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Wind power integration in island-based smart grid projects

A comparative study between Jeju Smart Grid Test-bed and Smart Grid Gotland

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Abstract

Wind power integration in island-based smart grid projects

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Smart grids seem to be the solution to use energy from renewable and intermittent energy sources in an efficient manner. There are many research projects around the world and two of them are Jeju Smart Grid Test-bed and Smart Grid Gotland. They have in common that they are both island-based projects and connected to the Power grid on the mainland by HVDC-link.
The purpose of this thesis is to compare the two projects and find out what challenges and strategies they have related to wind power integration.
The objective of the two projects were somewhat different. Jeju Smart Grid Test-bed are the starting point for South Korea's smart grid road map, where the objective ultimately is to construct a smart grid on a national scale in South Korea. For Smart Grid Gotland there are three main focus areas; electricity market, power quality and wind power integration. In this thesis focus is on wind power integration.
Wind power integration in smart grids would benefit from energy storage technology connected to the wind power-park to even out the power output. Properties for a potential energy storage connected to Näsudden wind power park situated on the southern tip of Gotland has been investigated and the result is that such an energy storage would likely need to be big and expensive, but able to stabilize the power output.

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Populärvetenskaplig sammanfattning

Smarta elnät tycks vara lösningen för att kunna integrera energi från förnyelsebara och intermittenta energikällor på ett effektivt sätt i energisystemet. Runt om i världen sker forskning och projekt kring smarta elnät och teknologin ses som en del i framtidens hållbara energiförsörjning. Det här examensarbetet handlar om två av dem projekten, *Smart Grid Gotland* och *Jeju Smart Grid Test-bed.* Båda projekten är belägna på öar och kopplade till fastlandet via HVDC-länk.

Syftet med uppsatsen är att jämföra de två projekten och se vilka utmaningar de ställts inför samt vilka strategier de använt för att möta dessa utmaningar. Genom analys av rapporter, intervjuer och studiebesök ges en bild av dessa utmaningar och strategier.

Målbilden för de två projekten har varit något olika där Jeju Smart Grid Test-bed varit ett bredare projekt och fungerat som start för Sydkoreas långsiktiga plan kring smarta elnät. Därför har man haft fokus på många olika områden och tonvikt har även lagts på att skapa nya affärsmodeller byggda på smart grid-lösningar.

På Gotland har man haft tre mål rörande elmarknad, el kvalité och vindkraftsintegration. I det här arbetet har fokus legat på vindkraftsintegration.

Båda öarna arbetar med att komma runt flaskhalsar kring HVDC-länken till fastlandet. I Gotlands fall så handlar det om att man vill bygga ut vindkraften på ön, men vid en sådan utbyggnad kommer det finnas problem med överföringskapaciteten till fastlandet, alltså via HVDC-länken. För att undvika flaskhalsproblematiken ämnar man att anpassa konsumtionen så att stor konsumtion av el sker vid tillfällen som vindkraften genererar mycket el, och på så sätt behöver lika mycket av energin överföras till fastlandet.

I fallet med Jeju Island uppstår flaskhalsen då mycket energi överförs från fastlandet till ön. Vid sådana tillfällen kan det bli brist på reaktiv effekt på ön då HVDC-länken bara överför aktiv effekt.

Arbetet innehåller också en del som undersöker möjligheten att koppla ett energilager till Näsuddens vindkraftspark på Gotland. Undersökningen kommer fram till att ett sådant energilager skulle behöva vara relativt stort men också att det skulle kunna vara en god lösning för att få en mer jämn energi-output från vindkraftsparken.

Preface

This report is the result of my master thesis, which will conclude my degree in Master's Programme in Sociotechnical Systems Engineering at Uppsala University. The Master's thesis has been written for the Division of Electricity at Uppsala University.

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Hampus Piehl

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1. Introduction

In the future, traditional electrical grids will be replaced by so called smart grids. These new grids will allow for a bigger proportion of renewable energy in the power system and a possibility for the consumer to affect the electricity bill by adapting personal consumption patterns, in order to avoid peaks in consumption by that lower the electricity bill. Smart grid technology is still in the early stages of development. Many test-beds are constructed around the world. Two of which are Jeju Smart Grid Test-bed and Smart Grid Gotland.

This Master's thesis intends to investigate similarities and differences between Jeju Smart Grid Test-bed and Smart Grid Gotland. Focus of this thesis is on wind power integration in smart grids, energy storage technology connected to wind power parks, smart grid solutions in households and bottle-necks in the systems. One method to more effectively integrate intermittent energy sources in the energy system is to use energy storage technology. The thesis will investigate the magnitude of a possible energy storage connected to Näsudden wind power park on the southern tip of Gotland and give an account for the potential role of energy storages in smart grids.

1.1 Research questions

- What strategy does Smart Grid Gotland and Jeju Smart Grid Test-bed employ around wind power integration in the grid?
- What differences and similarities are there in strategy and concept for the wind power integration between the two projects?
- What role do households have in the projects?
- Which are the bottle-necks in the systems?
- How would an energy storage connected to a wind power park function?
- What properties and order of magnitude would an energy storage connected to Näsudden wind power park need to have?

1.2 Structure

The thesis starts with a background with focus on wind power and how renewable energy affects the electrical grid. Thereafter, methods and approaches used in the study are presented. Chapter four and five accounts for the interviews performed while chapter six consists of a statistical investigation. Chapter seven and eight presents and discuss around the results. Chapter nine includes additional discussions and thoughts on the two projects. Enjoy the reading!

2. Background

This part contains general information about the electrical grid, renewable energy, wind power and how it all function together as a system. Emphasis is on the characteristics which will be affected by the transformation from normal to smart grid.

2.1 The electrical grid

The electrical grid is used to transfer power from one point to another. Usually power is transferred from generation plants to households, factories and other places where there is a demand for electricity and heating. These days electrical grids are big interconnected systems that consist of transmission lines, demand centers and distribution lines that connect generation plants and individual customers to the grid. (Glover, Sarma, Overbye, 2012)

The electrical grid can be divided into different classes. In Sweden the grid is divided into national grid, regional grid and local grid (Svenska Kraftnät 2013). There is a similar structure in other countries. The national grid can also be called the transmission grid and the function of the transmission grid is to transfer power long distances. The transmission grid operates at a high voltage due to that the losses in the lines are depending on the current squared and equal to $I^2 \cdot R$ (H.J. Bollen 2011). The lines in the transmission grid are connected to substations where the power is transformed to lower voltages (Glover, Sarma, Overbye, 2012). The lower voltage lines are called the distribution grid. The distribution grid is connected to factories and local substations that transform the power to voltages suitable for connecting with the households. The grid connected to households and with the lowest voltage is called the local grid (Glover, Sarma, Overbye, 2012).

The losses in the transmission lines equals to, in most countries, generally about 5-10% of the energy consumption depending on how far the power has travelled in the transmission lines (H.J. Bollen 2011).

The main object of the power grid is maintaining continuity of supply and voltage quality. Continuity of supply basically means the absence of supply interruptions and black-outs, while power quality refers to all other types of faults that can occur such as voltage dips, harmonics and flicker. (H.J. Bollen 2011)

In today’s conventional power grids most of the generation of electricity comes from thermal, nuclear, hydro or coal power plants. These big power plants are crucial for the conventional grid as they contribute to the stability of the grid as follow:

- Operational reserves: Part of the potential power generation in a power plant is not being used due to the ability to produce extra power in a situation where other components have been lost. Operating reserves is the additional capacity available to the system operator to use in emergency situations. For example, hydro plants can regulate the power output due to different situations by spending more or less water from the dam. Nuclear power plants are not used in this way.
- Frequency control: Many large power plants are equipped with frequency control. The frequency control guarantees the physical balance between the production and the load in the whole system. As a consequence of the frequency being kept on 50 or 60 Hz depending on the standard in different countries, there is balance between production and consumption.
- Voltage control: Is a control system in big power plants that keeps the voltage at a constant level. In the same way as active power and frequency are linked together,

there is a correlation between voltage and reactive power. For this reason, it is important with reactive power reserves in the system in case of unexpected events.

- Short-circuit capacity: Short-circuit capacity is a measure for the amplitude of the currents that can occur due to a fault in the electrical system. These currents can be very high and damage components of the grid. The short-circuit capacity is also a measurement for the grids ability to cope with changes in consumption, and a too low value of the short-circuit capacity will have adverse consequences, like risks of system instability after a fault or loss of a component or insufficient voltage quality. On transmission level, large conventional power plants are the only source of short-circuit capacity. As a result, the prevailence of large conventional power plants is closely related to short circuit capacity.
- Power system stability: In most power systems, the existence of large power plants makes the whole system more stable. Aside from instances mentioned above, large power plants contributes to the inertia of the system, which helps the frequency and angular stability. Large power plants are also often equipped with additional controllers to dampen oscillations.

To summarize, large power plants function as the back bone of conventional power grids and add many crucial capacities to the stability and safety of the grid. The system operator is responsible for the drift of the grid and identifies "must run production" as well as determines the power transfer capacity between different regions. (H.J. Bollen 2011)

In smart grids where a big percentage of the energy comes from renewable and/or intermittent energy sources, the role that big power plants have has to be addressed in another way (H.J. Bollen 2011).

2.2 Continuity of supply and voltage quality (H.J Bollen 2011)

There is no razor-sharp line between continuity of supply and voltage quality, but generally continuity of supply is closely related to the grid's susceptibility to black outs whereas voltage quality deals with the all other deviations from normal power infusion.

There are certain demands that the grid should fulfill such as minimize the occurance and length of major black outs. While the grid should be able to withstand hard weather, it cannot withstand natural disasters. Another demand is that the grid gradually should increase its SAIFI which means that the annual average number of interruptions per customer should be lowered.

Distributed energy production i.e. that energy is produced in many nodes of the grid rather than a single big power plant, leads to harmonics (harmonic is an integer of the frequency in the grid). Harmonics does already exist in the grid, generated from computers and televisions. However, these are not even in the way that harmonics from distributed energy sources are, and does therefore not impose any problem.

2.3 Renewable energy

In order to satisfy environmental objectives, more renewable energy has to be integrated in the grid. Renewable energy sources, such as wind power for example, are often located in the outskirts of the grid where the voltage stability is low. This becomes an increasingly larger problem as the wind farms expands, and deliver larger power outputs. In addition, power quality is also susceptible to wind power expansion, which can lead to problems with power quality and voltage stability in the grid. (Zou and Zhou, 2011)

Renewable energy connected to the distribution grid (the level under the transmission grid) can help unburden the transmission grid to transfer less power between areas. However it can also be problematic to integrate renewable energy sources to the grid as described in the points below.

- Renewable energy can cause excess voltage in the transmission lines, especially if the lines are already close to their transmission limit.
- If a fault occurs on a feeder-cable, uncontrolled island operation can occur, i.e. a generator runs a load without being part of the rest of the system. This can damage electronic equipment as well as personnel working with the grid.
- The local system can be overloaded if the local generation exceeds the local demand. This problem especially occurs in rural areas with big wind power installations or in city areas were rooftops have big installations of solar power.
- Distributed generation could increase harmonic distortions. (H.J. Bollen 2011)

Compared with the distribution network it is easier to connect renewable energy sources to the transmission grid because the transmission grid was built to have energy sources connected to it. However such an installation could involve difficulties as well. The difficulties generally concern wind power connected to sub transmission grid (a grid with lower voltage than the transmission grid), but should apply to other intermittent energy sources as well.

- Connection of new production sources on the grid leads to new power flows which can lead to overload or insufficient operating reserves (discussed in 'The electrical grid', the system operators margin or ability to take measures when a fault occurs or a component of the grid is dropped). Having a big enough operating reserve is part of the difficulty when it comes to integration of renewable energy in the grid. The margin is commonly set to be able to handle the loss of one big component (N-1 criterion) at the same time as maximum load occurs. For wind power and other intermittent energy sources it is hard to regulate the output of power and scenarios with minimum production and maximum consumption, or vice versa could occur. Combined with a major fault (N-1 criterion) a large operating reserve is needed. On the other hand, addition of transmission lines and energy storage technology is time-consuming and expensive.
- The produced power from some renewable energy power plants is decided by stochastic processes (such as wind blowing patterns). Therefore, the power output does not follow a demand and response model where the amount of output power is connected to the consumption of power at a given time. When most conventional electrical grids were built, engineers planned it for two types of extreme conditions; maximum load and minimum load. The production of electricity were to follow the consumption. In a grid with big intermittent energy sources there exist instead four extreme conditions.
  1. Minimum production and minimum consumption.
  2. Maximum production and minimum consumption.
  3. Minimum production and maximum consumption.
  4. Maximum production and maximum consumption.

  For geographically large systems there can be regional differences in load and consumption adding extra complexity to the grid.

- Due to the variations in power output of intermittent energy sources the grid need larger margins in transmission lines and other components of the grid. (H.J. Bollen 2011)

Renewable energy sources mean different consequences for the consumers depending on whether the renewable energy sources are connected to the distribution grid or the transmission grid. In the distribution grid consumers can notice changes in voltage and power quality. When renewable energy sources are connected to the transmission grid the consumers do not experience any changes in power quality but rather variations in the price of electricity. It is the job of the system operator to guarantee power quality. If the electricity comes from renewable energy sources the price will be low but if the electricity on the other hand comes from reserve power, the price will go up. To guarantee power quality and keep steady voltage, the system operator can stop certain power transactions or temporarily disengage certain power plants. (H.J. Bollen 2011)

As energy from intermittent energy sources often is cheaper than that of conventional power plants (hydro power does for example require that water in the dam is being spent, while solar power generates electricity when the sun is shining), the intermittent energy sources should be used whenever possible. However, as discussed earlier, conventional power plants contribute with important stability factors for the grid. (H.J. Bollen 2011)

2.4 Forecasting intermittent energy sources

Predicting the energy output from renewable energy sources and at the same time predicting variations in consumption can lead to big differences in power demand and power supply if predictions are wrong. In distribution grids, prediction errors can be reformed by load following reserves, which is basically the same thing as operating reserves, described earlier in the text. For large amounts of renewable energy there can be a need for additional reserves in addition to the operating reserves (H.J. Bollen 2009).

An alternative to increase the operational reserve or system reserve, is to place an energy storage reserve in connection to the wind power plants, which can have many benefits for the grid. Developing a good forecast system and a probability density function for errors in the forecast is of high importance when designing power systems (Bludszuweit, Dominguez-Navarro, Llombart 2008).

2.5 Wind power (T. Wizelius, 2007)

Wind power is the energy that can be exctracted from the wind. The wind is always varying but on a long scale perspective it has even patterns and statistically the winds in Scandinavia varies with only ± 10 % per year. Wind variations on second-basis is called turbulence and can damage wind power plants. The average wind, which is the average speed during a year, and form factor, which is a factor that shows wind variations, are measures that describe the wind at certain places. (Statens energiverk, 1985)

Due to reduced costs for wind power plant construction, wind power can begin competing with other energy sources on a commercial basis. It is important for the system operator with predictions of the wind power output to efficiently integrate the wind power in the power system. The wind speed is stochastically distributed and the wind power output is proportional to the cube of the wind speed. To effectively predict the wind speed in an area it is important to have large amount of meteorological data of that area (Yona, Senjyu, Toshihisa, Kim, 2013).

Capacity factor is a measure of how much power a wind power plant would be able to generate if there were optimal wind conditions all the time. It is therefore a theoretical value as the wind is ever changing. Capacity factor is an important factor when deciding where to build wind parks (Y. Ditkovich, A. Kuperman 2014).

In big power installments there can be a need for natural gas spinning reserves due to the intermittency of wind power. With small wind power installations this is less of an issue. Solar power can be a good supplement to wind power as sunny days has weaker winds, while cloudy days often have stronger winds. When wind power plants are spread out in a big area the output can be less variable and more predictable. Due to the intermittency of wind power, integrating wind power into the grid can bring about the need for increased regulation and larger operating reserves.

The output from wind power is proportional to the cube of the wind speed. For this reason power output from wind power plants does vary much more than wind speed. For example, if the wind speed is increasing from 7 m/s to 8 m/s, the theoretical power output increases with almost 50 %. If the wind speed doubles, the electricity output increases eight times. This implies that the placement of wind power plants is very important.

Average wind speed in a specific place is not the only important factor for wind power plant placement. But frequency distribution does also play a big role in the electricity production of a wind power plant. Two places with the same average wind can consequently have different energy output. When calculating the energy output of windmills in a certain area one often draws a plot with frequency on the Y-axis and wind speed on the X-axis. To calculate potential energy output, the cubed wind speed is multiplied with the frequency. The frequency of the wind does usually correspond quite well with Weibull distribution.

In conventional grids wind power plants are often placed in the outskirts of the grid where the grid is weaker. Often this is not a problem because the grid is just gaining another positive load, like an electric motor helping to supply the grid with energy. Variations in the wind power output can be compensated by other power sources, hydro power for instance. In Sweden, the wind is blowing more in wintertime than in summertime which aligns well with the nation's higher electricity consumption during the winter months.

