GS	5475	$/MWh,year	21
Benefits from load following	LF_GS	54600	$/MW,year	22
Benefits from electric service reliability	SR_GS	10000	$/MW,year	23
Fixed operation and maintenance cost	OMf_GS	7314	$/MW,year	24
Life time	y_GS	40	Years	25
Variable operation and maintenance cost	OMv_GS	2.23	$/MWh,year	26
Planning and construction time	t_PC_GS	1	Years	27
Charge/discharge time	t_dis	2	h	28
Efficiency	N_GS	0.90		29
Residual value in percentage of initial battery cost	RV_GS	0.25		30

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[18] (Zakeri & Syri, 2014, p. 591)
[19] Ibid.
[20] Ibid.
[21] See section 5.3.1.
[22] (Narula, et al., 2011, pp. 8-7)
[23] See section 5.3.3.
[24] (Zakeri & Syri, 2014, p. 591)
[25] See section 5.2.3.
[26] (Zakeri & Syri, 2014, p. 591)
[27] (Global Energy Storage Database, 2015a)
[28] (Zakeri & Syri, 2014, p. 591)
[29] (Zakeri & Syri, 2014, p. 580)
[30] (Enerdel, 2013)

Table 6: Input Data Transmission Model, Sweden

Input Data Transmission Sweden

Name	Short	Value	Unit	Source
Investment cost	IC_T	850820	$/MW	[31]
Annual reinvestment cost per year in Sweden	RI_T	0.204	$/MW,km,year	[32]
Annual operation and maintenance cost	OM_T	0.134	$/MW,km,year	[33]
Power capacity Sweden, normal winter	P_Swe	26200	MW	[34]
Total length of transmission in Sweden	L_Swe	15000	km	[35]
Power capacity for each line	P_Ta	700	MW	[36]
Life time	y_T	40	Years	[37]
Planning and construction time	t_PC_T	10	Years	[38]
Efficiency	N_T	0.97		[39]

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[31] (Svenska Kraftnät, 2013c)
[32] (Svenska Kraftnät, 2015a)
[33] (Svenska Kraftnät, 2014e, p. 62)
[34] (Svenska Kraftnät, 2014d, p. 9)
[35] (Svenska Kraftnät, 2014f)
[36] See section 5.4.
[37] (Energimarknadsinspektionen, 2010)
[38] (Svenska Kraftnät, 2013c)
[39] (Svenska Kraftnät, 2014e, p. 34)

5.7 Input Data China

In Table 7, general input data for the model for China is presented, followed by input data for grid storage and transmission in Table 8 and Table 9, respectively.

Table 7: General Input Data Model, China

General Input Data China				
Name	**Short**	**Value**	**Unit**	**Source**
Length of transmission	L	1000	km	[40]
Wind Power feed-in tariff zone II	EP	86.4	$/MWh	[41]
Hours per year	t	8760	h	
Interest rate including inflation rate	ir	5.5	%	[42]
Factor to convert SEK to U.S. Dollar	sd	12	%	[43]
Factor to convert Euro to U.S. Dollar	ed	106	%	[44]
Factor to convert CNY to U.S. Dollar	yd	16	%	[45]

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[40] See section 5.5.
[41] See section 3.2.2
[42] (Zakeri & Syri, 2014) (Energimarknadsinspektionen, 2011)
[43] (Microsoft, 2015)
[44] Ibid.
[45] Ibid.

Table 8: Input Data Grid Storage Model, China

Input Data Grid Storage China				
Name	**Short**	**Value**	**Unit**	**Source**
Li-ion battery cost (100 %)	BC_GS	795000	$/MWh	[46]
Power conversion systems cost	PCS_GS	405980	$/MW	[47]
Balance of plant cost	BOP_GS	84800	$/MW	[48]
Benefits from spot market	sp_GS	0	$/MWh,year	[49]
Benefits from load following	LF_GS	54600	$/MW,year	[50]
Benefits from electric service reliability	SR_GS	6000	$/MW,year	[51]
Fixed operation and maintenance cost	OMf_GS	7314	$/MW,year	[52]
Life time	y_GS	40	Years	[53]
Variable operation and maintenance cost	OMv_GS	2.23	$/MWh,year	[54]
Planning and construction time	t_PC_GS	1	Years	[55]
Charge/discharge time	t_dis	2	h	[56]
Efficiency	N_GS	0.90		[57]
Residual value in percentage of initial battery cost	RV_GS	0.25		[58]

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[46] (Zakeri & Syri, 2014, p. 591)
[47] Ibid.
[48] Ibid.
[49] See section 5.3.1.
[50] (Narula, et al., 2011, pp. 8-7)
[51] See section 5.3.3.
[52] (Zakeri & Syri, 2014, p. 591)
[53] See section 5.2.3.
[54] (Zakeri & Syri, 2014, p. 591)
[55] (Global Energy Storage Database, 2015a)
[56] (Zakeri & Syri, 2014, p. 591)
[57] (Zakeri & Syri, 2014, p. 580)
[58] (Enerdel, 2013)

Table 9: Input Data Transmission Model, China

Input Data Transmission China				
Name	**Short**	**Value**	**Unit**	**Source**
Investment cost	IC_T	797	$/MW	59
Annual RI and O&M cost	OMRI_T	0.02	%/year	60
Power capacity for each line	P_Ta	1000	MW	61
Life time	y_T	40	Years	62
Planning and construction time	t_PC_T	7	Years	63
Efficiency	N_T	0.97		64

5.8 Objective Function

The cost model has the objective to minimize the cost for investing either transmission or grid storage or a share of both technologies to avoid a certain amount of wind curtailment. Therefore, the cost model minimizes the cost for each unit of wind curtailment.

Annualized Cost-Benefit Analysis [$/ year]

$$ACBA = x_1 * \left(\frac{ka_{GS}}{t_{dis}} * (IC_{GS} + PCC_{GS}) + AVC_{GS} * 365 + AFC_{GS} + \frac{PCC_{GS}}{t_{dis}} - AB_{GS} - R_{GS}\right) +$$
$$x_2 * P_{Ta} * \left((IC_T + PCC_T - R_T * kn_T) * ka_T + AVC_T + AFC_T - AB_T\right)$$

5.9 Constraints

The constraints for the model are shown below.

$$x_1 * \frac{N_{GS}}{t_{dis}} + x_2 * P_{Ta} * N_T \geq P_{lack}$$

$$x_2 \geq 0$$

$$x_1 \geq 0$$

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[59] (Transmission & Distribution World, 2011)
[60] See section 5.2.4.
[61] See section 5.4.
[62] (Energimarknadsinspektionen, 2010)
[63] (Global Transmission Report, 2009)
[64] (Svenska Kraftnät, 2014e, p. 34)

5.10 Variables

x_1	Energy stored in the grid storage [MWh]
x_2	Amount of transmission lines [pcs]

5.11 Equations

$ka_{GS} = \frac{ir}{1-(1+ir)^{-y_{GS}}}$	Annuity factor Grid Storage
$ka_T = \frac{ir}{1-(1+ir)^{-y_T}}$	Annuity factor Transmission
$kn_{GS} = \frac{1}{(1+ir)^{y_{GS}}}$	Net present factor Grid Storage
$kn_T = \frac{1}{(1+ir)^{y_T}}$	Net present factor Transmission
$WC = P_{lack} * t_{WC}$	Wind Curtailment per year [MWh/year]
$IC_{GS} = BC_{GS} * t_{dis} + BOP_{GS} + \cdots$	
PCS_{GS}	Investment Cost Grid Storage [\$/MW]
$RI_{GS} = BC_{GS} * ((\frac{1}{(1+ir)^{10}}) + \cdots$	
$(\frac{1}{(1+ir)^{20}}) + (\frac{1}{(1+ir)^{30}})) * ka_{GS}$	Reinvestment Cost Grid Storage [\$/MW]
$AFC_{GS} = \frac{OMf_{GS}}{t_{dis}} + RI_{GS} * ka_{GS}$	Annual Fixed Costs Grid Storage [\$/MWh, year]
$AVC_{GS} = OMv_{GS}$	Annual Variable Costs Grid Storage [\$/MWh, year]
$AFC_T = (OM_T + RI_T) * L$	Annual Fixed Costs Transmission [\$/MW, year]
$AVC_T = 0$	Annual Variable Costs Transmission [\$/MW, year]
$PCC_{GS} = EP * t_{PC_{GS}} * t_{WC}$	Planning & Construction Cost Grid Storage [\$/MW]
$PCC_T = EP * t_{PC_T} * t_{WC}$	Planning & Construction Cost Transmission [\$/MW]
$R_{GS} = \left(BC_{GS} * \left(\frac{1}{(1+ir)^{40}}\right) + RI_{GS}\right) \ldots$	
$* ka_{GS} * RV_{GS}$	Residual Value Grid Storage [\$/MW]
$R_T = 0$	Residual Value Transmission [\$/MW]
$AB_{GS} = \frac{LF_{GS}+SR_{GS}}{t_{dis}} + sp_{GS}$	Annual Benefits Grid Storage [\$/MWh, year]
$AB_T = 0$	Annual Benefits Transmission [\$/MWh, year]

5.12 Results

This section shows the results from the cost-benefit model. The model has been adapted to the two countries studied, Sweden and China, with country specific input data as presented in section 5.6 and 5.7, respectively. Eight different cases have been studied for each country. The cases were chosen based on the parameters importance and level of impact of the result. The expected decrease of Li-ion battery cost, as presented earlier in 5.2, was considered as relevant for further investigation in the model. Moreover, the upcoming challenges associated with potential increase of wind curtailment, as presented in section 4.1.2.3, was also considered as highly relevant in order to study the impact depending on choice of technology. The model examines capacities installed from 100 MW to 3000 MW with steps of 100 MW.

- Battery cost - 100 %, 75 %, 50 % and 25 % of current battery cost.
- Wind curtailment - 100 hours and 1000 hours per year, respectively.