Wind power cannot function as a base power source because the production is varying. It cannot function as regulator power nor as peak power because it is not possible to produce electricity on demand from wind power. Wind power must therefore have another role in the electrical system. Wind power plants can be placed connected to the distribution grid and as long as wind power plants do not produce more than 10 % of the total energy production they do not impose a threat to system stability (more on this topic later).

Local wind power production can lead to decreased losses in the grid, and the power produced from wind power lets other power plants produce less power. However, installed wind power creates a demand for regulatory power as the wind is not always blowing.

As mentioned it is first when the percentage of energy generated from wind power exceed 10 % that the electric system has to be modified to be able to function properly. In all electrical grids there are emergency power plants that can immediately be started up and compensate for any one lost generation. This is part of the N-1 criteria. If wind power plants are spread out over a large geographical area the risk for nonexistent wind is very small implying that energy would always be extractable from the wind and that such spread of the windmills would result in an even production. Therefore, no extra emergency power is needed to be installed, even for big installations of wind power.

The more electrical grids become interconnected, the less emergency power in the system is needed. Interconnected electrical systems work very well together with wind power as the intermittency can be compensated for by the rest of the grid.

In grids where wind power exceed 10%, the system operator can place the same kind of demands on wind power plants as on conventional power plants, that is, the ability to regulate power output up or down. However, this demand will only be put on big off-shore plants as requiring these abilities from wind power parks increases the costs.

In the future, more efficient means of energy storage system will allow for more wind power in the grids. Good short term forecasts can lower the prices as the grid operator can have a clearer picture on how much electricity that will be generated from wind power some time in advance.

The amount of wind power that can be connected to the grid does not only depend on the voltage in the grid but also on the dimensioning of the electric cables and the distance to a transformer which can upgrade the voltage. There are however some rules of thumb that varies between countries. In Sweden 3,5 MW wind power can be connected to a 10 kV transmission line, 15 MW to a 20 kV line and 60 MW to a 40 kV line. The grid operator is responsible for the quality of the electricity and maintaining frequency as well as avoiding flicker. This may lead to that the system operator demands certain electro technical abilities from the wind power plants and the electric equipment used in the plant. If many wind power plants are built in one place, the grid might have to be strengthened in that part to cope with the energy flow.

2.6 Meterological forecast of wind speeds (Interview with Hans Bergström)

Weather forecasts are the main source of information when predicting wind power output. Meteorologists use forecasts from big international weather services to local weather services for their prognoses. Global weather forecasts are the primary point of reference when predicting wind power output in specific locations. These are also complemented with data from local weather forecasts. The different forecasts are then inserted in computational models and the values of different measurement result in an output of expected energy output. The computational models can also account for instances when several wind power plants clustered together affect the wind in that particular area. All data and prior experience are forged together in statistical computational methods based on statistics.

The grade of turbulence does affect wind power production to some degree but average wind speed affects power generation to a much larger extent. The altitude of measurement is also important to consider. For instance, wind flows at sea are relatively even while wind that travels in areas with obstacles can result in different speeds at different heights.

The most common way to determine wind speed in meteorological observations are based on 10 minute observations, which is called the average wind. The one-second wind can fluctuate much more and fluctuations within that time is called turbulence. The ten minute wind is praxis when using data for meteorological analysis. Average yearly wind speed is often used to determine where to build wind power plants. The ten minute wind observations are more interesting for the grid operator as these measures can be used to schedule how to control power flows in the grid. Hourly values are used to predict the amount of energy output from wind power plants. The reliability of these prognosis are hard to predict.

Weather forecasts are hard to do. All forecasts are based on observations of the atmosphere all over the globe. Important measuring parameters are temperature, moisture, pressure and wind speed. There are many ground stations for measuring, and also stations which can measure conditions on a higher altitude. There are radio stations in the atmosphere that can provide data from 10- 40 km height. There are also satellites that can observe cloud cast and formations to help predict future weather. The observations are used in different equations, such as fluid dynamics equations, momentum equations, thermo dynamic equations and energy equations. Together with temperature, water and gas laws, these equations become computer models.

It is also possible to calculate climate scenarios. One complicating factor is that it is hard to give an accurate picture of a situation at a very specific moment. Therefore, computer simulations can never be exact. Random samples are used in data assimilation when starting the process. The atmosphere is turbulent and the turbulence is a stochastic process. The atmosphere does also, on a longer scale have stochastic properties, which make long term predictions difficult. Beyond 10 days it is very hard to predict future weather. The persons in charge of the wind power plants send their output power predictions to the system operator, who then plans the energy flow according to wind power data (as well as other data). Prognosis meteorologist's forecasts are then delivered to Nordpool who fix the electricity price. Usually the prognosis is on 72 hours' time-interval.

Wind power plants usually start generating electricity around 3-4 m/s. There is also an upper limit where the wings of the plant stop rotating to not risk the safety of the plant. This limit is about 25 m/s. To give an accurate analysis about climate and wind speed, one has to measure the climate in a place for 30 years. Weibull distribution is often used as a measurement to describe wind speed. Multiple wind measurement has shown correlation between wind speed and the Weibull distribution. With the Weibull distribution it is possible to plot the wind speed as a graph over time which can give a good indication on how the wind speed varies and how useful it thereby would be to construct a wind power plant in a certain spot. Wind speeds exceeding 25 m/s are very rare, especially at land. Therefore it is more economically viable to turn off the plants at these high wind speeds than to build wind power plants that can generate energy from extreme winds.

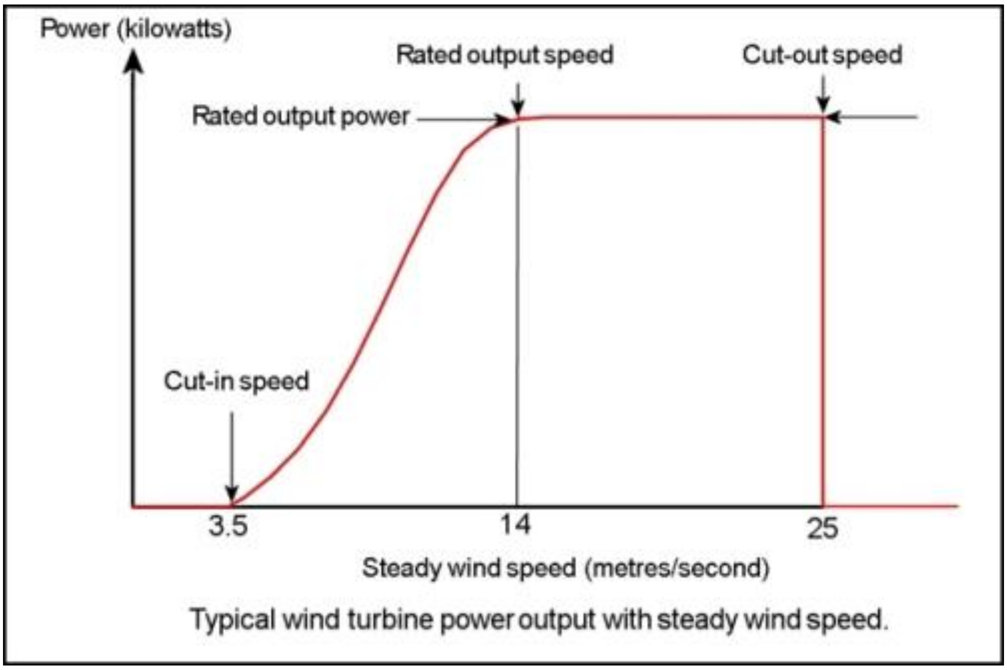

Figure 1. The figure shows the energy output of a typical wind power plant as a function of wind speed (wind-power-program.com 2013).

To be able to extract more energy from wind power, one would have to use more efficient generators (to be able to extract more energy from the wind at high wind speed, like 20 m/s). Due to this limitation in technology, a lot of potential energy is being lost.

The turn off limit results in a drastic change in wind power output when the wind speed is close to max. If it is just below 25 m/s, the wind power plant produces rated power, but if wind speed reaches higher, the plant has to shut down and produces no electricity (as seen in figure 1.).

Wind speeds that exceed maximum tolerable wind speed of the wind power plant and, forces the plant to shut down, is unusual but happens a few times per year. To cope with this the system operator have other power sources ready to kick in. Another option is to just risk outage if the consequences of an outage is more economically reasonable than strengthening the system.

Dispread wind power plants over Sweden or, in a larger scale, Europe would help to level the energy output from wind power. However, spreading wind power plants throughout Gotland would not have the same effect as the area is too small and wind speed is more or less the same on the island. At the same time, on an island it is common that the air and the ocean have different temperature which gives origin to thermal driven winds, and in those cases there can be changes in wind speed throughout the island. The usual case is that there are some spots where there is commonly more wind than in other spots. But the wind can vary. Suppose a company would like to run their operation based on wind power. If they were to have one wind power plant on Gotland and one plant in Skåne (the southernmost part of Sweden) the distance would be large enough for minimizing the risk of excessive wind speeds at both locations.

In a system with a big proportion of wind power, regulation is important. Concerning battery storage; another way to look at the wind power situation is that a lot of the produced power from wind power plants is being wasted, and that better energy storage systems would help capture the yielded power more efficiently. To find storage for extracted wind energy is in a way a more difficult challenge than finding alternative energy sources for days when the wind is not blowing. when the wind is not blowing. A suggestion from the respondent Hans Bergström is to produce hydrogen gas with the excessive wind power, and run cars and other vehicles on the gas.

During wintertime there can be a problem with ice formations on the wind power plants. One aspect is security, because the wind power plants can throw ice very long distances, several hundred meters in some cases. In occurrence of ice, new weight is attached to the blades, creating unbalance. Ice may slip of one blade but stick to another blade, creating problems with balance and unwanted loads. The main problem though is loss of production. Changing the blade profile changes the aerodynamics of the blade and can easily result in a loss of half of the production. In areas in northern Sweden from Dalarna and up, it is a reasonable assumption that 10 % of the energy is lost due to problems with ice, unless the ice formations is being taken care of. There are different techniques for heating the blades to get rid of the ice. Some plants have to be shut off while heating while other plants can keep running. Some plants use heating coils and some have hot air inside of the blades. The occurrence of ice does not have to do with temperature in the sense that colder temperature means more ice. Instead, ice-occurrence is most common with temperatures around zero, -5 or -10 degrees Celsius.

However, at extremely cold conditions there are material crispness to take in consideration. When the temperature is around -25 or -30 the wind power plants may have to shut down if not the wind power plant were built by special material which cope with such extreme cold is being used. Windmills operate on a relatively high altitude, where the temperature is higher than on the ground which makes the risk for extreme cold less of an issue. It can easily be -30 on the ground but only -20 or -10 on 100 meters altitude. The coldest places are generally dells, or long valleys. In those places there are a very weak winds, so wind power plants are not placed in those places anyhow. In the summer it is warmer on the ground than on higher altitudes, the temperature shifts more on ground level. Occurrence of ice is extra probable when wind power plants are placed on a mountain top and clouds collide with the rotating blades. In those circumstances, small water particles can attach to the blades and create ice.

2.7 Energy Storage

Energy storage is a mean to conserve energy. In an electrical grid, as described earlier, there has to be balance between consumption and production. An energy storage can help level off this balance and can be particularly useful in electricity systems with intermittent energy sources (H.J. Bollen 2011).

The placement of the energy storage in the grid is very important, as well as the following parameters;

- The amount of energy that can be stored, i.e. the difference between the maximum and minimum energy level in kWh.
- Maximum charging rate in kW, i.e. how fast the battery can be charged in conditions of surplus energy in the grid.
- Maximum discharging rate in kWh, how fast the battery can support the grid with energy.
- Losses during charging and discharging, i.e. how efficient the storage is.
- Losses while energy is being stored, including energy losses from heating or cooling the energy storage.

Other important factors are cost, life length, operational costs, size and weight. There are many different battery storage technologies to choose between. Lithium-ion batteries have become popular in recent years and they have been used or there are interest in using this kind of battery in both Smart Grid Gotland and Jeju Smart Grid Test-bed. Lithium-ion batteries have a high efficiency, high energy density and long lifetime, they can be charged and discharged about 4000 cycles, which equals to more than 10 years if they were to be used once every day. Lithium-ion batteries are small but quite expensive (H.J. Bollen, 2011).

In the present situation energy storages are most appropriate to install on distribution level. Energy storages could also function as a capacitor bank for reactive power. (H.J. Bollen, 2011)

There are certain challenges for energy storages to be more integrated in the electric system of today. The biggest challenge is high storage costs in comparison to benefits from the storage. Positive factors are for example that electric vehicles can be part of the energy system (Eyer, Corey, 2010).

There are many types of energy storage technologies, for example:

- Electrochemical batteries: Consists of two or more electrochemical cells. Chemical reactions in the cell create a flow of electrons. Current is created by chemical reactions between the cells, electrolyte and electrons.
- Flow batteries: In this battery the electrolyte is contained outside of the cell. This makes it easier to replace the electrolyte when it degrades.
- Capacitors: Are specially designed to be able to deliver a significant amount of energy over a short period of time.
- Compressed air energy storage: The technology is based on compressing the air with inexpensive energy. The compressed air can then later generate energy when there is a bigger need for electricity. To create energy, the air is released in a combustion turbine generator system. For very large energy storages the air can be stored in underground geologic formations such as depleted natural gas fields.
- Flywheel energy storage: consists of a wheel that spins around an axis. Energy into the flywheel energy storage causes the wheel to spin faster and when energy is about to be extracted, the generator causes the wheel to spin slower.
- Pumped hydroelectric: This energy storage system includes a turbine generator equipment, a waterway and one upper and lower reservoir for water. Water can be pumped to the higher dam. And when energy is expensive the energy storage can generate energy like a normal hydroelectric power plant.
- Superconducting magnetic energy storage: The medium of this energy storage consists of a coil made of superconducting material. The energy is stored in the magnetic field created by the flow of direct current into the coil. The coil has to be cooled, but apart from that it can keep the energy for as long as it is refrigerated.
- Thermal energy storage: For example, making ice and use it instead of cooling. (Eyer, Corey, 2010)

The usage of energy storage at present moment is due to how energy storage is defined. The hydro power plants in Sweden can be seen as gigantic energy storages with a capability of 30 TWh. Apart from that, energy storages are not used much at all, at least not in Sweden. Hospitals and other important buildings have UPS's, uninterruptable power supplies, to protect from black outs. In hospitals the UPS's often consists of big battery storages, combined with diesel generators. The only way to store energy on a large scale is in hydro power solutions. To pump the water to a higher altitude and then use it as a normal hydro power plant. In Germany for example, old mines are used for this purpose. Using dams and hydro power solutions for conserving energy is a space and weight consuming way of storing energy (Lundin, 2013).

Lithium batteries, which were used in the Jeju Island test-bed, has a disadvantage in life-length if they are to be charged and discharged many times per day. Commonly they can have a life length of 3000, 5000 or 10000 cycles and if they are used many times per day they won't last very long. In a vehicle for example they might have to charge even more often than that. On the other hand if they are part of some kind of emergency system and only are used very seldom, they can last very long (Lundin, 2013).

Generally batteries does not "like" to be charged or discharged with high in or output of power, although that is sometimes what it takes to be part of the system. For example, if the energy storage is connected to a wind power plant and need to take care off excess energy from the park, power input can be very big. Different technologies such as flywheel can handle big power-flows and many cycles better but have other disadvantages, they can't store big amounts of energy and not for a long time. In some situations UPS's (uninterruptible power supply) battery storage are better, while, for wind power parks there might be possible to use both kind of techniques perhaps in combination. However a park can have a power output of many MW, so the question is how to use the energy storage efficient. There is a risk that the energy storage would have to be very big and expensive. On an economic point of view where electricity price is the deciding factor it would, in today's situation, never be economically viable to have installed energy storage capability connected to the wind power park. However there can be other important factors such as keeping the voltage and frequency up to level and other power quality issues where energy storages can help out. Energy storages can be used for so much more than storing kWh, and these other areas may also be very important (Lundin, 2013).

Energy storages in areas with a weak grid could help out so an addition of the grid does not have to be built. Again, for a cost-effective energy storage, it is not the mere stored energy that is the important factor but rather the placement of the storage and how it can help with power quality issues (Lundin, 2013).

3. Method

This part will give a description about how the study has been realized and motivate for the choices made by the author.

3.1 Choice of subject and execution

This Master thesis is written for the division for electricity at Uppsala University and the instructor is Johan Lundin, postgraduate at the department. The author had an interest in writing about smart grids and after acquiring knowledge about two similar smart grid island-projects, Smart Grid Gotland and Jeju Smart Grid Test-bed, a comparative study was decided to be the subject of the study. A time period were used for deciding more in particular what the subject, within smart grids, would be. After reading reports, and especially after the interview performed at Vattenfall, wind power integration in smart grids was decided to be the focus of the study.

The comparison is to a big extent based on interviews with personnel at the two smart grid sites. To be able to compare the two projects in the best way possible, the same questions and focus were used both at the interviews with Smart Grid Gotland and at Jeju Smart grid Test-bed. Gradually during the interviews focus were directed towards various areas depending on knowledge and area of interest of the respondent, but the intention were to ask the same questions to all respondents.

Apart from the interviews with personnel at Smart Grid Gotland and Jeju Smart Grid Test-bed, a statistical investigation were made to investigate the magnitude of a possible energy storage connected to Näsudden wind power park. During the interviews about wind power integration, -connecting energy storage technology to wind power parks instead of strengthening the local grid came up as one solution to integrating intermittent energy sources into the grid.

3.2 Research approach

In this thesis a qualitative research approach has been used. Within the area of qualitative research there are many approaches to collect and analyze data. What is typical for a qualitive study however is that the author has an important role in both interpreting and analyzing the data (Dalen 2007). The main strength of qualitative interviews is the possibility to get a more advanced understanding of the subject through the possibility of attendant questions (Kvale and Brinkmann 2009).

3.3 Qualitative interviews (Dalen, 2007)

Since qualitative interviews play a major role in this thesis this part will inform the reader more about qualitative interviews and discuss how they are used in best practice.

As discussed earlier, in a qualitative interview the researcher must interpret the information from the informants, the interpretation is based both on the direct statement from the informant but also from the dialog between the researcher and the informant. In a dialog, the researcher's own understanding of the empirics will affect the interpretation.

In a qualitative interview-study, the researcher starts revising and analyzing the answers earlier than in other forms of scientific research. This has advantages as it helps improve the questions which will be asked in the next interview.

To get out max of the interview it is important to have good knowledge of the area, but also to think of what the respondent might answer to a particular question.

In semi-structured and structured interviews, there are a question formulae ready to be used before the interview. This is also the case in my study. I brought a sheet with questions to all of the interviews. When writing down the questions for the questionnaire it is important to consider if the question is rightly expressed.

- Is the question unambiguous and distinct?
- Is it a leading question?
- Does the question demand special knowledge or information which the informant does not have?
- Is the question too sensitive so that the informant does not want to answer it?
- Does the question allow the informant to formulate his or her own opinion?

During the interview it is important to use some sort of recording equipment to more exactly retail the views of the informant. It is also important to give the respondent the choice to read or listen to what was being said in the interview and perhaps modify some of the answers.

In this thesis the interviews have been semi-structured, which refers to the interviews emanating from already set up questions, but that many attendant questions were asked as well. This served as a good way to perform the interviews in my study since many unsurmised matters came up, requiring attendant questions.

3.4 Literature Review (Saunders, Lewis and Thornhill, 2009)

A literature review is used to demonstrate awareness of the current state of knowledge in the area. In this fashion, the reader gets a perspective on where the study fit into the research area.

In most research projects, literature reviews are made early in the process but there is often a need to continue with literature review throughout the whole process. As the research question gets more distinct, additional literature review might be needed.

Doing a literature review in the early stages of the thesis is advantageous as it helps to discover which research has already been done, and in that way helps define an area for the own study, if lucky they can also provide well-founded and interesting research questions.

In this thesis the literature review has been used to achieve more knowledge of the topic and to educate the reader about smart grids and wind power, in order to better understand the analysis and the material achieved from the interviews.

3.5 Statistical investigation

The thesis also includes a statistical investigation based on wind speed values from Näsudden on the southern tip of Gotland. More about the method for statistical investigation in chapter 6 “Statistical investigation”.

3.6 Discussion about the method and criticism of the sources

All the people who were interviewed about smart grids did in some way work with the projects. This could possibly have led to a more positive approach from the respondents towards smart girds in general and to the respective projects in particular. The impression I got from the interviews was that all the respondents answered objectively and to the best of their knowledge to the questions.

There were instances where the Smart Grid Gotland Pre-study and the respondent from Vattenfall gave different answers. This shows the importance of conducting interviews and endeavor to find out and describe the correct situation.

My main interest were to investigate strategies and experiences related to wind power integration, therefore I did not interview any people living in 'smart homes' on Jeju Island. In hindsight that would have been an interesting complement to the study and allowed for a broader understanding of the circumstances around smart homes on Jeju Island.

The interviews about Smart Grid Gotland, Wind power prediction and energy storage technologies were performed in Swedish. All interviews concerning Jeju Smart Grid Test-bed were performed in English. A difficulty in the implementation of the thesis were to find people in Korea who were both well informed about the project and good English speakers. If I had been able to speak Korean, the thesis could have gained a more precise survey about the project on Jeju Island.

4. Smart Grid Gotland (Smart Grid Gotland Pre-study, 2011)

This part shall explain more specifically about the project on Gotland.

Smart Grid Gotland is going on right now and the project are planned to be running between September 2012 until June 2015.

Smart Grid Gotland is a large scale test for the convergence of IT, telecom and the electricity market. To be able to fulfill the EU target for 2020, more renewable energy must be integrated into the electricity system and this causes a demand for smart grid solutions.

The term smart grid can mean both the distribution grid and the transmission grid. In the case of Gotland the 70 kV lines are used to some extent as transmission lines. From a smart grid system perspective Gotland will regulate its frequency and short circuit power.

Smart Grid Gotland aims to use dynamic voltage control in order to handle large amounts of renewable energy in the form of big installations of wind power but also small scale of photo voltaic power installations on rooftops. Small scale generation plants impose a challenge to the grid because the grid have to deal with two way communication and two way power flows.

Allowing the grid to be smart, many of the components communicate by using IT to interact in the grid. Examples of these components are:

- Smart meters.
- Distribution Automation: Certain components in the distribution grid work automatically, such as switches and breakers. To be less vulnerable to storms, electric cables will to a larger extent be placed under ground.
- Low loss transformers.
- Advanced Meter Infrastructure, AMI: Measures collects and analyses energy use based on the customers' smart meters. Enables two-way communication and is a prerequisite for the demand and response model of smart grids.
- SCADA (Supervisory Control and Data Acquisition): Is a computer monitoring system that monitors and control the functionality of the grid. Within SCADA there is a Distribution management System, DMS, which allows for a more efficient use of the distribution grid in order to minimize losses.
- Low voltage monitoring and control: Using the smart meters and sensors which indicates the load on the low voltage grid, losses can be reduced and loads can be distributed more effectively. Low voltage monitoring also includes the ability to connect small scale generation to the low voltage grid.
- Smart substation: Includes decentralization of switches and breakers. Smart substations will make measurement and automated management of the loads increasingly manageable as well as facilitating the quality and the voltage of the electricity in the regional grid. Smart substations will predict outages with increased precision and decrease the cost of maintenance. Therefore smart substations will decrease the length and quantity of outages.
- Energy storage: Li ion batteries are integrated in the distribution system. The batteries help with voltage control and power quality improvements. The batteries also allows for short term island operation (which means that part of the grid is disconnected from

the rest and is being run locally). Large scale energy storage can even be used as a generator in the grid and act as a power source when needed.
- Condition based maintenance: The risk management of the grid shall change from being reactive and preventive to being predictive and condition based. By replacing infrastructure before incidents rather than after, a higher availability of the grid can be allowed for.
- Hybrid Cars: The hybrid cars will have batteries which can be charged favorably when intermittent generation output is high. In a way the cars will act as large scale energy storage which not only are charged during periods of high intermittent generation, but also can act as a storage of energy and supply the grid when needed. The low voltage grid might have to be strengthened to have capacity of charging hybrid cars.
- Demand and Response: By using a demand and response model the system operator can manage the electricity consumption. Consumption can be reduced during peak hours and agreements between power utility and customer leads to a more efficient use of energy.

There already exists a grid at Gotland and the aim is to upgrade the existing grid to a smart grid. The local grid in the north of the island is weak. In that area there are factories and households as well as wind power generation which cause a need for power balance. Balancing power comes from the middle of the island were Gotland is connected to mainland Sweden with a HVDC-link. If a fault occurs with the HVDC-link, there are emergency generators which can support the island. Smart Grid Gotland intends to upgrade the north part of the grid so it can be operated in a safe way. This might call for dynamic control of reactive power for example.

Situated in the central region of Gotland is Visby, the largest town on the island. This is also where the HVDC link to the mainland is connected. The HVDC will provide with power when needed, but also export power from Gotland when the wind power generates more power than being consumed on the island. An energy storage will be installed that will help with innovative smart grid solutions as well as work as a dynamical reactive power reserve.

The distribution grid will partly be rebuilt to smart grid level to allow for increased controllability and better supervision. Visby will be a city where charging of hybrid cars will be made possible.

The wind power installations is mainly situated south of the island and is being transmitted to Visby by 70 kV AC transmission lines. In parallel with the AC transmission line, there is a HVDC line which can support when increased power are to be transmitted. The HVDC link increases the system stability and can function as a dynamical reactive power compensator. This is important when there is a lot of renewable production present. The grid in the south part of Gotland is quite modern and Smart Grid Gotland will mainly introduce measurement and control in the region.

The control of the whole system will be in Visby where the system controller will be located. In the smart grid system of Gotland, the aim is that much of the electricity shall come from wind power. As discussed earlier this will have consequences for the system stability. The smart grid will have measures to deal with this stability not least involving the customers in order to increase system stability.

All of the equipment used in smart grid Gotland has already been used before but the test is rather how all the parts can function together. The idea is to test the system and promote smart grids as a solution for other locations as well.

4.0.1 Distributed intermittent generation (Smart Grid Gotland Pre-study, 2011)

In Smart Grid Gotland, STATCOM technology is used to guarantee the security. STATCOM stands for Static Synchronous Compensator and is a regulating device used on alternating current. It works as a stabilizer for the system and can act as a sink or a source of reactive power depending on what is needed at a certain moment. Usually STATCOMs are used to support grids with poor power quality and to assure voltage stability.

- The Gotland STATCOM can act as a support for wind power as the system intend to have battery storage included for certain benefits of the grid. High increase or decrease in wind power is managed by an installed spinning reserve, which is a generation capability that can respond fast to compensate for exceeding generation or need for extra transmission outages.
- Customers will have information of the price of electricity at all times, which will help to adjust consumption after production. Taxes will be adjusted to favor renewable energy as well as making energy from renewable energy plants "first choice".
- Power quality: SVC lights will mitigate voltage sags.
- Frequency support: All energy storage devices should have an emergency frequency support or spinning reserve to support frequency in case of unexpected events.

4.0.2 Technical development (Smart Grid Gotland Pre-study, 2011)

In Smart Grid Gotland there are two substations (substations transform the voltage from low to high or vice versa) which will be modified, Källunge and Bäcks. They are located at each side of the rural grid. In special cases it will be possible to feed the grid from only one of the two smart grid substations. In the substations a switchgear transform the voltage from 70kV to 10 kV. In addition to this, Bäcks substation is connected to the HVDC light link to southern Gotland where most of the wind power is produced. At the substation Källunge there will be a 10kV Static Var Compensator system with battery storage connected to the grid.

4.1 Interview at Vattenfall with David Erol 2013-12-03

There are 3 main goals for the test project Smart Grid Gotland. The first goal is based on the function of the electricity market and is an ambition to by market forces implement more wind power on Gotland. It should consequently be economically viable to invest in wind power energy. The second goal is related to how customers can save money by adjusting electricity consumption in the established system, and how this adjustment are connected to wind power output. If the wind is blowing it shall be a bit less expensive with electricity and if the wind does not blow as much, more expensive. However it is hard to get a correlation since the price area is bigger than just Gotland. Gotland is part of price area S3, and the price in the area is somewhat the same in the whole area. Therefore it can be expensive to consume electricity even though it is blowing a lot at Gotland at a certain point of time. The ambition of the project is however correlation between local consumption and local energy generation. The third goal of Smart Grid Gotland concerns power quality in the grid.

The ambition of 'wind power integration' which is the respondent’s main project, is to integrate more wind power in the existing Gotland grid. There is a maximum limit in the system, and the Smart Grid Gotland research team are now investigating the maximum limit of the HVDC-link, which is the main bottle neck of the system. The HVDC link has a certain maximum transfer capability which sets the boundary for how much electricity that can be transmitted off the island. In a scenario where there is a lot off wind power generation, and at the same time small consumption on the island, almost all of the generated power has to be transported to the mainland. If more wind power plants were to be built on the island, the HVDC-link would not be able to transfer the power generated on the island to the mainland in the given scenario. The challenge is therefore to reduce peaks in exported power. To solve this, the system operator, Vattenfall, has a number of customers on the island which are participating in the smart grid test. In the customers houses or apartments Vattenfall can control the heat water tank, and the inside temperature. With this control, the system operator can influence how much energy the households consume and when. Research questions within this area is, how many extra customers is needed on Gotland to accomplish an extra 5 MW wind power on the island? What components is needed to shift consumption to peaks in wind power generation? To investigate this, times with peak distribution to the mainland is identified. To avoid peaks in distribution one looks at one day ahead and one day after the peak to see what measures that can be taken. Is the demand and response measures enough to avoid this peak? Can the demand and response model shift the consumption to synchronize with the peak transfer? By shifting the consumption to overlap the peak in wind power production, less power has to be transferred to the mainland. As mentioned earlier the system operator has control over warm water tanks and indoor temperature in the households participating in the test. If there is a predicted peak 7 hours ahead for example, the system operator can turn off water heating and indoor warming to create a bigger demand at the time of the peak. This will create a mini-peak in consumption synchronized with the wind power generation peak, and thereby reduce the exceeding power which has to be transferred to the mainland. However, there are certain boundaries which the system operator has to stay within such as temperature comfort zone. The comfort zone for indoor temperature is set to be between 18-22 degrees. For warm water tanks the temperature should be between 60-100 degrees. However these, limits can be discussed. In the morning when many people are taking a shower before work it is perhaps not an option to turn off warm water tanks in order to create a surge for electricity to heat water later at, perhaps, one o clock when there is an expected peak in wind power production. It would be a contraction to peoples comfort and customers would not be happy. It is similar with indoor temperature, comfort is highly valued by the customers and favorable incentives is needed to motivate them to be a part of the smart grid campaign. In summary it is possible to shift loads to different times but there also exist important boundaries for how much the load can be shifted.

The conclusion so far is that the system would benefit from a more local market. The intermittent energy sources has a close connection to local weather conditions. Therefore the market have to be local and correlate with the shifts in the output of the intermittent energy sources. As discussed earlier Gotland is part of the electricity price zone S3 which prevent a more direct correlation between local weather phenomena and electricity price on the Island.

The capacity of wind power on Gotland is 170 MW at the moment (December 2013). During the project it will rise to 195 MW. 195 MW installed wind power is the maximum of how much wind power Gotland can host with today’s grid. It is calculated from a scenario with maximum wind generation and minimum consumption on the island. This sort of scenario would mean that a lot of power has to be transferred to the mainland through the HVDC-link, and the HVDC capacity is the limiting factor in the system. If minimum consumption gets bigger, maximum wind power establishment can also increase. The goal is to allow the maximum wind power installation on Gotland to be 5 MW higher. This is planned to be done by shifting load to different time periods as explained earlier. One way to allow for more wind power in the grid would be to turn off wind power plants at times of maximum generation to lower the amount of energy which has to be transmitted to the mainland by the HVDC-link. This would however seem contradictionary, not least to the public, to turn off wind power plants during strong winds, although it might would have been the most economically viable option.

Smart Grid Gotland is as mentioned a test plant for a scenario with wind power integration into an existing grid. Analysis of the Island indicate that if the HVDC-link was not a bottle neck of the system, the transmission lines between the big wind power park at Näsudden and consumers located in and around Visby would be the next bottle neck of the system. The existing line between Näsudden and Bäcks, where the HVDC link to the mainland is located, would increasingly be a burden and would not be able to take on the load.

On the island there are, except wind and solar power, a gas turbine with power 120 MW. Two diesel generators with 19 MW power and an additional 10 MW gas turbine. These power sources start up if the HVDC-link for some reason is out of function and can be considered as emergency or reserve power. Moreover Gotland is supported by the HVDC link and renewable power sources on the island. On a yearly basis Gotland import more energy than they export.

So far it is still uncertain whether Gotland will use energy storages or not. Smart Grid Gotland would like to use energy storage technology as part of the test-bed, but it is very expensive. The collaborators of Smart Grid Gotland works on a solution. The price would be approximately 50-70 million Swedish krona. In the price research and development are included as well as attendant costs. When working with intermittent energy sources it is necessary to have energy storages as part of the system. The question though is whether a potential energy storage should be electrical, mechanical or in the form of pumped-storage hydroelectricity. The Gotland project are considering an electric energy storage and are now investigating how, theoretically a battery could be used to allow for more wind energy. One approach is that the battery storage should be used for absorbing and compensate for miscalculations in wind power output predictions. Upcoming peaks and dips in wind power output are based on wind speed prognosis and the only real knowledge about the prognosis is that it will not be right.