5.12.1 Sweden

In the following sections, the results from each different case with the country specific input data for Sweden are presented. The x-axis shows the capacity demand, which means the total capacity of variation moderators that needs to be installed. On the y-axis the actual installed capacity of each technology is seen. This capacity is as minimum equal to the capacity demand but it is possible with an overcapacity.

5.12.1.1 Case 1

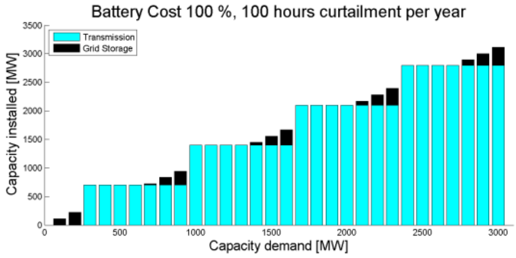

Figure 31: Case 1 Sweden

5.12.1.2 Case 2

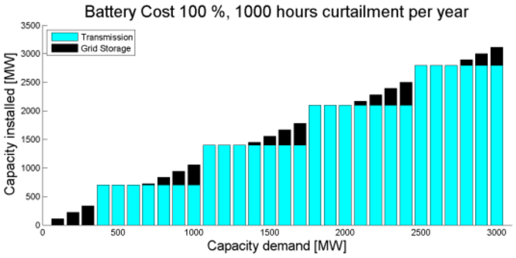

Figure 32: Case 2 Sweden

In Case 1 and 2, the battery cost represents an estimation of current market price at 100 and 1000 hours of curtailment per year, respectively. The results from Case 1 (Figure 31) shows that transmission is generally the most beneficial alternative. Grid storage is suitable for small capacities and as peak capacity, to avoid investments in overcapacity in some extent. This result can be compared to Case 2 (Figure 32) where the increase in hours of wind curtailment makes transmission more costly, which yields a result with larger share of storage in Case 2 compared to Case 1. However, it can be seen that it can be more optimal to invest in overcapacity than in grid storage at some capacities. For example, for a capacity demand of 500 MW the result shows that it is more cost-effective to install 700 MW of transmission capacity than to install 500 MW of storage capacity.

5.12.1.3 Case 3

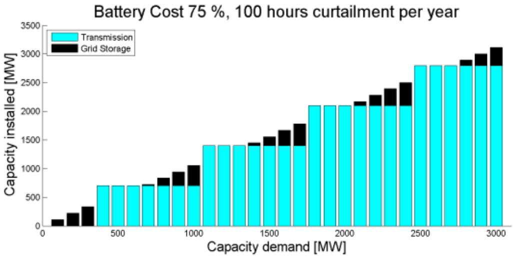

Figure 33: Case 3 Sweden

5.12.1.4 Case 4

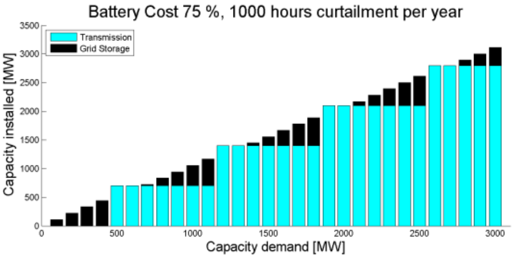

Figure 34: Case 4 Sweden

The results of Case 3 (Figure 33) shows that the battery cost reduction of 25 percent has increased grid storage's influence compared to Case 1. The amount of overcapacity in transmission becomes less in return for increased capacity of storage. Furthermore, in Case 4 (Figure 34) the increase in hours of wind curtailment makes transmission more costly, and together with the cost reduction of batteries, it yields a result with larger share of storage in Case 4 compared to Case 3. Investing in overcapacity gets less beneficial, but still occurs.

5.12.1.5 Case 5

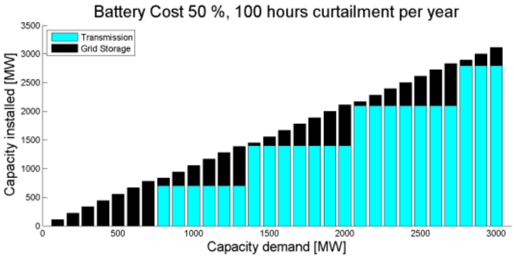

Figure 35: Case 5 Sweden

5.12.1.6 Case 6

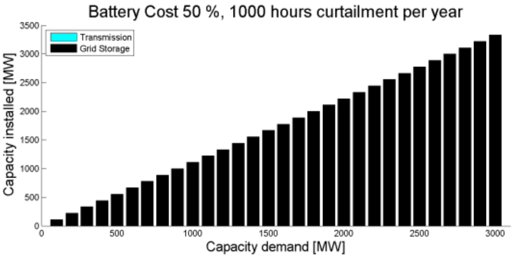

Figure 36: Case 6 Sweden

The result of Case 5 (

Figure 35) shows that a battery cost reduction of 50 percent of current battery cost has increased grid storage's influence even more, compared to Case 1 and 3. The amount of overcapacity in transmission becomes less in return for increased capacity of storage, but still occurs. Furthermore, in Case 6 (Figure 36) it can be seen that grid storage is more cost-effective than transmission for all capacities included in the model, from 100 to 3000 MW. The increase in hours of wind curtailment makes transmission more costly, and together with the cost reduction of batteries, it yields a result where the break-even point can be found somewhere between 25-50 percent battery cost decrease. This means that grid storage has become more beneficial to invest in than transmission.

5.12.1.7 Case 7

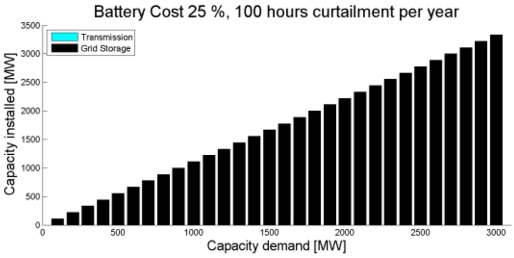

Figure 37: Case 7 Sweden

5.12.1.8 Case 8

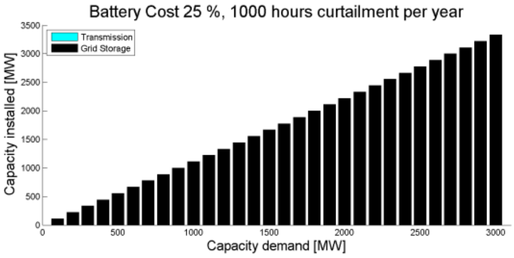

Figure 38: Case 8 Sweden

The results of Case 7 (Figure 37) shows that a battery cost decrease of 75 percent has led to that grid storage is more cost-effective than transmission for all capacities included in the model, from 100 to 3000 MW. Consequently, this means that somewhere between 50-75 percent battery cost decrease, the break-even point can be found for Case 7. The result of Case 8 (Figure 38) shows the same result as Case 6 since the break-even point has already been reached.

5.12.2 China

In following sections, the results from each different case with the country specific input data for China are presented. The x-axis shows the capacity demand, which means the total capacity of variation moderators that needs to be installed. On the y-axis the actual installed capacity of each technology is seen. This capacity is as minimum equal to the capacity demand but it is possible with an overcapacity.

5.12.2.1 Case 1

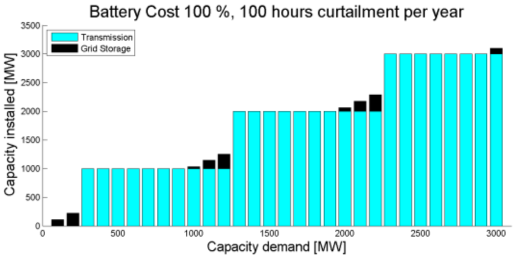

Figure 39: Case 1 China

5.12.2.2 Case 2

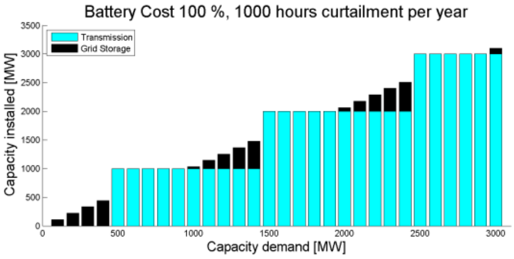

Figure 40: Case 2 China

In Case 1 and 2 the battery cost represent an estimation of current market price at 100 and 1000 hours of curtailment per year, respectively. The results from Case 1 (Figure 39) shows that transmission is generally the most beneficial alternative. Grid storage is suitable for small capacities and as peak capacity, to avoid investments in overcapacity in some extent. This result can be compared to Case 2 (Figure 40), where increased hours of curtailment increase the influence of storage. Furthermore, it can be concluded that it can be more optimal to invest in overcapacity than in grid storage at some capacities. For example, for a capacity demand of 400 MW the result shows that it is more cost-effective to install 700 MW of transmission capacity than to install 400 MW of storage capacity. It can also be stated that the time of wind curtailment have some effect on the results for these two cases.

5.12.2.3 Case 3

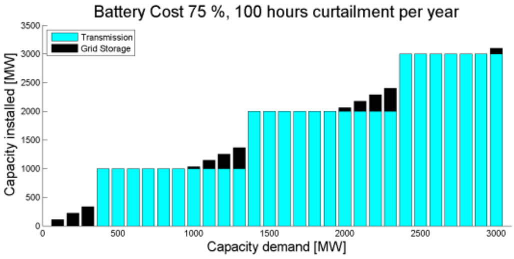

Figure 41: Case 3 China

5.12.2.4 Case 4

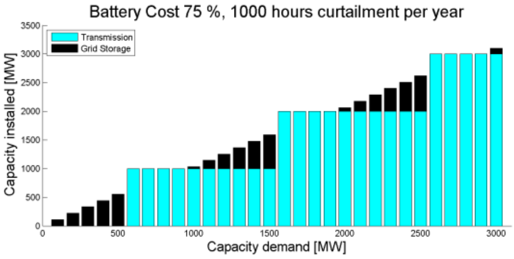

Figure 42: Case 4 China

The results of Case 3 (Figure 41) shows that the battery cost reduction of 25 percent has a minor effect of storage' penetration level compared to Case 1. This means that the battery cost reduction of 25 percent makes it cost-effective to avoid some investments in transmission overcapacity. Furthermore, in Case 4 (Figure 42) the increase in hours of wind curtailment makes transmission more costly, and together with the cost reduction of batteries, it yields a result with larger share of storage in Case 4, than in Case 3. Investing in overcapacity gets less beneficial, even though it still occur.