The Gotland project use different prognosis tools for different time scales. There is one algorithm for day ahead predictions based on a complicated computer program which is used to detect peaks in generation. Except persistent algorithms, hour ahead prediction is used. Hour ahead prediction is basically an assumption or conjecture that the wind speed will be the same the next hour as it has been this hour. Empiric studies has shown that this will give a matching result with a mean error on approximately 6 %. The fault percentage is the root mean square error. If battery storage technology were to be integrated in the system it should deal with the 6 % of prediction error. Both to be able to spend power as well as to absorb power. Vattenfall uses the software Wind power prediction tool for their forecasts. For predictions up to one hour the advanced algorithm have 6-8% fault while the simple method, just assuming the same wind speed, has 6% fault. Therefore, 1 hour is a breakpoint where prediction method is changed from simple version to algorithm version.

As mentioned, the long scale algorithm function is the basis for how the system operator use the ability to control warm water tanks and indoor temperature in apartments and houses. It is possible to rectify the expected power output one hour ahead. The misassumptions within the hour should be taken care of by the battery reserve power system. The battery storage that exists now are one 1.7 MW storage which can last for 7 minutes and one on 280 kW which can last for 10 minutes. The battery storage capability is at the moment very small and can only be part of very small systems when it comes with dealing to prediction errors (more about this later in the report). The respondent interpose that there are also other areas where battery storages would come in handy, such as strengthening the grid in terms of electricity quality and islanding as well as increase the short circuit effect. This is very hard however, the energy storages are too small. A question which is now worked upon is; how big would the energy storage have to be to be sufficient to deal with prediction miscalculations? Energy storage is the solution to effective wind power integration, unless the electrical grid system is really big and geographically large as so the wind is always blowing in some place. Smart Grid Gotland is a test-bed for larger, perhaps national scale smart grid solutions in the future. Sweden has a good regulation ability because of a lot of hydro power, Germany and other countries on the continent does not have hydro power in the same amount leading to that they have to compensate in some other way. Perhaps this can be compensated by big interconnected grids.

A good method for finding bottle necks in the system is to build a generic model of the system. In the model it is possible to see the power flows and how big percentage of the transmission lines which are being used at different power flows. If the transmission lines are used over their capacity they will burn up. To reach the European Union's "20 20 20" objective (20% reduction in greenhouse gas compared with 1990. Raising the share of renewable energy with 20%. An improvement in energy efficiency with 20%.) Sweden has to integrate more wind power in the power system. The generic model which is now being used to analyze Gotland's power system shall be the basis of the construction of the generic model which will show bottle necks in the Swedish power system (European commission, 2013).

Due to bottle necks in the system, frequency is not used as the govern variable. If the frequency rises it can trigger increased consumption "behind" a bottle neck. There could be a scenario with big wind power generation and big energy consumption, though the wind power energy cannot sufficiently reach the consumer because of insufficient transmission capability.

Generally on Gotland the wind power plants turn off at around 25 m/s. However if the wind speed is that high, cut off effect from the wind power plants are not the biggest problem. Trees starts falling down over transmission lines which is a bigger problem than wind power plants not generating any electricity. To be protected from extreme wind speeds, all the cables has to be buried and many other measures has to be taken. After protection measures for parts of the grid has been taken, cut off effect from wind power plants could be an issue. One method of dealing with cut off effect would be to use 'soft stops' i.e. that the power from wind power plants gradually lower with high wind speeds, and therefore there would not be drastic change in power output at the cut off wind speed.

The respondent argues that wind speeds are not the same all over the island and that plants located in different regions of the island would make a scenario where all wind power plants experience cut off wind speed is very unlikely and that there would bring on a more regular wind power output.

Even if all wind power plants did not generate any energy, it would not be a big concern for the electrical grid of Gotland since it is connected with the mainland through the HVDC link. Except supplying Gotland with energy the link also supplies the grid with important properties such as frequency control, operational reserves, voltage control and short circuit capacity.

Smart Grid Gotland is doing a literature study about Synthetic inertia, where the turbines are inelastic connected to the grid. When the frequency dips because of over-consumption or under production, there is a massive rotating mass keeping the frequency up. In for example hydro power, the turbine is inelastic connected to the grid and therefore the generation, the rotating blade of the hydro power plants has a direct connection to the frequency. Synthetic inertia would allow wind power plants to contribute to the grid in a similar way as hydro power plants. In wind power plants today there are no such connection. The modern wind power plants have electric equipment in-between the connection to the grid, so therefore it is not the same kind of direct connection. The rotor has one kind of frequency and it is then transformed by the electric equipment to match the frequency in the grid. However this does not allow for the same inertia as in common grids. The conception is that this should be able to be done synthetically. This could help with properties that big power plants usually help with, such as frequency control and operational control. Especially important is this on a market where the system administrator has taken responsibility to keep the frequency and electricity quality. In that case those properties cannot be compromised with. The wind power plants can also produce positive or negative reactive effect. A scenario could be that the wind power plants work like this even when the wind is not blowing. Future studies will show if this is something to invest in or not.

One challenge is to manage the price due to local conditions. As of now, customers receive a bill based on the market. The market is not always correlated to local electricity generation phenomena, therefore the grid would have to send a signal to the market to get a correlation. At Gotland a function will control certain components of the house and try to minimize the cost for the customer without hurting the comfort as discussed earlier. This is based on price signals. For the system operator, it is easier to 'control' the functions at the house instead of letting the customer do it. The customer has a choice, the rational choice would be to follow price signals but how can the operator know that the customer is following the price? That kind of system makes it harder to balance the loads and generation compared with the system operator 'controlling' the households. This kind of system is called direct control. A system based on price-signals by SMS or mail to the customer is called indirect control.

Smart Grid Gotland does not include electric vehicles in their project all tough that was an area that perhaps would be worked upon according to the pre-study (Smart Grid Gotland Pre-study, 2011).

5. Jeju Smart Grid Test-bed (Korea Electro-technology Research Institute (KERI), 2013)

This part shall explain about South Koreas energy situation and about Jeju Smart Grid Test-bed.

The project Jeju Smart Grid Test-bed lasted between December 2009 until May 2013.

In South Koreas electricity production 96% of the electricity comes from nuclear, coal, oil and gas. According to the Carbon Dioxide Information Analysis Center, Korea were the ninth highest country in carbon dioxide emission within the period 1950 until 2005. South Korea has decided to invest in renewable energy and the goal is that year 2050 20 % of the electricity shall come from renewable energy sources.

To be able to realize this goal, smart grid technology is a key component. Motivating factors for smart grids is; to take climate change responsibility, improve energy efficiency, reduce carbon dioxide emissions. There is also a will to create a growth engine within smart grids, for export of technology and to create new jobs. The Korean smart grid initiative is highly dependent on voluntary participation from large companies in the country. As a coordinator for Koreas smart grid project stands KSGI, Korea Smart Grid Institute. After the project Jeju Smart Grid Test-bed, Korea has set up a road map to reach the final target which is to implement a nationwide smart grid. Step 1 on the roadmap is to create a pilot smart city. This is planned to be done by 2016. Step 2 is multiple smart cities (year 2021), and in year 2030 step 3 shall be implemented, which is a nationwide smart grid.

So, Jeju Island was the first step of South Koreas smart grid plan. The peak load at Jeju Island is 680-700 MW and the installed capacity is 800 MW. There are two HVDC lines connected to the mainland, and they are each capable of transmitting 150 MW. The objective of Jeju Smart Grid Test-bed was to set up the world's largest smart grid test bed and the test included 7000 households.

Only a part of Jeju Island were included in the smart grid. Figure 2. Help distinguish Jeju Island and the area included in Jeju Smart Grid Test-bed.

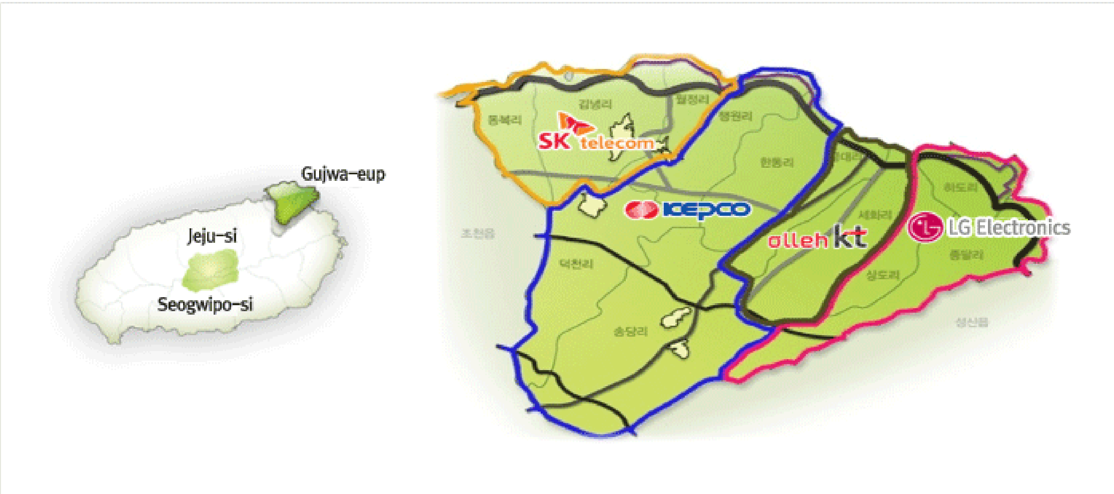

Figure 2. The picture shows the section of Jeju Island which were part of the smart grid test project. The picture to the right shows some of the companies involved in the project (smartgrid.jeju.go.kr, 2014).

5.1 Jeju Smart Grid Visitor Center 11/2 2014

The author of this thesis visited Jeju Island in February 2014. On Jeju Island there is a museum for smart grid ideas and technology called the Smart Grid visitor center. At the smart grid visitor center they arrange tours to show the ideas behind smart grid. Some of the information is very basic as the tour is directed towards school children and people who, before the visit, didn't know of smart grids. This section will retail some of the information from the tour at the visitor center.

The project at Jeju Island were divided into five areas: Smart Power Grid, Smart Place, Smart Transportation, Smart Renewable and Smart Electricity Service. The transmission lines in Jeju Smart Grid Test bed has four lines. Three is for transmission of electricity, and one is used for ICT. Usually when there is a black out, the engineers has to go looking for the place of the fault. With ICT technology the grid can give information directly about where and perhaps what kind of fault that has occurred.

Jeju Island is a Test-bed for electric vehicles and in an initial stage 200 cars were given out to citizens at Jeju. Jeju Island is a signally good location for electric vehicles as the Island is of the size that a fully charged electric car can take you almost anywhere on the Island in one upload. In a second stage more electric vehicles will be given to the public. There is a big need for energy storages in Jeju Island, not least to help integrating wind power in the system (more about that later). In Jeju Island there are many fish farms and when the farms for some reason are no longer in use for growing fish there is an idea that dammed up water can be used for hydro power.

At the Smart grid museum a smart home were simulated, showing how the Smart homes were reacting to different electricity pricing. In the first scenario, where the electricity price is low, everything works as normal. In the two other scenarios were electricity price is higher the light is dimmed, and if the person living in the house wants to use for example the washing machine, the machine "tells" the person that the electricity price at the moment is high and that it might be better to wash clothes later. However if the person really wants to wash clothes, or use any other component of the home at a certain time, it can be done, but the home 'informs' the person about the energy situation and that it might be cheaper to consume energy a while later. At high electricity price times, the lights in the houses are dimmed and lights in the refrigerator shut off in order to save energy.

5.2 Interviews in Korea

This part is a compilation of the interviews performed in Korea. The section has been divided into subdivisions to highlight the various topics. A more direct summary of the interviews can be found in appendix. Respondents were Ji Jin Kim guide and informant at the Smart grid visitor center at Jeju Island and Kang Dong-Joo and Seojong Soo from Korea Electro-technology Research Institute.

Jeju Smart Grid Test-bed started 2009 and a big challenge at that time was to build up the infrastructure (Ji Jin Kim, Smart grid visitor center 2014).

Further challenges and strategies were as follow…

5.2.1 Wind power integration

In Jeju Island there are 120 MW installed wind power, which corresponds to 12% of the total energy input to the Island (not to be confounded with the part of the Island which were part of

Jeju Smart Grid Test-bed). However only 5 % is used now because the wind power output is unstable and unpredictable. The Jeju government plans to be a carbon dioxide emission free Island in 2030 so the government wants to use energy in the wind and other renewable energy sources in an effective manner. At this moment Jeju Island has three thermal power plants located on the Island and two HVDC links connected to the mainland to help with energy supply. The HVDC-link could be used for exporting power from Jeju Island to the mainland but so far it has only been used for importing power (Ji Jin Kim, Smart grid visitor center 2014).

At the Total operation center, were the power flows are planned in Jeju, there is a system for predicting the power output connected to forecasts of wind speed (Ji Jin Kim, Smart grid visitor center 2014).

Considering that the wind power stands for such a small part of the total energy there have not been any problem with the wind power integration from a system perspective Kang Dong-Joo, KERI, 2014).

During the test period 10 megawatt wind power were used, which thus is low compared to the full capacity. Capacity wise the wind power was not a problem. However, compared to the power system of mainland Korea, the system is smaller and therefore more vulnerable to fluctuations. This is one reason why not all the installed wind power was used. More battery storage systems and power conditioning systems are needed to use the full potential. In electrical grid level the engineer's needs to consider both transmission and distribution level to deal with fluctuations. For the entire system this kind of fluctuations is not a problem but in local grids it can cause problems. The system has a rating limit for fluctuations, and the local system needs more buffering capacity. There is a need for a buffering capacity between the wind power park and the grid. This buffering system could be an energy storage or energy conditioning system (Kang Dong-Joo, KERI (Korea Electro technology Research Institute) 2014)).

Korea will have a similar problem on a large (national) scale as they plan to build a large wind power park in the west sea side, between Korea and China. Many experts in Korea worries about the system impact when the large scale wind power park is connected to the mainland grid. The limit of wind power capacity based on the grid structure of Korea is 20% according to power system experts in Korea. The Korean grid of today does not have a high level of flexibility when it comes to incorporating more renewable energy (Kang Dong-Joo, KERI, 2014).

5.2.2 Battery storage technology

The wind conditions in Jeju Island is very different from wind conditions in other places. In other places the wind direction is straight and stable but in Jeju the wind is very unstable and the direction of the wind keeps shifting. The wind speed does also keep changing, and therefore technology to stabilize the power output is needed to connect the wind power plants with the grid. More investments are needed to integrate the wind power fully in the system and thereby use all installed wind power. Battery storage is a crucial part of the required technology. With batteries connected, the output from renewable energy sources can be stabilized to better fit into the power system (Ji Jin Kim, Smart grid visitor center 2014).

Currently thermal units/fossil fuel generators cover the fluctuations from the wind power. So capacity-wise energy storage systems are not that important for the overall energy supply. If the wind power output is higher than expected, fossil fuel generators reduce their production, and if wind power output is low, the output from fossil fuel generation plants are increased. There is a large capacity to make up for wind power. There is also the HVDC-link which can level up and down the power transfer to the Island depending on how much electricity that is being generated on the Island. In the future, with more installed wind power, Jeju might face the same challenges as Gotland such as the HVDC-link to the mainland being a bottle-neck in the system.However with the current situation there is no such bottle-neck concerning the HVDC-link (Kang Dong-Joo, KERI, 2014).

The energy from wind power is small compared to the total energy use on the island and therefore energy storage technology is not needed so much as a power source but more so to stabilize the system. In Ju Jeon substation there is a 4MW PCS and 8MW battery. The equipment is used for as a test and to help stabilize the grid (Ji Jin Kim, Smart grid visitor center 2014).

During the project there were tests with Led-batteries and Lithium Ion batteries (Ji Jin Kim, Smart grid visitor center 2014).

The role of the battery storage system was both to supply with power and to give stability to the grid. The battery storage needs to act as a buffer in the power system and store the energy from renewable energy sources. Another reason why energy storage systems were used was that companies involved in the smart grid project were trying to create new business models based on energy storage technology. The business-model they were trying to create involved using batteries in a demand response model (Kang Dong-Joo, KERI, 2014).

5.2.3 HVDC Technology

The HVDC-link connecting Jeju Island to the mainland were used for stabilizing the grid during the test period. Normal case were that the Test-bed could support itself but during peaks in energy consumption the test-bed also received energy from the HVDC-link. The biggest challenge concerning the goal ‘Smart renewable’ were to stabilize the system. The power grid is stable but when a big proportion of renewable energy is connected to the grid, it makes the whole system unstable. Being a big challenge this area has been continually tested at Ju Jeon substation after the project was finished (Ji Jin Kim, Smart grid visitor center 2014).

The HVDC link were connected to the Island during the full test period and Jeju Island, not to be mistaken with the region used in the test.bed, were supported with power 80-90 % of the time counted from 8760 hours per year (Kang Dong-Joo 2014).

Concerning operational reserves, voltage control and short circuit capacity, there are an independent EMS (Energy Management System) which schedules and controls the overall Jeju Island System (Kang Dong-Joo, KERI, 2014).

The HVDC link from the mainland supplies the island with active power but not with reactive power. If there is a big transfer of active power from the mainland to Jeju Island there could be a shortage of reactive power as there are many switches and loads on the Island which are in need of reactive power. There are synchronizing condensers and Statcoms installed on the Island to help with reactive power but in some scenarios they are not enough. Jeju Island are also supplied by thermal units which can provide with reactive power. The thermal units have some contingencies which could lead to loss of generation. If the thermal units for some reason are down, there can be problems with keeping up the frequency. In those situations Jeju Island needs to gain more power from the mainland to keep up with the load. But as the

HVDC-line transfers more power the need reactive power is also bigger and thereby the problem with not enough reactive power support on the Island. The bottle neck of the System is therefore not the HVDC-link but rather the system as a whole, or the reactive power generation units on the Island. (Seojong Soo, KERI, 2014)

5.2.4 Smart Homes

Many people participating in the project were old and did not really understand the project. They received a smart meter, special washing machine and an IHD, In Home Device, controller, making their home a ‘Smart Home’. They liked it because they got machines and home equipment for free as well as a lower electricity bill due to the ‘smartness’ of the system. However, the respondent Ji Jin Kim, argue that people living in smart homes during the project didn’t really actively participated in the smart home concept because they didn’t understand the system or they were not interested. The ‘Smart Home’ test were expanded to some living areas in Jeju City, were more young people live. The young people showed more interest in the smart grid solutions and adapted their behavior after the smart grid solutions (Ji Jin Kim, Smart grid visitor center 2014).

Jeju Island is kind of a country side in Korea and the population there consists to big proportion of old people. However this is changing as Jeju Island is a famous tourist attraction in Korea and young people move there to work with the tourists. Alltough, still the population is mainly old (Kang Dong-Joo, KERI, 2014).

Kang Dong-Joo agrees that consumer engagement been a big challenge during the test period since the people in the area were old and had difficulties in understanding the concept of smart grids and demand and response pricing (Kang Dong-Joo, KERI, 2014).

Compared to Gotland, the smart homes had a different function where the people living in the Jeju Smart Homes had many choices on how to adapt their energy consumption. “That’s why we failed” says Kang Dong-Joo. Most people living in the smart homes of Jeju Island were old and they had a hard time understanding how to adapt their consumption after the variant pricing. Smart Grids in Korea are in the beginning stage and in the future the demand response solutions can be developed into automatically demand response solutions which does not need active participation of the people living in the smart homes. But in that kind of system, the automatically demand response system must understand the context of the individual person living in the home. All people have different preferences, living pattern and behavior. In individual homes the system needs to learn to adapt to home owners behavior around energy consumption. It is a give and take situation between energy saving functions and convenience which later can be evolved into automatic functions. The system needs to the human’s choice into consideration and adapt to it. The respondent talks about technology development within the field, for example, Swedish company Ericsson is working on a “Internet of things” solutions. In order for the system to work, machines needs to understand the human preferences and act with a sort of artificial intelligence (Kang Dong-Joo, KERI, 2014).

Kang Dong-Joo thinks that it would have worked better if there were less choices for people and more automatically functions. “People are too busy” so it is almost impossible for them to care about their energy usage at all times (Kang Dong-Joo, KERI, 2014).

Smart grid could be very successful in Korea as Korean people are very technology-updated and experienced in using smart devices such as smart phones. Education about benefits with smart grids and how they work could be an important factor in Korea when influencing people to a smart consumer behavior (Ji Jin Kim, Smart grid visitor center 2014).

Korea has a kind of unique situation as more than 60% percent of the residential sector consists of apartments. Therefore Korea has a high possibility to save energy by applying energy management systems in buildings perhaps combined with energy storage systems (Kang Dong-Joo, KERI, 2014).

5.2.5 Future plans and evaluation

In 2030 Jeju government has set up a goal to be a carbon dioxide free island. To achieve this ambition they will use wind power, small scale hydro power and wave power. They will also focus on the demand side. For example to replace all non-electric vehicles with electric vehicles within 10 years. Currently Jeju Island is heavily dependent on fossil fuel plants which is a dependence that will take time to transcend out of. There could be problems with system stability with more renewable energy integrated in the grid. The power grid will need to be rebuilt to have bigger flexibility. More energy storage systems and super capacitors need to be installed (Kang Dong-Joo, KERI, 2014).

Looking back at the project, perhaps five different study fields were too much and too ambitious. The focus of the test could have been smaller. The respondent thinks that it could have been beneficial if the test were directed to only battery storage technology and EMS, energy maintenance system, in factories and homes (Ji Jin Kim, Smart grid visitor center 2014).

The government will provide 400 electrical vehicles to the public next year. The Korean government are very interested in smart grids and have made big investments. The next stage of Korea’s smart grid plans is to implement smart grid in mainland cities (Ji Jin Kim, Smart grid visitor center 2014).

Concerning prosperities and failures of the Jeju Island project the respondent points out that the project failed to create an effective demand response model which was the main failure of the project. It was a test for technical and economic feasibility around smart grid solutions and the results are relevant on a global basis, not only for Jeju Island (Kang Dong-Joo, KERI, 2014).

The economic impact of smart grid solutions is very limited in an Island such as Jeju Island or for that part Gotland. This is because the population is small and therefore the economic impact becomes small as well. When Smart grid technology is deployed in city areas, there can be more economic benefits and stronger business models can be created. The city is a kind of platform with many business-models. In that sense Jeju Island was not a good site for testing the Smart grid as it was not an ideal spot for business-models (Kang Dong-Joo, KERI, 2014).

Due to Jeju Smart Grid Test-bed, Korea has been recognized as one of the first developers of Smart grid in the world. In marketing perspective it was a very successful smart grid project as Jeju Island is a famous sight-seeing location and got many people’s attention. Many people travel to Jeju Island for vacation and while at the Island got to know about the smart grid. The project meant smart grid technology became known to many people (Kang Dong-Joo, KERI, 2014).

Because of the Jeju project, many Korean companies became engaged in Smart grid technology and did research about smart grid solutions. There were many trial and errors but at least the Jeju project was a starting point for many companies to invest in green technology and in smart grids (Kang Dong-Joo, KERI, 2014).

Ji Jin Kim, which were interviewed at the Smart Grid information center in Jeju said that the Jeju project incorporated too many sectors. I wanted to hear Kang Dong-Joo's opinion about that.

Kang Dong-Joo does not agree that there were too many focus areas in jeju Smart Grid Test-bed. Considering the national road map of smart grids, which also focuses on many sectors, there were benefits with the Jeju project having many focus areas as well. However, it was a pilot project, and that is why it has limited economic impact and perhaps why companies had difficulties in creating business models (Kang Dong-Joo, KERI, 2014).

One option to create a market for renewable energy in Korea would be to raise the taxes for coal, oil and nuclear power. However, that would lead to a higher energy price in Korea and to social resistance. The respondent argues that the Korean people would not appreciate that kind of tax-raise. Electricity price is currently a strong political issue and it would not be easy for politicians to enforce tax-raise. There is though the renewable portfolio standard, which is currently on 2 %. The renewable portfolio standard is a standard which shall secure renewable power generation in relation to other installed capacity. This standard is currently at 2 % (Kang Dong-Joo, KERI, 2014).

Another issue concerning the national road map for smart grid in Korea is that there just isn't enough renewable energy sources in mainland Korea to supply the country. This is an argument for why Korea also in the future will use nuclear power (Kang Dong-Joo, KERI, 2014).

6. Statistical investigation

In the interview with the respondent from Vattenfall it was announced that Smart Grid Gotland participants are interested in testing energy storage technology connected to wind power parks. As I received wind data from Näsudden, located on the southern tip of Gotland, I thought it would be interesting to investigate how big, and what kind of energy storage that would be useful at the location.

According to the interview with the respondent from Vattenfall, the energy storage technology that interests Smart Grid Gotland is an energy storage that can make up for short time malpredictions. As described earlier there are two prediction methods which are used for predicting the wind power electricity generation. One of the methods is day ahead prediction which uses many parameters combined in an algorithm for predicting the future wind speed. The other prediction method is for short term predictions. It is it basically an assumption that the future short time wind speed will be identical to the present wind speed. One hour is the breakpoint for when the long time prediction methods becomes more accurate than the short time prediction method.

The wind data which will be used in the research are from a measuring station on Näsudden located on the southern tip of Gotland. The wind speed has been measured at different altitudes for every tenth minute from 2000-05-19 at 9.30 AM until 2002-01-15 9.20 AM. That means 7+12=19 months of data or 85568 ten minute average wind data values.

This investigation looks at how big the prediction errors were on ten minute basis. For example: If the 10 minute average wind speed at a certain time were 6 m/s, then the prediction for the next 10 minute average wind speed are also predicted to be 6 m/s, according to the short term prediction method. If the next wind speed in fact were 6,2 m/s, there were thus a malprediction of 0,2 m/s. The objective for potential energy storage technology connected to the wind power park is to compensate for the short scale prediction errors and the investigation intends to find out how much power the energy storage would have to make up for, how often it would need to be used, and what storage capacity it would need to have.

6.1 Wind power output.

The energy output of wind power plants are correlated to the wind speed as follows:

$$P = \frac{1}{2} C_p \rho A v^3 \qquad (1)$$

Equation 1. P=power, C_p= the power factor of the windmill, ρ = the air density, and A is the area of the swept rotor (Eriksson 2008).

So the output of energy from the wind power is as discussed in earlier chapters:

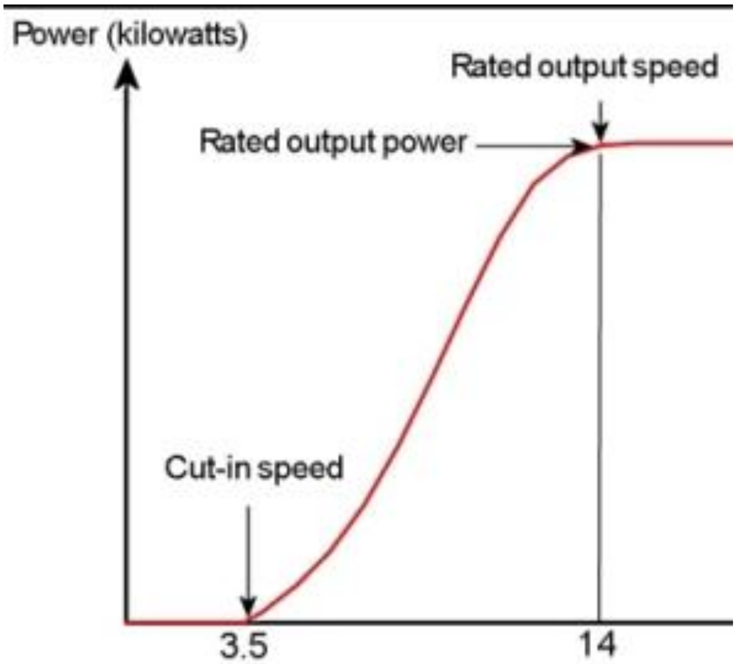

Figure 3. The figure shows the energy output of a typical wind power plant as a function of wind speed (wind-power-program.com 2013).

In figure 3, the wind power output is close to linear, while the equation for wind power output includes the cubed value of the wind speed, which indicates an exponentially growing curve(the theoretical wind power output compared with an actual power output is shown is shown in figure 4.). In the equation the swept area of the wind turbine is constant and the air density is also constant (in the sample data the wind density has small variations but they will not be taken into account in this investigation). The power factor C_p however is the reason why the curve is close to linear. C_p, the power factor of the wind power plant, describes the relationship between the electricity that can be produced by the wind turbine and the total energy in the wind.

$$C_p = \frac{P_\omega}{W_{tot}} \qquad (2)$$

Equation 2. $C_{p,}$=d*escribing the relationship between total energy in the wind and the energy that can be extracted by wind turbines.* P_ω*=Electricity produced by wind turbine.* W_{tot}*=Total energy available in the wind (harnessnature.com 2014).*

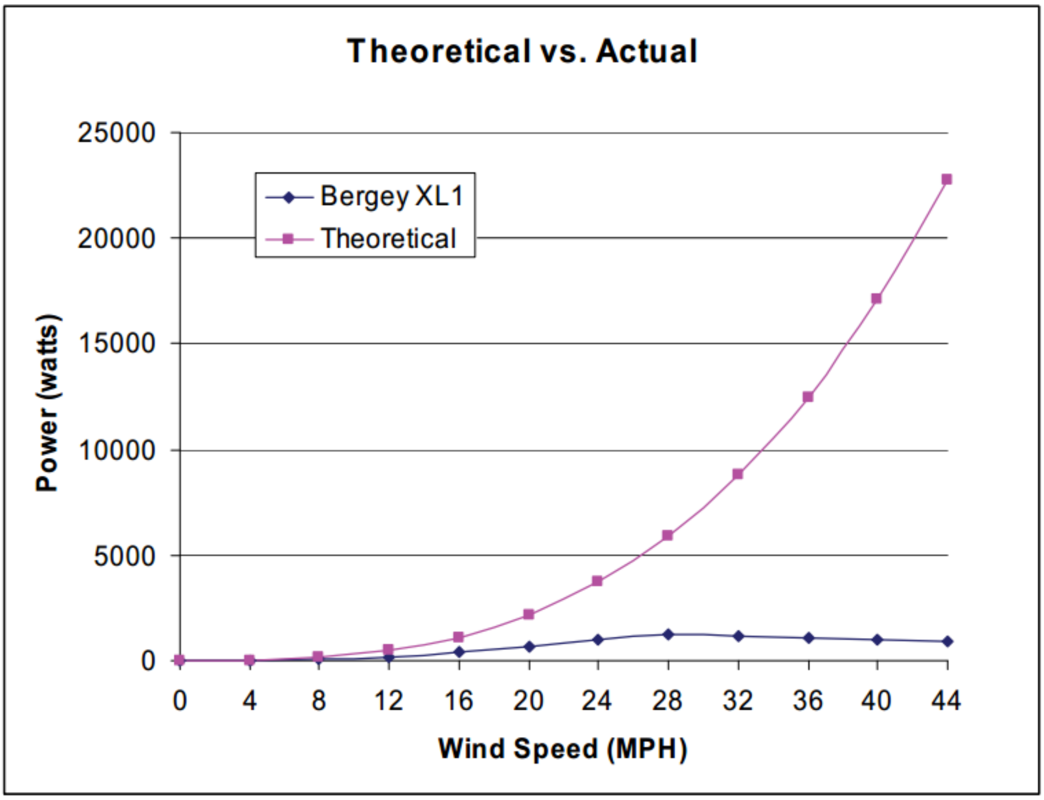

Figure 4. The graph elucidates the relationship between the theoretical wind energy output, and the actual wind energy output of a certain plant, in this case a Bergey XL 1 (harnessnature.com 2014).

The C_p (which is showcased in figure 5.) differ between different plants but in general have a curve of somewhat the same shape.

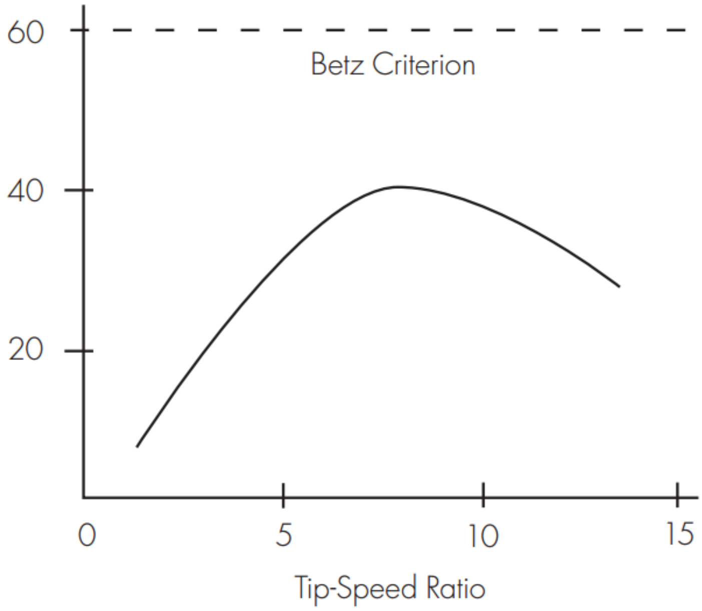

Figure 5. The C_p-curve of a typical wind power plant. The Betz Criterion is the maximum C_p-value. Because the C_p-value is multiplied by the cubed wind speed in the equation, the wind energy output of a wind power plant is somewhat linear.