5.12.2.5 Case 5

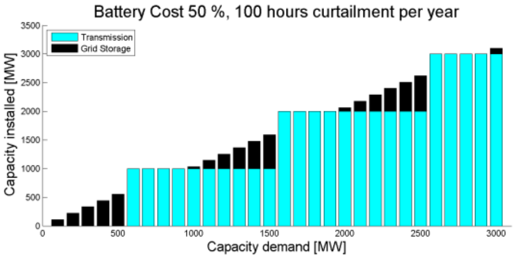

Figure 43: Case 5 China

5.12.2.6 Case 6

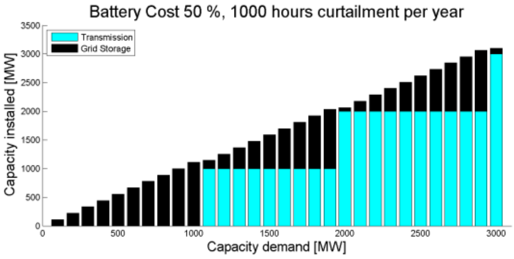

Figure 44: Case 6 China

The result of Case 5 (Figure 43) shows that a battery cost reduction of 50 percent of current battery cost has increased grid storage's influence even more, compared to Case 1 and 3. The amount of overcapacity in transmission becomes less in return for increased capacity of storage, but still occurs. Furthermore, in Case 6 (Figure 44) the increase in hours of wind curtailment makes transmission more costly, and together with the cost reduction of batteries, it yields a result with larger share of storage in Case 6, than in Case 5. Investing in overcapacity is no longer beneficial.

5.12.2.7 Case 7

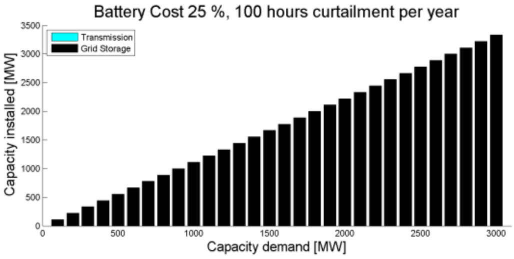

Figure 45: Case 7 China

5.12.2.8 Case 8

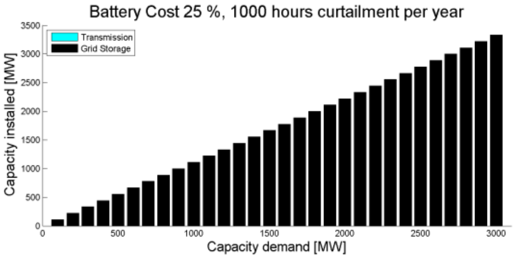

Figure 46: Case 8 China

The results of Case 7 (Figure 45) and Case 8 (Figure 46) shows that a battery cost decrease of 75 percent has led to that grid storage is more cost-effective than transmission for all capacities included in the model, from 100 to 3000 MW. Consequently, this means that somewhere between 50-75 percent battery cost decrease grid storage gets more beneficial than transmission, the break-even point has been reached.

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6. DISCUSSION

In this chapter the research findings together with the results from the cost-benefit model are discussed. First, grid storage's market potential for integration into the energy infrastructure in Sweden and China is discussed. Furthermore, the outcome of the results from the cost-benefit model is discussed together with potential sources of errors.

6.1 Market Conditions

The need for balancing measures in the energy infrastructure is increasing on both emerging and developed markets. Both transmission expansion and grid energy storage integration are becoming increasingly relevant to study as variation moderators. Stakeholders on the power market can draw benefit from studies, such as this, when making future investment-decisions. Moreover, policy-makers should also consider research of variation moderators in the energy infrastructure to promote a sustainable energy infrastructure. At the same time as the transmission grid needs to be expanded, energy storage systems are becoming increasingly interesting in several areas of application. Development of Smart grids, electric vehicles and home batteries drives the battery development forward and increases potential to cost reductions. As technology is developed in one area of application, advantages can be gained in other areas such as grid storage. Technology progress and research findings continue to change the market conditions for variation moderators.

6.1.1 Sweden

The need for variation moderators highly depends on the future electricity market structure. Future scenarios, addressed in section 3.1.4, indicate substantially higher demand of variation moderators in the Nordic energy infrastructure. Despite these indications, the Swedish TSO does not intend to increase responsibility of balancing the power system in a near future. It is therefore doubtful that the grid operator considers investing in grid storages. However, a regulating framework for storage systems could be an eye-opener for ownership potential. Present ownership and operational uncertainties need to be clarified in EU regulations. The future development of the market structure will be influenced by European directives, which today hinder potential investments in the EU market for grid battery storages. Directives about grid storages ownership can influence the market structure and increase the market potential for storage devices in Sweden and in the rest of Europe. However, an integrated intraday market in Northern Europe can influence the entire energy market and reduce the need for balancing reserves. The demand of variation moderators is thereby dependent on political decisions about the energy market structure, both in Sweden and neighbouring countries.

Although problems related to intermittent power generation are not extensive in Sweden today, a long-term perspective is necessary to be prepared for upcoming challenges. Potential challenges in future scenarios presented in section 3.1.4 should be considered when planning the future power system. Wind power integration can otherwise be hindered due to long planning and construction time of the transmission grid. As wind power generation increases in Sweden and other developed economies, grid storage integration can become a fast solution to future challenges on the power market due to the short construction time.

High investment costs and low experience level are major barriers for market penetration of grid storage in Sweden. It is therefore likely that Sweden will wait for a cost reduction of grid battery storage before investing in the technology. Other countries already have several more on-going battery storage projects than Sweden (Global Energy Storage Database, 2015b). Thereby, these countries have better opportunities to take the lead in the grid storage development. As the market matures and cost reduces, market actors in Sweden might realise the benefits of grid battery storage.

6.1.2 China

Due to large problems related to congestion, investments in transmission development can be prioritized in China. The developing country already faces challenges due to transmission limitations. Although grid storage integration can relive these concerns, it cannot completely replace the need to invest in transmission expansion in order to reach the load centres. Moreover, the experience level of building new transmission lines is high compared to the uncertainties of investing in a new technology.

However, there are also aspects that indicate integration of grid storage. China has shown efforts to become a leader in the development of technologies related to low-carbon energy, which can suggest that China will be in the forefront of grid storage development. According to The Electrical Energy Storage Magazine (2014) the energy storage industry in China has grown rapidly, with 90 battery storage projects in operation, under construction or planned the last two years.

Grid storage can reduce issues related to wind curtailment in a shorter time perspective than transmission. Because of the short construction time, grid storage can be a fast solution to China’s current wind curtailment problems. Today, wind curtailment causes financial losses and brings major challenges to the grid. These challenges need to be solved fast as the amount of installed intermittent energy sources keep increasing due to ambitious energy targets. According to The Electrical Energy Storage Magazine (2014) several wind farms in China’s north-eastern areas have already been equipped with energy storages to reduce wind curtailment caused by high wind penetration, high wind variability and limited transmission capacity. Grid storages located close to the source of generation can reduce the need for network expansion and also enable ownerships by power producers. As grid battery storages becomes more available on the market, storage devices connected to wind farms can be expected to increase.

6.1.3 Market Contrasts

China's business climate with high constitutional control can be more advantageous for grid battery storage. Short decision paths can speed up the decision making process and realize grid storage projects in a shorter time frame compared to developed countries as Sweden, where the decision processes are extensive. In addition, industries in developing countries can challenge unpredictable market fluctuations than in slow-growing industries as discussed in section 3.2.4. Furthermore, China has more than 100 Li-ion battery manufacturers, where some are focusing on grid scale energy storages (The Electrical Energy Storage Magazine, 2014). This also indicates that China can take a forefront role of grid storage technology development. With several manufacturers available, national battery prices can decrease and grid storage systems can be integrated to the grid infrastructure.

6.2 Driving Forces

A number of market forces drive the development of variation moderators. For both transmission and grid storage development, *energy targets* and *congestion* are two major driving forces. Energy targets set by several nations drives the increase of intermittent renewable energy sources, which create a need for variation moderators. Furthermore, problems related to congestion can be relieved by both transmission expansion and grid storage integration.

6.2.1 Grid Storage

Grid storage has many benefits as a variation moderator but also some downsides, as earlier presented in chapter 4. The most important drivers acknowledged is presented in Figure 47 where their relation to each other has been tried to be clarified in a pedagogical way. Based on market entry barriers and market forces recognized in chapter 4, the four most important driving forces are *Technology Development, Congestion, Recognition by Policymakers* and *Energy Targets*. From these driving forces, sub factors have been identified to clarify what drives the development of grid storage.

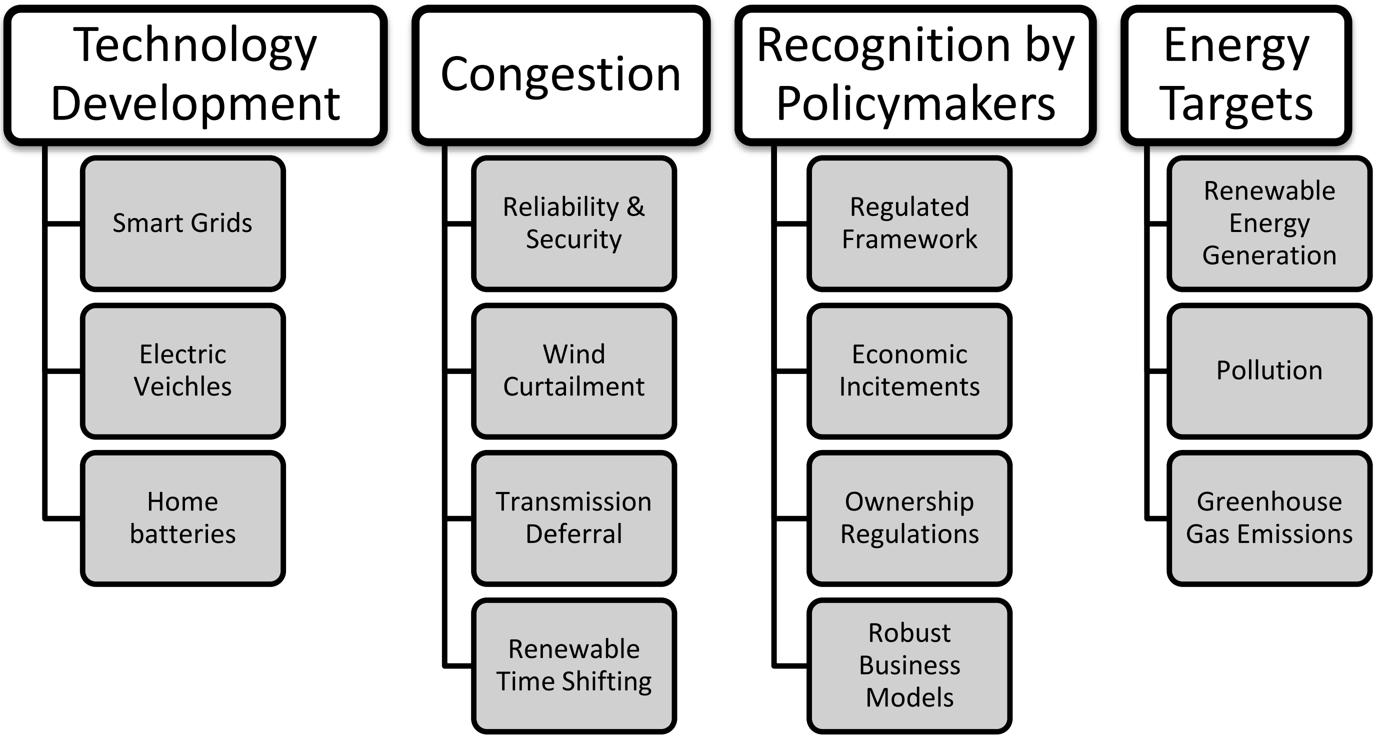

Figure 47: Acknowledged Driving Forces - Grid Storage

6.2.2 Transmission

Transmission has many benefits as a variation moderator and is also currently the most common technology used for that purpose worldwide. The most important drivers acknowledged for its continuous expansion in Sweden and China is presented in Figure 48 and Figure 49, respectively. Their relation to each other has been tried to be clarified in a pedagogical way. Based on the market forces recognized in chapter 4, the three most important driving forces in Sweden are *Congestion*, *Politics* and *Energy Targets*. In China, *Congestion*, the *Growing Economy* and *Energy Targets* has been recognized as the three most important driving forces. From these driving forces, sub factors have been identified to clarify what drives the development of transmission in Sweden and China, respectively.

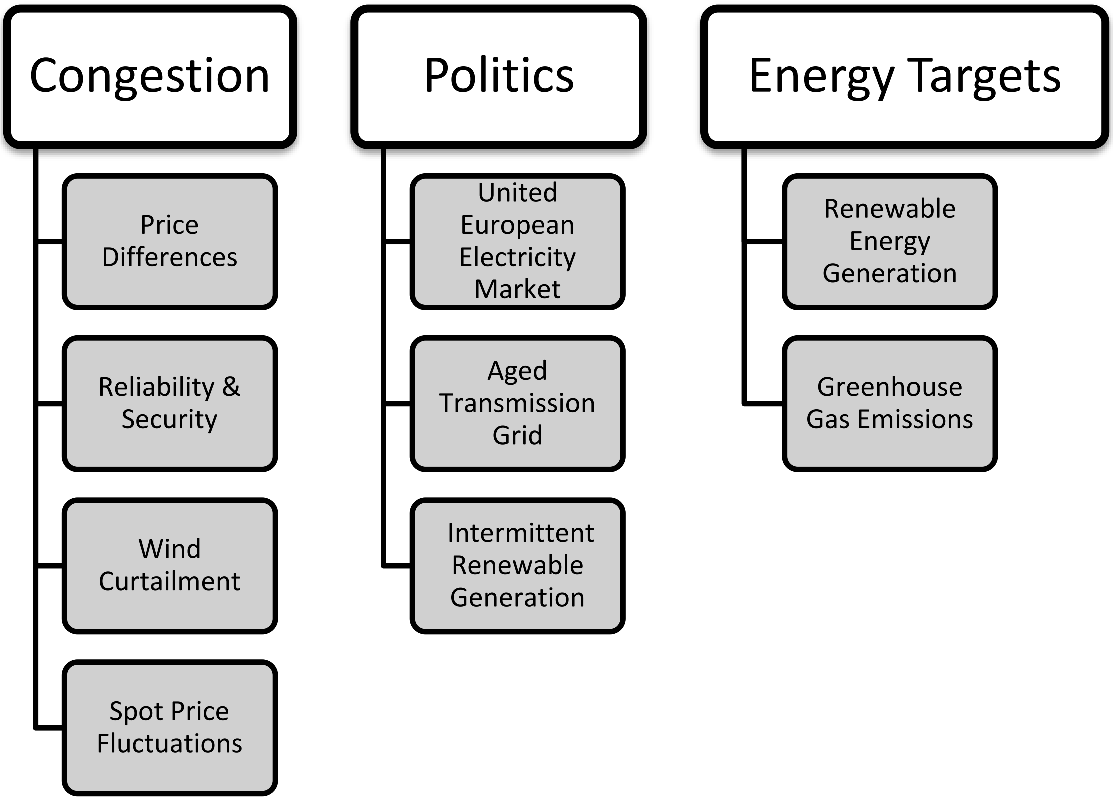

Figure 48: Acknowledged Driving Forces – Transmission in Sweden

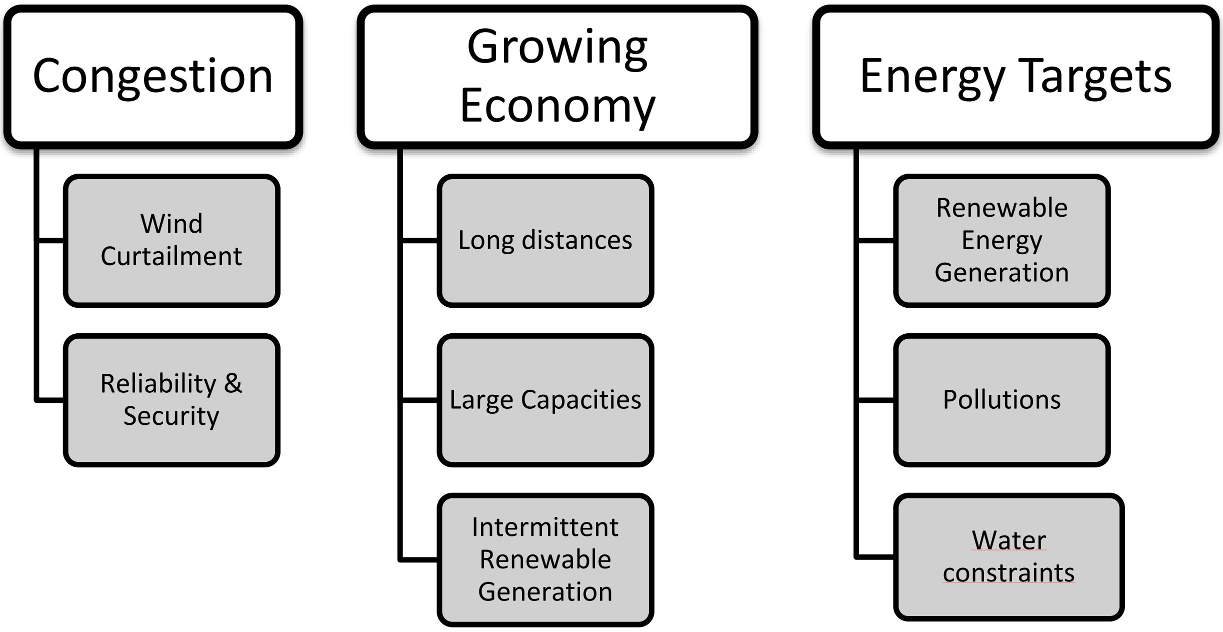

Figure 49: Acknowledged Driving Forces – Transmission in China

6.3 Cost-Benefit Model

The results from the cost-benefit model have been presented in section 5.12 for both Sweden and China. The factors affecting the outcome of the results is analysed and discussed further in the sections below.

6.3.1 The Impact of Li-ion Battery Cost Development

From the result of the cost-benefit model, it can be seen that the cost reduction of batteries are essential for its penetration on the power market. Grid storage influence increases with battery cost reductions for both Sweden and China. Grid storage flexibility is valuable for small capacities and as peak capacity. In that way, the results confirm that grid storage can contribute to transmission deferral, meaning that it is possible to avoid costly upgrades and investments of overcapacity of transmission as earlier discussed in section 4.1.2.2. By integrating grid storage, costly investments in the transmission grid can be postponed.

In Case 6 to Case 8 for Sweden and Case 7 and Case 8 for China, the break-even point between transmission and storage is passed. Storage is thereby a more advantageous investment than transmission for all capacities. Forecasts by other researchers (Figure 7 and Figure 21) have predicted this decrease to occur around year 2020 for Case 6 and around year 2030 for Case 7 and Case 8. As presented earlier in section 4.1.2.1 Tesla Motors has already announced home battery prices close to the battery cost modelled in Case 5 and 6. The announcement confirms the fast development and cost decrease of battery storages and shows that storage has a high potential to be a beneficial alternative in the future energy infrastructure. Even though it would not be possible to build grid storages exclusively, transmission capacity can be decreased and the transmission grid can be used in a more effective way by integrating storage technologies.