So, due to this, the investigation will use a linear calculation method for calculating the different power outputs at different wind speeds.

6.2 Näsudden wind power park.

The total installed power on Näsudden is 94,86 MW. In the plans for Smart Grid Gotland, an extra 5 MW wind power will be installed (David Erol, 2014). Therefore the battery storage would need to compensate for a park with the rated output 99,86 MW.

The wind power plants at Gotland reach rated output when the wind speed is 12-14 m/s (Vattenfall 2013). Probably the wind power plants at Näsudden have different rated output speeds between 12-14 m/s. In this investigation the rated power wind speed will be set to 13 m/s.

The parameters C_p, the power factor, and A, the area of the swept rotor, are unknown. As the park consists of plants of different models, constructed different years (Wizelius 2011), it is hard to know the exact power factor and swept area of all the plants.

This investigation intends to give a synoptic view of the magnitude of an energy storage connected to the park. Therefore a linear model will be used: Power output is equal to X (properties for the park) · wind speed. In this fashion, wind power output can be calculated backwards from 99,86 MW = X·v(rated wind speed output 13 m/s), and give values for other wind speeds. A slight loss of accuracy will apply to the values close to cut off wind speed, around 13 m/s, and cut in wind speed, around 3 m/s (see *figure 3.*).

6.3 Different wind speed at different altitudes.

The wind speed is not constant but varies with altitude (see table 1. in appendix).

Table 1 in appendix is a cutting from the ark with wind speeds which will be used in the investigation. The cutting shows how the wind speeds differ at different altitudes. The wind power plants at the location have a tower-height of up to 80 meter and rotor diameter of up to 100 meter (Vattenfall, 2013). The different wind speeds will be fitted into the Area for the swept rotor (showcased in figure 6.). There are assumedly different models of wind power plants at the location, however, in this investigation power plants with a tower height of 80 meter and a rotor diameter of 100 meter will be set as standard.

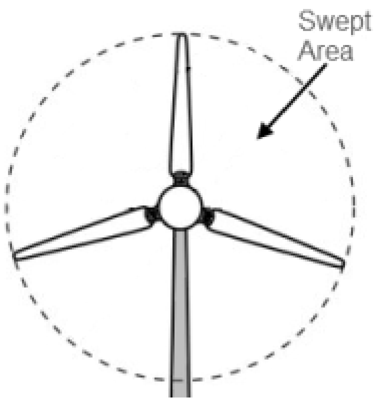

Figure 6. Swept area (TWN Wind Power Inc., 2010).

Since the wind speed is different at different altitudes, the power output from the wind does also vary with altitude. The measurement data is from 10, 38, 54, 75, 96, 120 and 145 meters altitude, and are displayed in figure 7, on a swept area of a putative wind power plant.

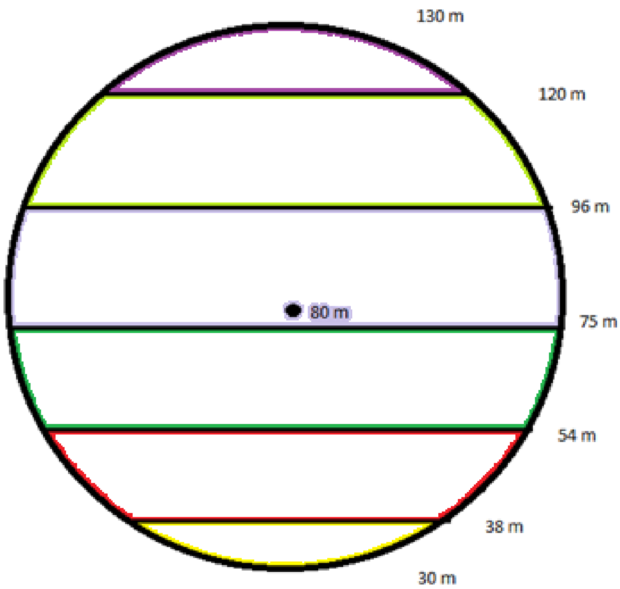

Figure 7. The figure illustrate the altitudes where the wind speed has been measured on plant with tower height 80 m and a swept area with radius 50 meter.

To simplify from the measurement points, the power output is set to be constant within the areas shown in figure 8.

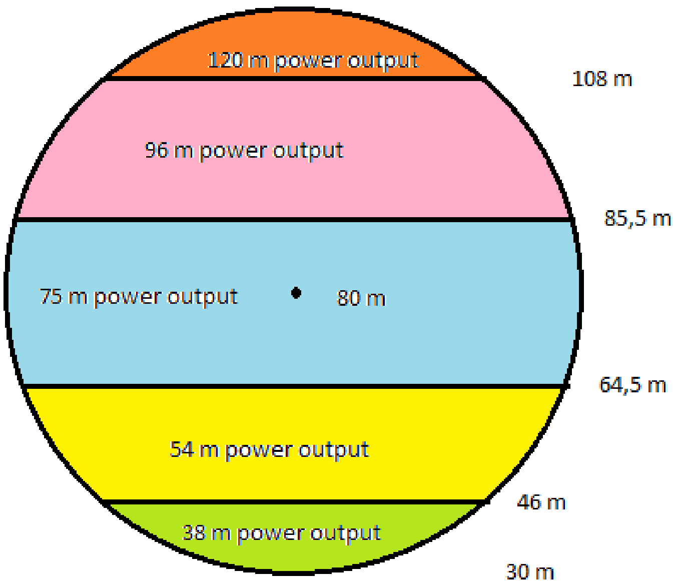

Figure 8. "Power areas" from the wind speed measurement points. The borders has been computed as follows: Border 1 (46 m) = wind speed measurement height 1+distance to height2/2, Border 2(64,5) = height 2+distance to height3/2, and so on.

As discussed earlier this investigation will use a linear model to calculate power outputs at different wind speeds, and an "X" will be determined to help calculate. X = 99,86 MW divided by 13 m/s = $7{,}297\cdot10^6$.

The area of the swept rotor is A= $\pi\cdot 50^2 = 7854\ m$. The 38, 54, 75, 96, 120 meter power output all represent a percentage of the total swept rotor area. To determine the percentage of each measurement point of the wind data, circle segment calculations will be performed according to the following formula illustrated in figure 9.

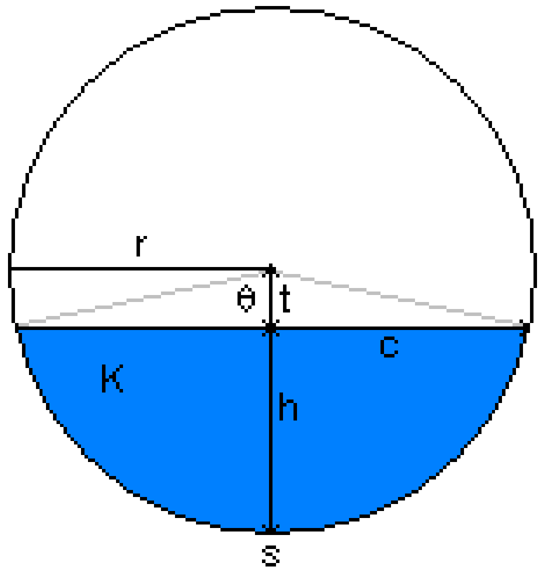

Figure 9. "How to calculate a circle segment" (ajdesigner.com 2012).

$$K = \frac{r^2(\theta - \sin\theta)}{2}$$ (ajdesigner.com 2012) *(3)*

Where θ is calculated as illustrated in figure 10.

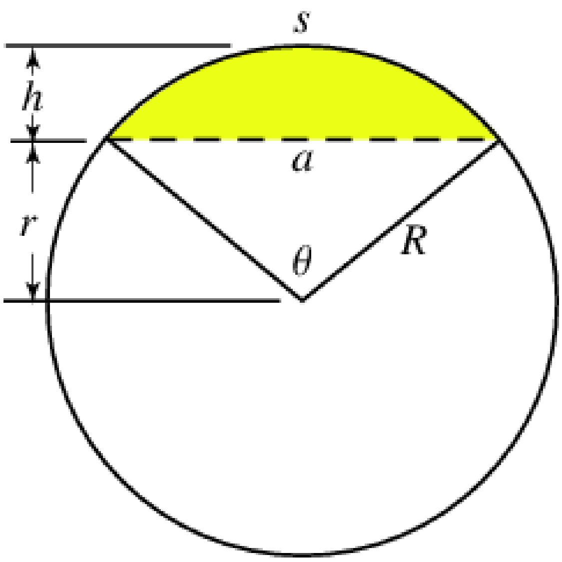

Figure 10. "How to calculate θ" (Math world, 2014).

So the first segment of the circle, the 38 m wind, represents 10,33% of the total swept area or 811 m^2. Calculations for all circle segments were made leading to the following data:

- 38 m wind: 811 m^2 or 10,33 % of the total area.
- 54 m wind: 1591 m^2 or 20,26 % of the total area.
- 75 m wind: 2073 m^2 or 26,40 % of the total area.
- 96 m wind: 2096 m^2 or 26.70 % of the total area.
- 120 m wind: 1281 m^2 or 16,31 % of the total area.

The percentage of the swept area with different power output is visualized in figure 11.

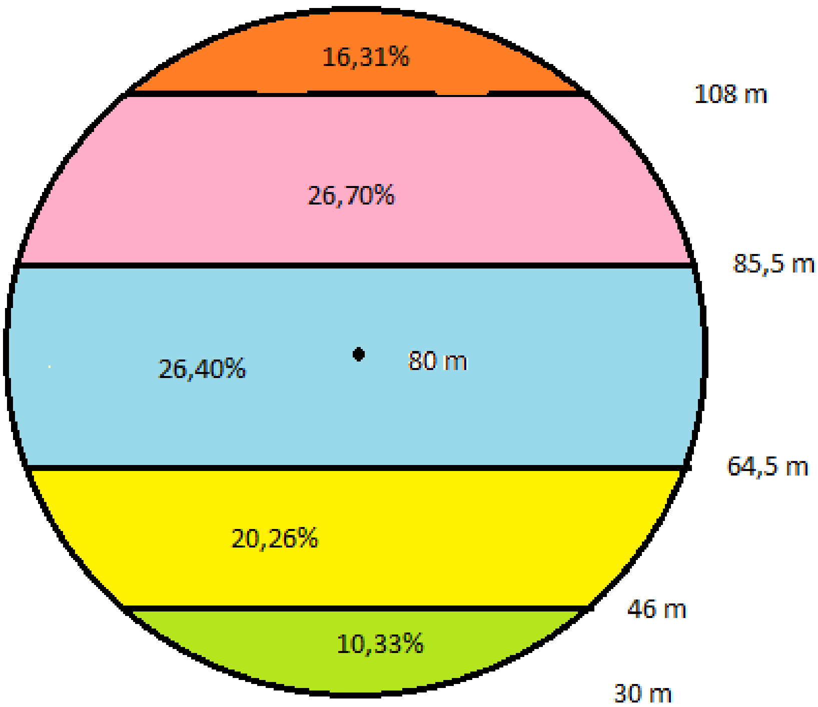

Figure 11. Percentage represented by the wind speed measured on a certain altitude.

6.4 Execution.

81687 time-values were used in the investigation. This is because the measurement at some of the heights after that point only show zeros after 81687 values due to a technical error.

6.4.1 Implementation

The wind power output at different wind speeds and at different altitudes and time were calculated in the excel document as shown in table 2 in appendix.

Those values were multiplied with the percentage from the swept rotor of the wind power plant, creating the vector in table 3 appendix.

So, those values are the output values from the wind power plant. On a 10 min basis they generate the following energy (see table 4. in appendix).

To determine the difference in energy output, the difference between two subsequent values were calculated for the vector with kWh. This difference is the excessive energy or lack of energy that the energy storage should make up for (table 5 in appendix shows this vector).

Where negative numbers implies that the energy storage can be charged and positive numbers implies that the energy storage needs to supply the grid with power to compensate for prediction mistakes.

6.5 Vagueness of the investigation and assumptions.

The investigation is based on a simple linear model, the actual model of the power output is more complex. Rated wind speed is set to be 13 m/s. The actual rated wind speed is around 12-14 m/s for different wind power plant models. All wind power plant models are not certain to have tower height 80 meter and rotor diameter 100 meter which is the assumption in this investigation.

This calculation would imply that all wind power plants face the wind straight up and not are affected by wind shadows (another plant or obstacle blocking the wind). This is however not an unfounded assumption. The wind power plants are constructed in such a way that they turn to face the wind straight up, in order to use the full potential of the swept area. Furthermore, when constructing the wind power park, the engineers design the placement of the individual plants in such a way that wind shadow shall be as small as possible.

7. Results and analysis: Energy storage connected to the Näsudden wind power park

This part will give account for the results in the statistical investigation and relate the result to existing energy storage technology. As discussed earlier, energy storages could help stabilize the power output from wind power parks. In future power grids, with a larger proportion of the energy coming from intermittent energy sources, energy storage technology could be an alternative to strengthening the local grid. The results below present's properties that would be beneficial for an energy storage connected to Näsudden wind power park.

- The maximum power that the energy storage would have to provide on a 10 minute basis to compensate for prediction errors were: 9642,5 kWh. Figure 12 shows the quantity of power flows, where maximum power output and input is included. Figure 12 and figure 13 elucidates that the majority of power flows are far from the extreme values.
- The maximum energy available to charge the energy storage due to prediction errors on a 10 minute basis were: 10089,3 kWh.

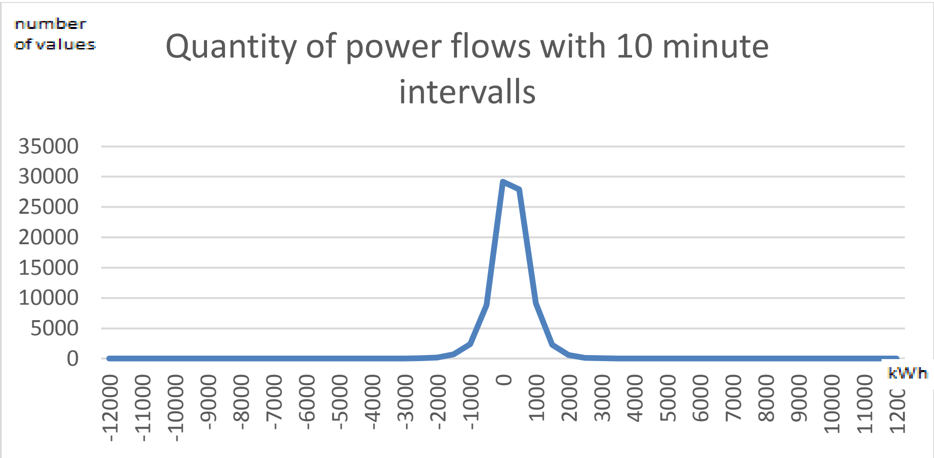

Figure 12. Chart including the maximum values, showing that these are quite unusual.

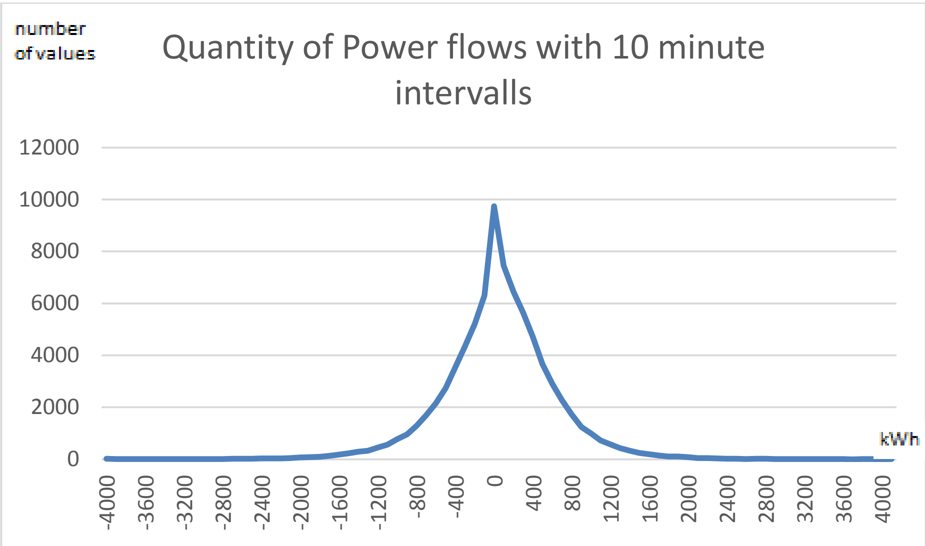

Figure 13. Chart showing the same thing but with concentration point on the middle values.

- Quantity of numbers within the range -1050 kWh and +1050 kWh: 75805 or 92,8 % of the time. The distribution of lesser power flows can be seen in figure 13.
- Quantity of 10-minute periods with zero (<50 kWh, >-50kWh) in or output: 9737 times or 11,5 % of the time.