6.3.2 The Impact of Residual Value

Battery storage units have valuable metals that could be sold and reused in future batteries or other products. This yields an income that is included in the model every time the batteries have to be replaced during the total system life time. This value has large impact on the results, since the battery investment cost is reduced. Without the residual value of the battery investment, the influence of grid storage decreases in all cases for both Sweden and China. The break-even point is then reached at a battery cost reduction of between 50-75 percent for both Sweden and China.

Transmission is on the other hand assumed to have zero residual value. The cost for demolition is assumed to be equal to the income from the valuable metals that could be obtained from the transmission lines. If a residual value would be considered in the model, transmission investments would be more beneficial.

6.3.3 The Impact of Wind Curtailment

From the cost-benefit model, it is clear that the amount of wind curtailment influences the outcome of the results. For most capacities, the influence from grid storages increases as hours of wind curtailment increase. The reason for this is the short construction time, from the planning stage to operation, of grid storage in comparison to transmission. For every year of construction for both storage and transmission, the loss of income due to wind curtailment is added as a cost in the model. The shorter construction time of grid storage is one of the benefits of integrating storage instead of expanding the transmission grid. Unnecessary spill of available energy due to lack of transmission capacities can be avoided if investments in grid storages are realised within a short timeframe. Previous research, included in section 4.1.2.3, has found that grid storage investments are not cost-effective enough to reduce wind curtailment today. However, considering the risk of increased wind curtailment and the fact that several economic benefits can be received from grid storage integration, investments can become more cost efficient from a system perspective. The cost-benefit model is constructed from a system perspective, where the results show the most beneficial alternative to invest in, in order to reduce curtailment.

6.3.4 The Impact of Benefits

The benefits included in the model highly influence the outcome of the results. Benefits for grid storage have been chosen from a system perspective. There are numbers of varied benefits presented in previous research for different types of storage applications. Benefits also differ depending on what market actor owns and operates the storage. Only a few benefits are included in the model and have been evaluated to give the most realistic analysis as possible. These are chosen from a system point of view and with the purpose of regulating renewable intermittent energy supply.

In China's controlled market it is not possible to benefit from renewable energy time shifting, since a predetermined feed-in tariff is used for electricity from wind power plants. Thereby, the benefit from renewable energy time shifting is only included for Sweden, where the price is set on a competitive spot market. By this means, the profitability of grid storage is less in China's controlled market compared to Sweden's competitive market. Furthermore, the cost model is based on the current market structure and spot prices. Furthermore, the value of the benefit can increase if the electricity price increases in Sweden. Also a larger share of intermittent power generation can lead to more fluctuations on the spot market that can increase the value of the benefit. If Sweden's spot market changes and develop towards a power market, such as Elbas, the value of grid storage systems can be changed. The value of the benefit highly depends on market structure.

The benefits from renewable load following is considered as the most valuable benefit in the model with the largest impact on the results. The benefit is received by comparing storage to other, more expensive, solutions to adjust the frequency such as thermal power generation. However, the value of renewable load following is also highly market specific, depending of area, time and other alternative solutions to load following.

Electric service reliability has also been included since storage can provide backup for unexpected wind generation shortfalls that otherwise could cause electric service outages. A reliable and secure electricity supply is important in the energy infrastructure and involves a social value. Major power losses can lead to financial losses in the whole society, for instance production losses in industries. The value of this benefit is smaller than for load following, but do still have impact on the results.

6.3.5 Source of Errors

The outcome of the result depends on the accuracy of the cost data for grid storage and transmission. There is however limited public information about specific project data, which has led to that some data was estimated in the model. The cost-benefit model is based on data and estimations of existing transmission projects in Sweden and China, providing recent information about country specific conditions. Since these data are project specific, other projects might have other specifications involving higher or lower costs. The results from the model is also country specific, but the model can be applied for any country specific case, where length, cost and capacity of the transmission line can be compared to the option of integrating grid storage. Regarding grid storage cost data, no country specific data has been used due to lack of available public information. The benefits included in the model are country specific to some extent. Benefits from renewable load following has not been found for the country specific conditions and is thereby based on previous literature, as presented in section 5.3.2. Benefits from electric service reliability is also based on previous literature and validated as presented in section 5.3.3. Previous literature includes several models and theories developed and confirmed in the U.S. and Western Europe. It is unclear whether these instruments can be applicable in other countries. However, since no sufficient data has been available for the specific countries, the information has been applied for both market conditions.

Accuracy of additional input data and the model design also influence the outcome of the results. The model is created to suit properties for AC transmission lines, with stepwise intervals for the installed capacity, which highly effects the structure of the model. The additional input data also influence the result and involves interest rate, financial life time and charging and discharging time of the storage unit. The value for the interest rate used in the model is based on recommendations for energy infrastructure projects in Sweden and for grid storage investments presented in other literature. This value has been applied as a general input data, not country specific, which could be a source of error for the China cases. The financial life time is also based on previous literature for both technologies and not country specific. It is possible that this figure depend on country specific conditions, such as required rate of return from investors. The charging and discharging time is a parameter that highly influences the specification of the grid storage, since it determines the size of the storage unit and thereby the size of benefits and investment cost. This parameter has a large impact of the results in the model, since both the benefits and the investment cost is influenced.

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7. CONCLUSIONS

The purpose of this study was to investigate market forces for transmission and grid storage development as variation moderators for intermittent power generation. Since battery grid storage is an emerging technology, market entry barriers for integrating storage into the grid was also identified. The most important market forces identified are presented and discussed in chapter 6. The aim was also to investigate the most beneficial combination of grid storage integration and transmission expansion in the future power system, in a system perspective. Based on the case study research design, a cost-benefit model was created for two diverse market conditions. The modelled results are presented in section 5.12, where the most beneficial combination of grid storage integration and transmission expansion is investigated.

Due to the inductive approach and the fairly unexplored area, validity measurements are not considered as a major concern. Although limited access to adequate and specific market data influence the accuracy of the final results, the focus has been set on creating a research base in the field of study. Few technical-economic studies have previously been performed where market conditions for grid storage is compared to transmission expansion. The thesis is thereby a forerunner in the research area and can be considered as a starting point for other research work within the field of study to build upon. Based on the market analysis in chapter 4, identified driving forces in chapter 6, along with the cost-benefit analysis found in section 6.3, several interesting conclusions can be drawn from this thesis. These conclusions are presented in Figure 50 below.

Battery cost reduction is crucial for grid storage market penetration

- The cost development of Li-ion batteries will highly influence the cost efficiency of grid storage and decrease market entry barriers. In the long term, costs are expected to be reduced and investments in grid storage will be more beneficial. The point where battery storage investments becomes more beneficial than transmission investments for shaving is predicted to occur within a time frame of 10-15 years.

Grid storage can provide faster solutions for problems related to congestion

- Due to the faster construction time of grid storage, challenges related to congestion can be reduced in a shorter time perspective compared to long project time of transmission grid development.
- Wind curtailment drives further reinforcements in the energy infrastructure. Grid storage can become a fast solution to future challenges on the power market, particularly in China where the rate of wind curtailment is high.

Grid storage is most suitable for peak shaving and transmission deferral applications

- Grid storage can bring flexibility to the transmission grid and is most suitable for small capacities. By integrating grid storage it is possible to postpone costly investments of transmission upgrades, which would lead to overcapacity.

Low grid storage market experience can be beneficial for transmission investments

- Uncertainties related to low market experience in building and operating grid storage is a barrier and can hinder future investment decisions. For transmission projects, the experience level is high and can therefore be favourable in investment decisions.

Regulatory framework is essential for grid storage integration into the energy infrastructure

- Introduction of a regulatory framework in the EU is necessary to stimulate the market for grid storage. The potential of grid storage depend on market entry barriers, which is highly influenced by policy decisions. Ownership uncertainties need to be clarified and EU's unbundling directive regarding storage ownership is today a major barrier in the EU countries.
- China’s business climate with shorter decision paths can be advantageous for grid storage integration. A regulatory framework for market actors of grid storage projects can be realized in a shorter time frame compared to market structures in developed countries with longer decision paths, such as Sweden.

Figure 50: Conclusions

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8. FUTURE RESEARCH

The market for battery storage is constantly changing. Future research work within the field of study need to adapt as development in other market areas of storage applications affects the grid storage potential. Cost reduction of battery storage can make grid storage a lucrative investment option in the future power system. Economic viability of grid battery storage has in this research been compared to transmission grid development. The true potential of grid storage can be further investigated by comparing grid storage to other alternative solutions that also can bring flexibility in the power system. One example is to evaluate grid storage potential to demand response solutions as variation moderator.

Further progress of the research findings is to investigate appropriate location of grid storage systems in the transmission grid. In this research, grid storage is viewed from a system-perspective as a part of the energy infrastructure, without consideration of where in the system the grid storages are located. Location of the storage sites are however an important aspect to be considered when planning the power system and can be further examined.

The cost-benefit model performed in this work can be viewed as a foundation for extended research within the area. The model performance can be refined to increase rigorousness to the research findings. The benefits included in the model are based on estimations and can be further examined to increase model accuracy. Because of many potential grid storage applications, benefits can be modified in further research. To increase research validity the input data can also be tried in other model designs.

The two markets investigated in this thesis are Sweden and China. These countries have different market conditions but are at the same time facing similar problems due to increased amount of intermittent energy sources. Specific market situations and changes within the countries can be further examined to find deeper understanding of national grid storage potential and transmission expansion. A market perspective can be used to identify the most feasible area for grid battery storage integration.

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Appendix I – Code Cost-Benefit Model Sweden

```
function [] = Sweden()
clc
clear all
close all
format bank
format compact

for t_WC=100:900:1000
m_new =1;

% Creates a loop for different battery costs
for j=0.25:0.25:1
m = m_new;

LB = 1;
UB = 30; % Sets amount of maximum capacity in 100 Watts.
dt = 1;

if UB == 10
XPlot_LB = LB*100;
XPlot_UB = UB*100;
XPlot_dt = UB*dt*100/10;
end
if UB == 20
XPlot_LB = LB*100*0;
XPlot_UB = UB*100;
XPlot_dt = UB*dt*100/10;
end
if UB == 30
XPlot_LB = LB*100*0;
XPlot_UB = UB*100*(1+1/6);
XPlot_dt = UB*dt*100/6;
end

% Creates a loop for different power to be installed
for n=LB:dt:UB
```

```
% Loads input data
load .\Model_v5.1\InputData_Sweden.mat

% Additional Input Data
P_lack = 100*n;                                          % [MW]            Lack of power
WC = P_lack*t_WC;                                        % [MWh]           Wind curtailment per year
BC_GS = 795*10^3*ed*j;                                   % [$/MWh]         Storage section cost

% Total investment cost
IC_GS = BC_GS*t_dis+BOP_GS+PCS_GS;                       % [$/MW]
RI_GS = BC_GS*((1/(1+ir)^10)+(1/(1+ir)^20)...            % [$/MWh]
    +(1/(1+ir)^30));

% Annual costs over time
AFC_GS = OMf_GS/t_dis+RI_GS*ka_GS;                       % [$/MWh,year]    Annual fixed costs
AVC_GS = OMv_GS;                                         % [$/MWh,year]    Annual variable costs
AFC_T = (OM_T+RI_T)*L;                                   % [$/MW,year]     Annual variable costs
AVC_T = 0;                                               % [$/MW,year]     Annual fixed costs

% Costs for loss of income during planning and construction time
PCC_GS = EP*t_PC_GS*t_WC;                                % [$/MW]
PCC_T = EP*t_PC_T*t_WC;                                  % [$/MW]

% Residual value
R_GS = RV_GS*(BC_GS*(1/(1+ir)^40)+RI_GS)*ka_GS;          % [$/MWh,year]
R_T = 0;                                                 % [$/MW,year]

% Benefits
AB_GS = sp_GS+(LF_GS+SR_GS)/t_dis;                       % [$/MWh,year]     Annual benefits storage
AB_T = 0;                                                % [$/MWh,year]     Annual benefits transmission

% CONSTRAINTS for minimization
% ----------------------------------------------------------------------
% - EGS*N_GS/tload - P_T*A*N_T <= -P_lack
% - A <= 0
% -EGS <= 0
UB_GS = 10000;                                           % Upper boundary for grid storage
```

```
    A =[-N_GS/t_dis -P_Ta*N_T;...
        0 -1;...
        -1 0];

    b = [-P_lack;0;0];

    % MINIMIZATION
    % ------------------------------------------------------------------------

    % x(1) Energy storage
    % x(2) Amount of transmission lines
    %options = optimoptions(@fmincon,'Algorithm','active-set');

    x0 = [100;0];                                               % Start values for calculation
    [x,out] = fmincon(@(x) myfun(x,IC_GS,t_dis,ka_GS,...
        kn_GS,AVC_GS,t_WC,AFC_GS,PCC_GS,R_GS,AB_GS,P_Ta,...
        IC_T,PCC_T,ka_T,kn_T,AVC_T,AFC_T,R_T,AB_T),x0,A,b);     % The minimum is found for the objective function.

    % Creates an if statement to find best solution for <700MW capacities
   if x(2) < 1 && n <= (P_Ta/100)
        xnew(2)=1;
        xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=1;
        else
            xnew(2) = 0;                                        % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  700MW < capacities <1400
   if x(2) > 1 && x(2) < 2 && n > (P_Ta/100)  && n < (2*P_Ta/100)
       xnew(2)=2;
```

```
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=2;
        else
            xnew(2) = 1;                                        % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  1400MW < capacities <2100
   if x(2) > 2 && x(2) < 3 && n >= (2*P_Ta/100) && n < (3*P_Ta/100)
       xnew(2)=3;
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=3;
        else
            xnew(2) = 2;                                        % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  2100MW < capacities <2800
   if x(2) > 3 && x(2) < 4 && n >= (3*P_Ta/100) && n < (4*P_Ta/100)
       xnew(2)=4;
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=4;
```

```
        else
            xnew(2) = 3;                                        % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  280MW < capacities <3500
   if x(2) > 4 && x(2) < 5 && n >= (4*P_Ta/100) && n < (5*P_Ta/100)
       xnew(2)=5;
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
           xnew(2)=5;
        else
           xnew(2) = 4;                                         % x values are rounded to integers to create step
wise
        end
   end

    P_GS(n,m) = (x(1)/t_dis*N_GS+(x(2)-xnew(2))*P_Ta*N_T)/N_GS; % The amount of transmission power rounded is added
                                                                % or subtracted from optimal storage power.
    if x(1) == UB_GS && xnew(2) == 0                            % Creates a constraint that says if storage reaches
upper boundary,
        P_T(n,m) = P_Ta*round(P_lack/(P_Ta*N_T));               % investment in transmission has to be done.
        P_GS(n,m) = (P_lack-P_Ta*N_T)/N_GS;
    else
        P_T(n,m) = xnew(2)*P_Ta;
    end

    if P_GS(n,m) > UB_GS                                        % Sets the optimal power's if optimum GS Power
exceeds upper boundary.
           P_T(n,m) = P_Ta*round(P_lack/(P_Ta*N_T));
           P_GS(n,m) = (P_lack-P_T(n,m)*N_T)/N_GS;

           if P_GS(n,m) > UB_GS                                 % If storage power still exceeds upper boundary,
transmission power is rounded upwards.
```

```
                P_T(n,m) = P_Ta*ceil(P_lack/(P_Ta*N_T));
                P_GS(n,m) = (P_lack-P_T(n,m)*N_T)/N_GS;
            end
    end

    % Creates a constraint so storage can not be negative.
    if P_GS(n,m) < 0
        P_GS(n,m) = 0;
    end

    P_inst = P_GS(n,m) + P_T(n,m);
    P_overcap(n,m) = P_GS(n,m)*N_GS+P_T(n,m)*N_T-P_lack;
    Share_GS(n,m) = P_GS(n,m)/P_inst*100;
    Share_T(n,m) = P_T(n,m)/P_inst*100;

        if t_WC == 100
        Share_tot_100(n,1) = Share_GS(n,m);
        Share_tot_100(n,2) = Share_T(n,m);
            else if t_WC == 1000
            Share_tot_1000(n,1) = Share_GS(n,m);
            Share_tot_1000(n,2) = Share_T(n,m);
                end
        end
end
m_new = m+1;                                                  % Counter for looping battery cost.
end
    %---------------------------------------------------
    %--------------------Plotting----------------------
    %---------------------------------------------------

if t_WC == 100
% Creates a matrix with shares of both technologies for case 100
for k=LB:dt:UB
Out_Power100(k,1) = P_T(k,1);
Out_Power100(k,2) = P_GS(k,1);
Out_Power100(k,3) = P_T(k,2);
Out_Power100(k,4) = P_GS(k,2);
Out_Power100(k,5) = P_T(k,3);
Out_Power100(k,6) = P_GS(k,3);
```

```
Out_Power100(k,7) = P_T(k,4);
Out_Power100(k,8) = P_GS(k,4);
end
end
if t_WC == 1000
% Creates a matrix with shares of both technologies for case 1000
for k=LB:dt:UB
Out_Power1000(k,1) = P_T(k,1);
Out_Power1000(k,2) = P_GS(k,1);
Out_Power1000(k,3) = P_T(k,2);
Out_Power1000(k,4) = P_GS(k,2);
Out_Power1000(k,5) = P_T(k,3);
Out_Power1000(k,6) = P_GS(k,3);
Out_Power1000(k,7) = P_T(k,4);
Out_Power1000(k,8) = P_GS(k,4);
end
end
end

 scrsz = get(0,'ScreenSize');
 figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
 hold
 P = bar(Out_Power100(:,[1 2]),'stacked');
 C = ['c','k'];
 for n=1:2
 set(P(n),'FaceColor',C(n));
 end
 title('Battery Cost 25 %, 100 hours curtailment per year','FontSize',20)
 xlabel('Capacity demand [MW]','FontSize',16);
 range=(XPlot_LB:XPlot_dt:XPlot_UB);
 set(gca,'XTickLabel',range)
 ylabel('Capacity installed [MW]','FontSize',16);
 xlim([0 31])
 ylim([0 3500])
 legend('Transmission','Grid Storage','Location','NorthWest')
 set(gcf, 'PaperPositionMode', 'auto')
 saveas(gcf,'.\Model_v5.1\Outputs\Sweden\7_25_100','tiff')

 scrsz = get(0,'ScreenSize');
```

```
figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power100(:,[3 4]),'stacked');
C = ['c' 'k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 50 %, 100 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\Sweden\5_50_100','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power100(:,[5 6]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 75 %, 100 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\Sweden\3_75_100','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
```

```
hold
P = bar(Out_Power100(:,[7 8]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 100 %, 100 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\Sweden\1_100_100','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power1000(:,[1 2]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 25 %, 1000 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\Sweden\8_25_1000','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
```

```
P = bar(Out_Power1000(:,[3 4]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 50 %, 1000 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\Sweden\6_50_1000','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power1000(:,[5 6]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 75 %, 1000 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\Sweden\4_75_1000','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power1000(:,[7 8]),'stacked');
```

```
 C = ['c','k'];
 for n=1:2
 set(P(n),'FaceColor',C(n));
 end
 title('Battery Cost 100 %, 1000 hours curtailment per year','FontSize',20)
 xlabel('Capacity demand [MW]','FontSize',16);
 range=(XPlot_LB:XPlot_dt:XPlot_UB);
 set(gca,'XTickLabel',range)
 ylabel('Capacity installed [MW]','FontSize',16);
 xlim([0 31])
 ylim([0 3500])
 legend('Transmission','Grid Storage','Location','NorthWest')
 set(gcf, 'PaperPositionMode', 'auto')
 saveas(gcf,'.\Model_v5.1\Outputs\Sweden\2_100_1000','tiff')

function out = myfun(x,IC_GS,t_dis,ka_GS,kn_GS,AVC_GS,...
    t_WC,AFC_GS,PCC_GS,R_GS,AB_GS,P_Ta,IC_T,PCC_T,ka_T,kn_T,AVC_T,...
    AFC_T,R_T,AB_T)
% Objective function - Annuity of investment with respect to previous
% spilled energy

% x(1) Energy storage [MWh]
% x(2) Amount of transmission lines [pcs]

out = [x(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+AVC_GS*365+AFC_GS...
    -AB_GS-R_GS)+x(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T)]';
```