The energy stored will fluctuate over time according to fluctuations in wind speed. If the wind does increase many 10-minute time-periods in a row, there will be a peak in stored energy. Reversed, if the wind speed keeps decreasing a minimum in stored energy will originate. Figure 14 shows the amount of stored energy in energy storage during the time period of the simulation. Following are relevant observations of the amount of energy in the storage:

- If the energy storage would start at “zero” i.e. when the calculations start there are no energy stored in the energy storage, the maximum energy which would need to be hosted would be 8266,6 kWh.
- Calculated in the same fashion with starting energy “Zero”, the minimum amount of energy in the storage would be -7543,6 kWh, meaning of course that the energy storage need to have an amount of “starting energy” when connecting it to the wind power park.

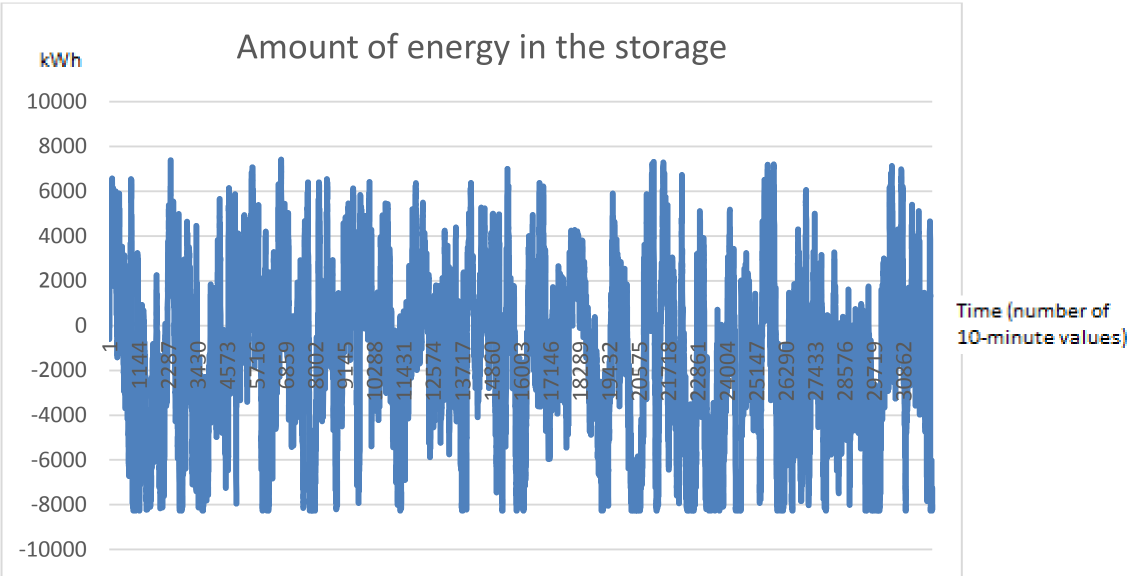

Figure 14. The graph shows how the energy levels differs with time in the energy storage.

- The positive values in the graph in figure 14 indicates that energy needs to be extracted from the storage, even though there are no energy available (at least not generated from the wind park). Therefore, the energy storage would have to have starting energy of at least 7543,6 kWh, and capacity to store 7543,6 + 8266,6 kWh = 15810,2 kWh.
- Hence, the capacity of the energy storage would need to be at least 15810,2 kWh ≈ 16000 kWh.

7.1 How often does "very high" energy output occur?

The installed power of the park will be 99,86 MW, and when this power occurs there are problems with bottlenecks in the system. If "very high" energy output is defined as above 80 or 90 MW, how often does it occur? The occurrence of power output is showcased in figure 15.

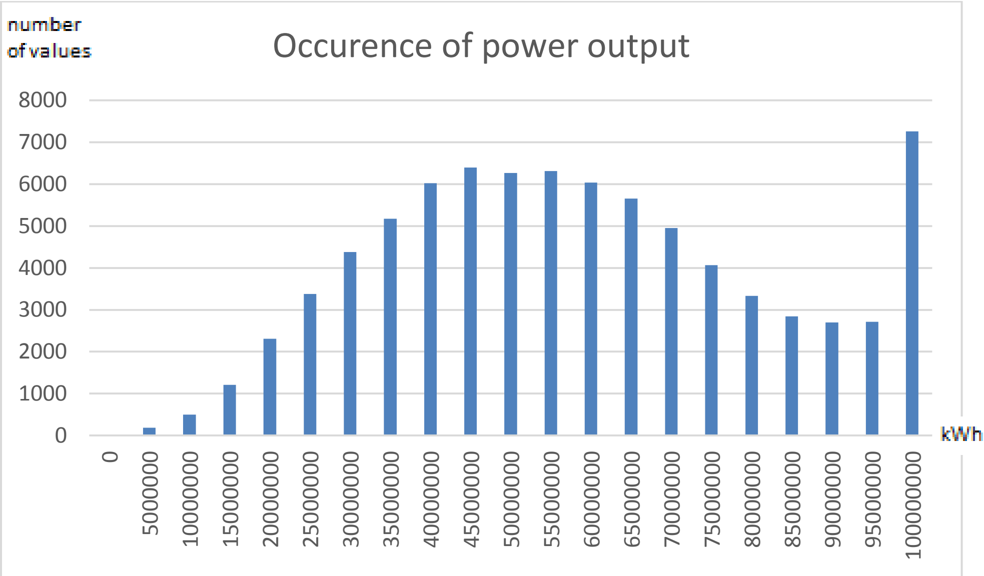

Figure 15. The graph shows how often variant power outputs occur. The most common output is max-output. This is because all values of wind speed between 13-25 m/s generates max-output according to the model.

- The above graph shows how often different power outputs occur. Max power output occurs around 8,9 % of the time, indicating that bottlenecks in the system can be a problem.

7.2 Discussion

The statistical investigation gives an idea of size and field of application for an energy storage connected to Näsuddden Wind Power Park. However generally, the same reasoning could apply for other wind power parks of different magnitude.

Empiric studies has proved that wind speed follows the Weibull distribution (Tore Wizelius 2007). Therefore the results from the investigation made in Näsudden can also be relevant to other wind power parks. As mentioned earlier average wind and form factor are measures to determine the wind at a certain place and many wind measurements has shown a correlation between wind speed and Weibull distribution. So given this investigation, a wind power park with rated power 99,86 MW would need an energy storage with capacity 16 MWh. A bigger or smaller wind power park would mean a somewhat proportionally bigger or smaller energy storage. The properties of energy storages connected to wind power parks would be similar as wind speed follows the Weibull distribution and therefore have a similar pattern all tough different locations. Figure 16 shows a fitted Weibull distribution to the wind speed values measured at 75 m altitude.

The respondents in Korea with whom I discussed the wind in Jeju Island both said that the wind there were more fluctuant and unpredictable than in other places. What properties an energy storage would need to have at Jeju Island, and if it would differ in properties compared to the energy storage calculated in this thesis could be a topic for future studies.

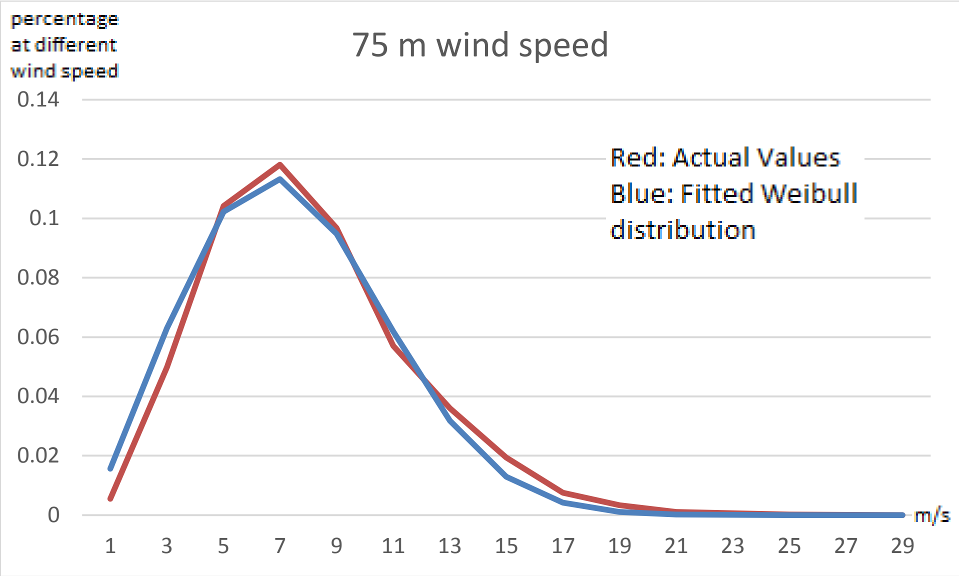

Figure 16. The figure shows the real values measured at 75 m altitude (red) and values from a fitted Weibull distribution (blue).

7.3 What type of energy storage would be suitable for Näsudden Wind Power Park?

The statistical investigation suggested the following properties for a battery storage connected to the Näsudden wind power park with 94,86 + 5 MW =99,86 MW installed power:

- Capacity: 15810,166 kWh ≈ 16MWh.
- Maximum power output: 9640 kWh, power 58 MW.
- Maximum power input: 10009 kWh, power 61 MW.
- Frequency of zero in or output: 11,5 % of the time.
- Frequency of in or output higher than 1050 kWh, power 6,3 MW: 7,2% of the time.

Given these properties there are different energy storage technologies which could be used with different advantages and disadvantages. In this scenario flywheel energy storage or lithium-ion battery storage could be a good choice. The flywheel technology allows for fast discharge and charge, it can also cope with numerous charging and discharging without wearing out. However if the battery storage are not to be used very frequently, batteries might be a better option.

How much money an energy storage could save is obviously depending on the electricity price. For the energy storage investigated in this thesis, as discussed earlier, the main purpose is not to save money but to help stabilizing the power output. To give the reader an idea of the magnitude and type of energy storage, this part will discuss some of the energy storages out on the market.

7.3.1 Siemens 4PS (Power Stack)

The technology is based on Lithium-ion batteries. In new distribution grids with higher share of intermittent energy sources, this energy storage there can compensate for imbalances between generation and load. According to Siemens website this battery storage can help deal with imbalances as well as influence grid stability and power quality.

- Max. power output: 4·118 kVA
- Max Capacity: 20·45 kWh
- Efficiency: 92% (Siemens.com/siestorage 2014)

Since the energy storage which should be connected to Näsudden wind power park needs a capacity of 16 MWh the following calculations were made.

$$\frac{S}{M_c} = Q \qquad (4)$$

S=Needed storage capacity, M_c*=Module capacity, Q=Quantity of modules needed.*

$$\frac{16\ MWh}{(20\cdot45kWh)} = 17.77\ modules$$

Hence, 18 Siemens 4PS Modules would be needed meet the demands.

$$\frac{O}{M_o} = Q \qquad (5)$$

O= Maximum power output needed, M_o*= Module power output, Q=Quantity of modules needed.*

$$\frac{9642{,}5kWh(10\ minute)}{\left(4\cdot118kVA\cdot\frac{1}{6}\right)} = 122{,}6\ modules$$

To be able to make up for Maximum power output, 123 Siemens 4PS Modules would be needed. However for a more normal case, output 1050 kWh or less (equal to 92.8 % of the time)...

$$\frac{1050\ kWh\ (10\ minute)}{(4\cdot118kVA\cdot\frac{1}{6})} = 13{,}35\ modules$$

... 14 Siemens 4PS Modules would be needed.

Hence it would be a reasonable assumption that 18 Siemens 4PS modules would be satisfactory to cover most of the fluctuations in wind power output.

7.3.2 ABB Energy storage DynaPeaQ

The Lithium-Ion battery-based energy storage DynaPeaQ is constructed to deal with rapid changes in wind power output and thus help integrate wind power in weak grids. A normal sized DynaPeaQ-facility can deliver 20 MW to the grid in periods of 15-45 minutes. Maximum power for the technology is to deliver 50 MW for 60 minutes (Second Opinion Energi, 2011).

Normal sized DynaPeaQ-facility: Storage capacity: 6.6 MWh -15 MWh. Power: 20 MW

Maximum for the DynaPeaQ-technology: Storage Capacity: 50 MWh. Power: 50 MW

Size wise the storage capacity seems to be sufficient, required storage capacity needed: 16 MWh compared with maximum storage capability of a DynaPeaQ Energy storage, 50MWh.

Required power is 57 MW while the DynaPeaQ can deliver 50 MW

The DynaPeaQ Energy storage seems like a good solution in this scenario. 92,5 % of the time the output power required from the storage is 6,3 MW or lower so concerning power it should be sufficient most of the time. However, it is perhaps at the most extreme scenarios that the energy storage is most needed to stabilize the power output to keep the stability of the grid…

7.3.3 Conclusion

There seems to exist compatible products on the market. Unfortunately I could not find any quotation of prices, except the information from Vattenfall, -that they estimate the price to be 50-70 million Swedish krona including research and development to have a sufficient energy storage connected to Näsudden wind power park (David Erol, 2013). The choice of energy storage technology is a question of benefits in using the storage, versus expenses of the storage. If the grid close to a wind power park is weak it would perhaps cost more to strengthen the grid than the price of an energy storage, which would give economic incentives for investing in energy storage technology.

8. Results and analysis: A comparison between Jeju Smart Grid Test-bed and Smart Grid Gotland

This part shall answer the main questions which were asked in the beginning of the essay and include a comparison between Smart Grid Gotland and Jeju Smart Grid Test-bed.

- *What was/is the overall purpose of the project?*

  Jeju Island: The project were divided into five areas. Smart Power Grid, Smart Place, Smart Transportation, Smart Renewable and Smart Electricity Service. The ambition of the project was also to create new business models based on smart grid technology and to be the start of South Koreas Road Map in smart grid technology. The respondents which were interviewed for this essay had somewhat different opinions whether five focus areas were too many. If the areas investigated were fewer more concentration could be put on the remaining areas which perhaps would have led to better results. On the other hand, as Jeju Island was the first smart grid project of many to come, there was a point in covering many different areas.

  Gotland: The three main goals of Smart Grid Gotland are: Electricity market; making it economically viable for companies to invest in wind power on the Island. Customer behavior; the electricity price should be connected to local weather conditions so as the energy price is lower when the wind blows. Integrate more wind power in the existing grid; including come up with solutions on how to deal with the HVDC which in present system is a bottleneck if there were to be more wind power integrated.

- *What strategy does Smart Grid Gotland respective Jeju Smart Grid Test-bed employ around wind power integration in the grid?*

  Jeju Island: On a large scale there has been no problem with wind power integration as the installed wind power only stands for 12 % of the total power installed to support the Island. The wind in Jeju Island is very variable and the local grid around the wind power plants is weak and would need more equipment such as energy storage technology or energy conditioning system to stay within the rating limit for fluctuations.

  Gotland: One of the main goals of Smart Grid Gotland is to integrate more wind power into the existing grid. When the wind power parks at Gotland produce rated power, and consumption on the Island is low, there is problems with the HVDC-link to the mainland being a bottle neck in the system. To install more wind power in the grid, smart grid solutions are used to shift consumption to times with high wind power energy output.

- *What is the role of the 'Smart Homes' in the respective systems?*

  Jeju Island: Jeju Smart Grid Test-bed employed an ambitious Smart Home technology were the participants could make many choices to save money by adjusting consumption. The outcome of the smart home technology were not as successful as hoped, the people living in the smart homes did either not understand how to use the smart components properly or they did not see enough benefit in doing so. Many of the people living in the smart homes were old which all the respondents think influenced their will to use the Smart Home solutions.

Gotland: In Gotland the Smart Home solution will work automatically as the system operator is in control of indoor temperature and temperature of warm water tanks between certain comfort limits. It is yet to be seen how well it will work.

- *What bottlenecks are there in the two systems?*

  Jeju Island: During times when the HVDC-link from the mainland needs to provide the island with power there can be a lack of reactive power on the island as the link only supplies with active power. This is a kind of bottle-neck in the system and to solve the problem more reactive power generation units are needed on the island. Another solution would be to have more generation on the island to reduce the required power from the mainland.

  Gotland: Gotland has a big wind power park on the southern tip of the island. There is a bottle-neck challenge concerning the HVDC-link to the mainland. The next bottle-neck challenge in the system is the link between the big Wind Power Park, Näsudden, and consumers in and around Visby. One of the main aspects of Smart Grid Gotland is to investigate how a large scale wind power park can be integrated in an existing grid and finding and solving bottle-necks in the system is part of the project. The Bottle-neck problem in Gotland are really only apparent in summertime. In wintertime the households on the island consumes more energy for heating and wind power plants may produce less power due to ice sticking to the blades.