Appendix II – Input Data Sweden

```
clear all
clc
close all
% -----------------------------------------------------------------------
% -----------------------------Input data--------------------------------
% -----------------------------------------------------------------------
% General Data
%---------------------------------------------------
sd = 0.12;                          % [.]                   SEK to U.S. Dollar
yd = 0.16;                          % [.]                   CNY to U.S. Dollar
ed = 1.06;                          % [.]                   EURO to U.S. Dollar
EP = 334.5099*sd;                   % [$/MWh]               Average spot price benefits storage
t = 8760;                           % [h]                   Hours per year
ir = 0.055;                         % [.]                   Interest rate
L = 500;                            % [km]                  Length of transmission

% Lithium-Ion Grid Storage Sweden
%---------------------------------------------------
t_PC_GS = 1;                        % [years]               Planning and construction time
OMf_GS = 6.9*10^3*ed;               % [$/MW,year]           Fixed Operation and Management cost
OMv_GS = 2.1*ed;                    % [$/MWh,year]          Variable Operation and Management cost
PCS_GS = 383*10^3*ed;               % [$/MW]                Power conversion systems cost
BOP_GS = 80*10^3*ed;                % [$/MW]                Balance of plant cost
RV_GS = 0.25;                       % [.]                   Residual value in percantage of initial battery cost
N_GS = 0.9;                         % [.]                   Efficency, Source:
y_GS = 40;                          % [years]               Payback time
ka_GS = ir/(1-(1+ir)^(-y_GS));      % [.]                   Annuity factor
kn_GS = 1/(1+ir)^y_GS;              % [.]                   Net present factor
t_dis = 2;                          % [h]                   Discharging time, Source: LCC analysis- critical view.pdf
sp_GS = (379-254)*sd*365;           % [$/MWh,year]          Income benefits from spot market
LF_GS = 54600;                      % [$/MW,year]           Benifits from Renewable Load Following
SR_GS = 10000;                      % [$/MW,year]           Benifits from Electric Service Reliability (1h power
outages/year)

% Transmission Input data (Sweden 180km HVAC + 250km HVDC 400 kV) Source:
% http://svk.se/Projekt/Utbyggnadsprojekt/Sydvastlanken/Information/
%---------------------------------------------------
```

```
IC_T = 7.3*10^9*sd/(1200*429)*L;  % [$/MW]             Investment cost transmission
P_Ta = 700;                       % [MW]               Power transmission
t_PC_T = 10;                      % [years]            Planning and construction time
L_Swe = 15000;                    % [km]               Total length of transmission in Sweden
P_Swe = 26200;                    % [MW]               Power capacity Sweden
OM_T = 440*10^6*sd/(P_Swe*L_Swe); % [$/MW,km,year]     Total fixed operation and maintenance cost per year in
Sweden
RI_T = 667*10^6*sd/(P_Swe*L_Swe); % [$/MW,km,year]     Total reinvestment cost per year in Sweden
N_T = 0.97;                       % [.]                Efficency
y_T = 40;                         % [years]            Payback time Transmission
ka_T = ir/(1-(1+ir)^(-y_T));      % [.]                Annuity factor
kn_T = 1/(1+ir)^y_T;              % [.]                Net present factor

% -----------------------------------------------------------------------
% -------------------------End of Input data-----------------------------
% -----------------------------------------------------------------------

save .\Model_v5.1\InputData_Sweden.mat
```

Appendix III – Code Cost-Benefit Model China

```
function [] = China()
clc
clear all
close all
format bank
format compact

for t_WC=100:900:1000
m_new =1;

% Creates a loop for different battery costs
for j=0.25:0.25:1
m = m_new;

LB = 1;
UB = 30; % Sets amount of maximum capacity in 100 Watts.
dt = 1;

if UB == 10
XPlot_LB = LB*100;
XPlot_UB = UB*100;
XPlot_dt = UB*dt*100/10;
end
if UB == 20
XPlot_LB = LB*100*0;
XPlot_UB = UB*100;
XPlot_dt = UB*dt*100/10;
end
if UB == 30
XPlot_LB = LB*100*0;
XPlot_UB = UB*100*(1+1/6);
XPlot_dt = UB*dt*100/6;
end

% Creates a loop for different power to be installed
for n=LB:dt:UB
```

```
% Loads input data
load .\Model_v5.1\InputData_China.mat

% Additional Input Data
P_lack = 100*n;                                          % [MW]           Lack of power
WC = P_lack*t_WC;                                        % [MWh]          Wind curtailment per year
BC_GS = 795*10^3*ed*j;                                   % [$/MWh]        Storage section cost

% Total investment cost
IC_GS = BC_GS*t_dis+BOP_GS+PCS_GS;                       % [$/MW]
RI_GS = BC_GS*((1/(1+ir)^10)+(1/(1+ir)^20)...            % [$/MWh]
    +(1/(1+ir)^30));

% Annual costs over time
AFC_GS = OMf_GS/t_dis+RI_GS*ka_GS;                       % [$/MWh,year]   Annual fixed costs
AVC_GS = OMv_GS;                                         % [$/MWh,year]   Annual variable costs
AFC_T = (OM_T+RI_T)*L;                                   % [$/MW,year]    Annual variable costs
AVC_T = 0;                                               % [$/MW,year]    Annual fixed costs

% Costs for loss of income during planning and construction time
PCC_GS = EP*t_PC_GS*t_WC;                                % [$/MW]
PCC_T = EP*t_PC_T*t_WC;                                  % [$/MW]

% Residual value
R_GS = RV_GS*(BC_GS*(1/(1+ir)^40)+RI_GS)*ka_GS;          % [$/MWh,year]
R_T = 0;                                                 % [$/MW,year]

% Benefits
AB_GS = sp_GS+(LF_GS+SR_GS)/t_dis;                       % [$/MWh,year]    Annual benefits storage
AB_T = 0;                                                % [$/MWh,year]    Annual benefits transmission

% CONSTRAINTS for minimization
% -----------------------------------------------------------------------
% - EGS*N_GS/tload - P_T*A*N_T <= -P_lack
% - A <= 0
% -EGS <= 0
UB_GS = 10000;                                           % Upper boundary for grid storage
```

```
    A =[-N_GS/t_dis -P_Ta*N_T;...
        0 -1;...
        -1 0];

    b = [-P_lack;0;0];

    % MINIMIZATION
    % ------------------------------------------------------------------------

    % x(1) Energy storage
    % x(2) Amount of transmission lines
    %options = optimoptions(@fmincon,'Algorithm','active-set');

    x0 = [100;0];                                              % Start values for calculation
    [x,out] = fmincon(@(x) myfun(x,IC_GS,t_dis,ka_GS,...
        kn_GS,AVC_GS,t_WC,AFC_GS,PCC_GS,R_GS,AB_GS,P_Ta,...
        IC_T,PCC_T,ka_T,kn_T,AVC_T,AFC_T,R_T,AB_T),x0,A,b);    % The minimum is found for the objective function.

    % Creates an if statement to find best solution for <700MW capacities
   if x(2) < 1 && n <= (P_Ta/100)
        xnew(2)=1;
        xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=1;
        else
            xnew(2) = 0;                                       % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  700MW < capacities <1400
   if x(2) > 1 && x(2) < 2 && n > (P_Ta/100)  && n < (2*P_Ta/100)
       xnew(2)=2;
```

```
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=2;
        else
            xnew(2) = 1;                                        % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  1400MW < capacities <2100
   if x(2) > 2 && x(2) < 3 && n >= (2*P_Ta/100) && n < (3*P_Ta/100)
       xnew(2)=3;
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=3;
        else
            xnew(2) = 2;                                        % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  2100MW < capacities <2800
   if x(2) > 3 && x(2) < 4 && n >= (3*P_Ta/100) && n < (4*P_Ta/100)
       xnew(2)=4;
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
            xnew(2)=4;
```

```
        else
            xnew(2) = 3;                                                 % x values are rounded to integers to create step
wise
        end
   end
   % Creates an if statement to find best solution for  280MW < capacities <3500
   if x(2) > 4 && x(2) < 5 && n >= (4*P_Ta/100) && n < (5*P_Ta/100)
       xnew(2)=5;
       xnew(1)=100*n*t_dis-(xnew(2)-1)*P_Ta*t_dis;
        C_GS = xnew(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+...
        AVC_GS*365+AFC_GS-AB_GS-R_GS)+(xnew(2)-1)*P_Ta*...
        ((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T);
        C_T = xnew(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)...
        *ka_T+AVC_T+AFC_T-AB_T);
        if C_T < C_GS
           xnew(2)=5;
        else
           xnew(2) = 4;                                                  % x values are rounded to integers to create step
wise
        end
   end

    P_GS(n,m) = (x(1)/t_dis*N_GS+(x(2)-xnew(2))*P_Ta*N_T)/N_GS; % The amount of transmission power rounded is added
                                                                 % or subtracted from optimal storage power.
    if x(1) == UB_GS && xnew(2) == 0                             % Creates a constraint that says if storage reaches
upper boundary,
        P_T(n,m) = P_Ta*round(P_lack/(P_Ta*N_T));                % investment in transmission has to be done.
        P_GS(n,m) = (P_lack-P_Ta*N_T)/N_GS;
    else
        P_T(n,m) = xnew(2)*P_Ta;
    end

    if P_GS(n,m) > UB_GS                                         % Sets the optimal power's if optimum GS Power
exceeds upper boundary.
           P_T(n,m) = P_Ta*round(P_lack/(P_Ta*N_T));
           P_GS(n,m) = (P_lack-P_T(n,m)*N_T)/N_GS;

           if P_GS(n,m) > UB_GS                                  % If storage power still exceeds upper boundary,
transmission power is rounded upwards.
```

```
               P_T(n,m) = P_Ta*ceil(P_lack/(P_Ta*N_T));
               P_GS(n,m) = (P_lack-P_T(n,m)*N_T)/N_GS;
           end
    end

    % Creates a constraint so storage can not be negative.
    if P_GS(n,m) < 0
        P_GS(n,m) = 0;
    end

    P_inst = P_GS(n,m) + P_T(n,m);
    P_overcap(n,m) = P_GS(n,m)*N_GS+P_T(n,m)*N_T-P_lack;
    Share_GS(n,m) = P_GS(n,m)/P_inst*100;
    Share_T(n,m) = P_T(n,m)/P_inst*100;

        if t_WC == 100
        Share_tot_100(n,1) = Share_GS(n,m);
        Share_tot_100(n,2) = Share_T(n,m);
            else if t_WC == 1000
            Share_tot_1000(n,1) = Share_GS(n,m);
            Share_tot_1000(n,2) = Share_T(n,m);
                end
        end
end
m_new = m+1;                                                          % Counter for looping battery cost.
end
    %---------------------------------------------------
    %--------------------Plotting-----------------------
    %---------------------------------------------------

if t_WC == 100
% Creates a matrix with shares of both technologies for case 100
for k=LB:dt:UB
Out_Power100(k,1) = P_T(k,1);
Out_Power100(k,2) = P_GS(k,1);
Out_Power100(k,3) = P_T(k,2);
Out_Power100(k,4) = P_GS(k,2);
Out_Power100(k,5) = P_T(k,3);
Out_Power100(k,6) = P_GS(k,3);
```

```
Out_Power100(k,7) = P_T(k,4);
Out_Power100(k,8) = P_GS(k,4);
end
end
if t_WC == 1000
% Creates a matrix with shares of both technologies for case 1000
for k=LB:dt:UB
Out_Power1000(k,1) = P_T(k,1);
Out_Power1000(k,2) = P_GS(k,1);
Out_Power1000(k,3) = P_T(k,2);
Out_Power1000(k,4) = P_GS(k,2);
Out_Power1000(k,5) = P_T(k,3);
Out_Power1000(k,6) = P_GS(k,3);
Out_Power1000(k,7) = P_T(k,4);
Out_Power1000(k,8) = P_GS(k,4);
end
end
end

 scrsz = get(0,'ScreenSize');
 figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
 hold
 P = bar(Out_Power100(:,[1 2]),'stacked');
 C = ['c','k'];
 for n=1:2
 set(P(n),'FaceColor',C(n));
 end
 title('Battery Cost 25 %, 100 hours curtailment per year','FontSize',20)
 xlabel('Capacity demand [MW]','FontSize',16);
 range=(XPlot_LB:XPlot_dt:XPlot_UB);
 set(gca,'XTickLabel',range)
 ylabel('Capacity installed [MW]','FontSize',16);
 xlim([0 31])
 ylim([0 3500])
 legend('Transmission','Grid Storage','Location','NorthWest')
 set(gcf, 'PaperPositionMode', 'auto')
 saveas(gcf,'.\Model_v5.1\Outputs\China\7_25_100','tiff')

 scrsz = get(0,'ScreenSize');
```

```
figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power100(:,[3 4]),'stacked');
C = ['c' 'k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 50 %, 100 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\China\5_50_100','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power100(:,[5 6]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 75 %, 100 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\China\3_75_100','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/2 scrsz(3)/2 scrsz(4)/3])
```

```
hold
P = bar(Out_Power100(:,[7 8]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 100 %, 100 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\China\1_100_100','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power1000(:,[1 2]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 25 %, 1000 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\China\8_25_1000','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
```

```
P = bar(Out_Power1000(:,[3 4]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 50 %, 1000 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\China\6_50_1000','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power1000(:,[5 6]),'stacked');
C = ['c','k'];
for n=1:2
set(P(n),'FaceColor',C(n));
end
title('Battery Cost 75 %, 1000 hours curtailment per year','FontSize',20)
xlabel('Capacity demand [MW]','FontSize',16);
range=(XPlot_LB:XPlot_dt:XPlot_UB);
set(gca,'XTickLabel',range)
ylabel('Capacity installed [MW]','FontSize',16);
xlim([0 31])
ylim([0 3500])
legend('Transmission','Grid Storage','Location','NorthWest')
set(gcf, 'PaperPositionMode', 'auto')
saveas(gcf,'.\Model_v5.1\Outputs\China\4_75_1000','tiff')

scrsz = get(0,'ScreenSize');
figure ('Position',[800 scrsz(4)/16 scrsz(3)/2 scrsz(4)/3])
hold
P = bar(Out_Power1000(:,[7 8]),'stacked');
```

```
 C = ['c','k'];
 for n=1:2
 set(P(n),'FaceColor',C(n));
 end
 title('Battery Cost 100 %, 1000 hours curtailment per year','FontSize',20)
 xlabel('Capacity demand [MW]','FontSize',16);
 range=(XPlot_LB:XPlot_dt:XPlot_UB);
 set(gca,'XTickLabel',range)
 ylabel('Capacity installed [MW]','FontSize',16);
 xlim([0 31])
 ylim([0 3500])
 legend('Transmission','Grid Storage','Location','NorthWest')
 set(gcf, 'PaperPositionMode', 'auto')
 saveas(gcf,'.\Model_v5.1\Outputs\China\2_100_1000','tiff')

function out = myfun(x,IC_GS,t_dis,ka_GS,kn_GS,AVC_GS,...
    t_WC,AFC_GS,PCC_GS,R_GS,AB_GS,P_Ta,IC_T,PCC_T,ka_T,kn_T,AVC_T,...
    AFC_T,R_T,AB_T)
% Objective function - Annuity of investment with respect to previous
% spilled energy

% x(1) Energy storage [MWh]
% x(2) Amount of transmission lines [pcs]

out = [x(1)*(ka_GS/t_dis*(IC_GS+PCC_GS)+AVC_GS*365+AFC_GS...
    -AB_GS-R_GS)+x(2)*P_Ta*((IC_T+PCC_T-R_T*kn_T)*ka_T+AVC_T+AFC_T-AB_T)]';
```

Appendix IV – Input Data China

```
clear all
clc
close all
% ----------------------------------------------------------------------
% -----------------------------Input data--------------------------------
% ----------------------------------------------------------------------
sd = 0.12;                         % [.]                  SEK to U.S. Dollar
yd = 0.16;                         % [.]                  CNY to U.S. Dollar
ed = 1.06;                         % [.]                  EURO to U.S. Dollar
EP = 540*yd;                       % [$/MWh]              Wind Power feed-in tariff II
t = 8760;                          % [h]                  Hours per year
ir = 0.055;                        % [.]                  Interest rate
L = 1000;                          % [km]                 Length of transmission

% Lithium-Ion Grid Storage China
%----------------------------------------------------
t_PC_GS = 1;                       % [years]              Planning and construction time
OMf_GS = 6.9*10^3*ed;              % [$/MW,year]          Fixed Operation and Management cost
OMv_GS = 2.1*ed;                   % [$/MWh,year]         Variable Operation and Management cost
PCS_GS = 383*10^3*ed;              % [$/MW]               Power conversion systems cost
BOP_GS = 80*10^3*ed;               % [$/MW]               Balance of plant cost
RV_GS = 0.25;                      % [.]                  Residual value in percantage of initial battery cost
RI_GS = 369*ed*10^3/5;             % [$/MW,year]          Yearly reinvestment cost
N_GS = 0.9;                        % [.]                  Efficency, Source:
y_GS = 40;                         % [years]              Payback time
ka_GS = ir/(1-(1+ir)^(-y_GS));     % [.]                  Annuity factor
kn_GS = 1/(1+ir)^y_GS;             % [.]                  Net present factor
t_dis = 2;                         % [h]                  Discharging time, Source: LCC analysis- critical view.pdf
sp_GS = 0;                         % [$/MWh,year]         Income benefits from spot market
LF_GS = 54600;                     % [$/MW,year]          Benifits from Renewable Load Following
SR_GS = 6000;                      % [$/MW,year]          Benifits from Electric Service Reliability (1h power
outages/year)

% Transmission Input data (China 500 kV Ac total length 1634 km) Source:
% http://tdworld.com/projects-progress/sgcc-jinping-sunan-800kv-uhv-dc-transmission-project-progresses-smoothly
%----------------------------------------------------
IC_T_Swe=7.3*10^9*sd/(1200*429)*L;% [$/MW]            Investment cost transmission
```

```
IC_T = 5.7*10^9/(1000*1634)*yd*L;  % [$/MW]               Investment cost transmission
P_Ta = 1000;                       % [MW]                 Power transmission
t_PC_T = 7;                       % [years]              Planning and construction time
L_Swe = 15000;                    % [km]                 Total length of transmission in Sweden
P_Swe = 26200;                    % [MW]                 Power capacity Sweden
OM_T = 440*10^6*sd/(P_Swe*L_Swe); % [$/MW,km,year]       Total fixed operation and maintenance cost per year in
Sweden
RI_T = 667*10^6*sd/(P_Swe*L_Swe); % [$/MW,km,year]       Total reinvestment cost per year in Sweden
OMRI_T = (OM_T+RI_T)/IC_T_Swe*L;  % [1/year]             Reinvestment, operation and maintenance cost in percantage
of investment per year
N_T = 0.97;                       % [.]                  Efficency
y_T = 40;                         % [years]              Payback time Transmission
ka_T = ir/(1-(1+ir)^(-y_T));      % [.]                  Annuity factor
kn_T = 1/(1+ir)^y_T;              % [.]                  Net present factor

% -----------------------------------------------------------------------
% -------------------------End of Input data-----------------------------
% -----------------------------------------------------------------------

save .\Model_v5.1\InputData_China.mat
```

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