- *What is the role of energy storage systems in the two projects?*

  Jeju Island: There is a 4 MW PCS, a sort of energy storage battery converter, and an 8 MW battery installed at the substation Ju Jeon which are used for stabilizing the grid. During the project on the island there were also tests with Lithium-ion batteries and led batteries. More energy storage technology are needed to integrate all of the wind power into the grid. During the test project 200 electric vehicles were used. The power stored in the cars were however not used as batteries during the project on Jeju Island.

  Gotland: Smart Grid Gotland are investing the possibilities to use energy storage technology during the project. A large scale energy storage are likely not economically durable but small scale energy storage to compensate for short time prediction mistakes might be.

- *How does the two projects compensate for stability factors, such as short circuit capacity and frequency control?*

  Jeju Island: The HVDC-link were used to stabilize the system during the test-period. There is also a system called EMS, Energy Management System, which controls the overall power flows of the Jeju Island System.

  Gotland: The grid at Gotland is supported by a HVDC-link to the mainland during the project and the HVDC-link supports the Island with important stabilizing properties.

9. Discussion and conclusions

This part of the essay will discuss the results and in general about the two projects. During the research for the essay many interesting matters came up outside of the interviews in unofficial conversation. Some of the author's thoughts and reflections will also be featured, and those perspectives will be given account for here.

9.1 Achievement of the projects

Jeju Island and Gotland are two of the first projects within the field of smart grid technology. There are big expectations on the potential benefits with smart grids and a strong engagement to bring about the technology. At Jeju Island the smart grid technology has not been able to create new business models based on the technology, and in Gotland smart grid technology aim to increase the installed capacity of the wind power park from 94,86 MW to 99,86 MW, which, in the context and percental (about 5 %) is quite a modest increase of the capacity.

One can therefore argue that the projects has (the Gotland project is fairly newly started though) had a lack of success. The real progress of the projects seems to be the exposure for smart grid technology and launch of smart grid ideas and projects. In the future, with bigger projects and more participating households, perhaps in a city, the economic outcome as well as the, energy-more-efficiently-used outcome might increase. The profitability of smart grids will also likely depend on political decisions and access to non-intermittent energy sources. With inexpensive non-intermittent energy available, the incentives for smart grid decrease.

In both Gotland and Jeju Island, the comfort of the people living in the Smart Homes are of great importance. Using energy more efficient comes in second place to living comfort. The transformation to Smart Homes will likely come step by step not to intrude on the comfort. In an transformation towards smart grid in the future, smart homes will play an important role, but smart homes does also require understanding of the system and a will to participate from the individuals living in the smart homes. Education will be important for this transformation, but even more so, economic incentives.

9.2 Climate change in Korea

Korea has four very distinct seasons. Spring, summer, autumn and winter. The summer is very hot and humid and the winter is quite cold. During the spring and autumn the weather is pleasant and resembles with Swedish summer weather. Korean people are dolorously conscious about spring and autumn getting shorter and shorter, while the length of summer and winter is increasing. One of the effects of the climate change is a higher use of energy as heating is required in the wintertime and air conditioners is required in summertime. The different energy usage pattern in different seasons is an additional challenge for a nationwide smart grid in Korea.

9.3 Smart grid Islands without HVDC-connections

A hypothetical question is how the Islands would make do without the HVDC-connection to mainland. The immediate answer is that both the Islands and especially Jeju Island would have problems with insufficient energy capability on the Island. Another result would be a more distinct difference in energy supply between different times in a day, creating a more distinct difference in electricity price and a more influential demand response model. Smart grid solutions and technology would be more put to the test without the HVDC-link, but the living standards for the people living on the Island would presumably have been decreased.

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Appendix

Interview at Vattenfall 2013-12-03

This is a summary of the interview held at Vattenfall with David Erol, who works with wind power integration in the project Smart Grid Gotland. Some of the passages are very similar to earlier retailed information as the text is not a transliteration but rather a review of the important matters discussed during the interview.

There are 3 main goals for the test project Smart Grid Gotland. The first goal is based on the function of the electricity market and is based on an ambition to by market forces implement more wind power on Gotland, it should consequently be economically viable to invest in wind power.

The second goal is related to how the customers can save money by adjusting electricity consumption in the established system, and how this adjustment are connected to wind power output. If the wind is blowing it shall be a bit less expensive with electricity and if the wind does not blow as much, more expensive. However it is hard to get a correlation since the price area is bigger than just Gotland. Gotland is part of price area S3, and the price in the area is somewhat the same in the whole area. Therefore it can be expensive to consume electricity even though it is blowing a lot at Gotland at a certain point of time. The ambition of the project is however local consumption. There are also issues around power quality. The market and the technological system both stand in front of challenges all tough very different.

The ambition of 'wind power integration' which is the respondent’s main project, is to integrate more wind power in the existing Gotland grid. There is a maximum limit, and they are now investigating the maximum limit of the HVDC-link, which is the main bottle neck of the system. The HVDC link has a certain maximum transfer capability which sets the boundary for how much electricity that can be transported from the island. In a scenario where there is a lot off wind and at the same time small consumption on the island, almost all of the generated power has to be transported to the mainland. If more wind power plants were to be built on the island, the HVDC-link would not be able to transfer the power to the mainland in the given scenario. The challenge is therefore to reduce peaks in exported power, to make the power flow more even over time.

To solve this, the system operator Vattenfall has X number of customers on the island. In the houses or apartments of these customers they can control the heat water tank, and the inside temperature of the houses. The conclusion so far is that the system would benefit from a more local market. The intermittent energy sources has a close connection to local weather conditions. Therefore the market have to be local and correlate with the shifts in the output of the intermittent energy sources.

The capacity of wind power on Gotland is 170 MW right now (December 2013). During the project it will rise to 195 MW. 195 MW installed wind power is the maximum of how much wind power Gotland can host with today’s grid. It is calculated from a scenario with maximum wind generation and minimum consumption on the island. That would consequently lead to a scenario where a lot of power has to be transferred to the mainland through the HVDC-link, and the HVDC capacity is the limiting factor for additional wind power addition. If minimum consumption gets bigger, Maximum wind power establishment can also increase. The goal is to allow the maximum wind power installation on Gotland to be 5 MW higher. This is planned to be done by shifting the load to different time periods.

How many extra customers is needed on Gotland to accomplish an extra 5 MW wind power on the island? What components is needed to shift consumption after peaks in wind power generation? To investigate this, peak distribution to the mainland is identified. To avoid peaks in distribution one looks at one day ahead and one day after the peak to see what measures that can be taken. Is the demand and response measures enough to avoid this peak? Can the demand and response model shift the consumption to synchronize with the peak transfer? By shifting the consumption to overlap the peak in wind power production, less power has to be transferred to the mainland. As mentioned earlier the system operator has a somewhat control over warm water tanks and indoor temperature. If there is a predicted peak 7 hours ahead for example, the system operator can turn off water heating and indoor warming to create a bigger demand at the time of the peak. This will create a mini-peak in consumption synchronized with the wind power generation peak, and thereby reduce the exceeding power which has to be transferred to the mainland. However, there are certain boundaries which the system operator has to stay within such as temperature comfort zone. The comfort zone for indoor temperature is set to be between 18-22 degrees. For warm water tanks the temperature should be between 60-100 degrees. However these, limits can be discussed. In the morning when many people are taking a shower before work it is perhaps not an option to turn off warm water tanks in order to create a surge for electricity to heat water at, let's say, one o clock when there is an expected peak in wind power production. It would be a contraction to peoples comfort and customers would not be happy. It is similar with indoor temperature, comfort is highly valued by the customers and favorable incentives is needed to motivate them to be a part of the smart grid campaign. In summary it is possible to shift loads to different times but there also exist important boundaries for how much the load can be shifted.

On the island there are, except wind and solar power, a gas turbine with power 120 MW. Two diesel generators with 19 MW power and an additional 10 MW gas turbine. These power sources start up if the HVDC-link for some reason is out of function and can be considered as emergency or reserve power. Moreover Gotland is supported by the HVDC link and renewable power sources on the island. On a yearly basis Gotland import more energy than they export.

So far it is still uncertain whether Gotland will use energy storages or not. Smart Grid Gotland would like to use as part of the test-bed, but it is very expensive. The collaborators of Smart Grid Gotland works on a solution. The price would be approximately 50-70 million Swedish krona. In the price R and D are included as well as attendant costs. When working with intermittent energy sources it is necessary to have energy storages as part of the system. The question though is whether a potential energy storage should be an electrical, or a mechanical energy storage in the form of pumped-storage hydroelectricity. The Gotland project are considering an electric energy storage and are now investigating how, theoretically a battery could be used to allow for more wind energy. One approach is that the battery storage should be used for absorbing miscalculations in prediction and compensate for them. Upcoming peaks and dips in wind power output are based on prognosis and the only real knowledge about the prognosis is that it will not be right.

The Gotland project use different prognosis tools for different time scales. There is one algorithm for day ahead predictions based on a complicated computer program, and then there are hourly predictions which is just the assumption that the next hour will have the same wind as this hour. The algorithm function as the basis for how the system operator use the ability to control warm water tanks and indoor temperature in apartments and houses. It is possible to rectify the expected power output one hour ahead. The misassumptions within the hour should be taken care of by the battery reserve power system. The battery storage that exists now are one 1.7 MW storage which can last for 7 minutes and one on 280 kW which can last for 10 minutes. The battery storage capability is at the moment very small and can only be part of very small systems when it comes with dealing with prediction errors.

The respondent interpose that there are also other areas where battery storages comes in handy such as strengthening the grid in terms of electricity quality and islanding as well as increase the short circuit power. This is very hard however, the energy storages are too small. A question now worked upon is; how big would the power of the energy storage have to be to be sufficient to deal with prediction miscalculations?

Smart Grid Gotland does not include electric vehicles in their project all tough that was an area that perhaps would be worked upon according to the pre-study.

Smart Grid Gotland uses a 'day ahead' prediction method with a 24 hour prognosis to detect peaks in generation. Except persistent algorithms, hour ahead prediction is used. Hour ahead prediction is basically an assumption or conjecture that the wind speed will be the same the next hour as it has been this hour. Empiric studies has shown that this will give a matching result with a mean value of approximately 6 %. The fault percentage is the root mean square error. If battery storage technology were to be integrated in the system it should deal with the 6 % of prediction error. Both to be able to spend power as well as to absorb power. Vattenfall uses the software Wind power prediction tool for their forecasts. For predictions up to one hour the advanced algorithm have 6-8% fault while the simple method, just assuming the same wind speed, has 6% fault. Therefore, 1 hour is a breakpoint for where prediction method is changed from simple version to algorithm version.

The Gotland project has focused a lot on the maximum limit. Theoretically there could be an endless amount of wind power, but the bottle neck is the HVDC link. The bottle neck however does only occur when there is a lot of wind. One does not want to turn off the wind power, it would be a waste of energy. However it could be the cheapest way to deal with the problem.

Smart grid Gotland is a test-bed for larger, perhaps national scale smart grid solutions in the future. Sweden has a good regulation ability because of a lot of hydro power, Germany and other countries on the continent does not have hydro power in the same amount leading to that they have to compensate in some other way. Perhaps this can be compensated by big interconnected grids.

What will happen when a lot of wind power is installed in an existing grid? Smart Grid Gotland is a test plant for that kind of scenario. Analysis of the grid on the island indicate that if the HVDC-link was not a bottle neck of the system, the transmission lines0 between the big wind power park at Näsudden and consumers located in and around Visby would be the next bottle neck of the system. The existing line between Näsudden and Bäcks, where the HVDC link to the mainland is located, would be increasingly burden and would not be able to take on the load.

A good method of finding bottle necks in the system is to build a generic model of the system. In the model it is possible to see the power flows and how big percentage of the transmission lines whuch is being used for different power flows. If the transmission lines are used over their capacity they will burn up. To reach the European Union's "20 20 20" objective (20% reduction in greenhouse gas compared with 1990. Raising the share of renewable energy with 20%. An improvement in energy efficiency with 20%) Sweden has to integrate more wind power in the power system. The generic model which is now being used to analyze Gotland's power system shall be the basis of the construction of the generic model which will show bottle necks in the Swedish power system (European commission, 2013)(David Erol, 2013).

Due to bottle necks in the system, frequency is not used as the govern variable. If the frequency rise it can trigger increased consumption “behind” a bottle neck. There could be a scenario with big wind power generation and big energy consumption, though the wind power energy cannot sufficiently reach the consumer because of insufficient transmission capability.

Generally on Gotland the wind power plants turn off at around 25 m/s. However if the wind speed is that high, cut off power from the wind power plants are not the biggest problem. Trees starts falling down over transmission lines, which is a bigger problem than wind power not generating any electricity. To be protected from extreme wind speeds all the cables has to be buried and many other measures has to be taken. After protection measures for parts of the grid has been taken, cut off effect from wind power plants can be an issue. One method of dealing with cut off effect could be to use ‘soft stops’ i.e. that the power from wind power plants gradually lower with high wind speeds, and therefore there would not be drastic change in power output at the cut off wind speed.

The respondent argues that wind speeds are not the same all over the island and that plants located in different regions of the island would make a scenario where all wind power plants experience cut off wind speed is very unlikely and that there would bring on a more regular wind power output.

Even if all wind power plants did not generate any energy, it would not be a big concern for the electrical grid of Gotland since it is connected with the HVDC link. Except supplying Gotland with energy the link also supplies the grid with important properties such as frequency control, operational reserves.

Smart Grid Gotland is doing a literature study about Synthetic inertia, where the turbines are inelastic connected to the grid. When the frequency dips because of over-consumption or under production, there is a massive energy rotating mass. In for example hydro power, the turbine is inelastic connected to the grid and therefore the generation, the rotating blade of the hydro power plants has a direct connection to the frequency. In modern wind power plants there are no such connection.

The modern wind power plants have electric equipment in-between the connection to the grid, so therefore it is not the same kind of direct connection. The rotor has one kind of frequency and it is then transformed by the electric equipment to match the frequency in the grid. However this does not allow for the same inertia as in common grids. The conception is that this should be able to be done synthetically. This could help with properties that big power plants usually help with, such as frequency control and operational control. Especially important is this on a market where the system administrator has taken responsibility to keep the frequency and electricity quality. In that case those properties cannot be compromised with. The wind power plants can also produce positive or negative reactive power. A scenario could be that the wind power plants work like this even when the wind is not blowing. Future studies will show if this is something to invest in or not.

One challenge is to manage the price due to local conditions. The customers receive a bill based on the market. The market is not always correlated to local electricity generation phenomena, therefore the grid would have to send a signal to the Market to get a correlation. At Gotland a function will control certain components of the house and try to minimize the cost for the customer without hurting the comfort as discussed earlier. This is based on price signals. For the system operator, it is easier to 'control' the functions at the house instead of letting the customer do it. The customer has a choice, the rational choice would be to follow price signals but how can the operator know that the customer is following the price? That kind of system makes it harder to balance the loads and generation compared with the system operator 'controlling' the households. This kind of system is called direct control. SMS or mail to the customer is called indirect control.

Energy storage is the solution to effective wind power integration, unless the electrical grid system is really big and geographically big so the wind is always blowing in some place.

Interview at the Smart Grid Visitor Center 2014-02-11

This is a summary of the interview held at the Smart Grid Visitor Center at Jeju Island. The respondent were Ji Jin Kim, guide and informant at the visitor center. Some of the passages are very similar to earlier retailed information as the text is not a transliteration but rather a review of the important matters discussed during the interview.

In Jeju Island there are 120 MW installed wind power, which corresponds to 12% of the total energy input to the Island. However only 5% is used now because the wind power output is unstable and unpredictable. The Jeju government plans to be a carbon dioxide emission free Island in 2030 so the government wants to use all the energy in the wind and other renewable energy sources in an effective manner. At this moment Jeju Island has three thermal power plants located on the Island and two HVDC links connected to the mainland. The HVDC-link could be used for exporting power from Jeju Island to the mainland but so far it has only been used for importing power.

The wind conditions in Jeju Island is very different from wind conditions in other places. In other places the wind direction is straight and stable but in Jeju the wind is very unstable and the direction of the wind keeps shifting. The wind speed does also keep changing, and therefore technology is needed to connect the wind power plants with the grid. More investments are needed to integrate the wind power fully in the system and thereby reach 12%. Battery storage is a crucial part of the required technology. With batteries connected, the output from renewable energy sources can be stabilized to better fit in the power system.

At the Total operation center, were the power flows are planned in Jeju, there is a system for predicting the power output connected to forecasts of wind speed.

The energy from wind power is small compared to the total energy use on the island and therefore energy storage technology is not needed so much as a power source but more so to stabilize the system. In Ju Jeon there is a 4MW PCS and 8MW battery and the equipment is used for testing the stabilization.

During the project a 3MW battery and Lithium Ion battery technology were used and there were also tests with led-batteries.

HVDC were used for stabilizing the grid during the test period. In normal case the Test-bed could support itself but during peaks in energy consumption the HVDC link were used. The biggest challenge concerning the goal 'Smart renewable' were the stabilization of the system. The power grid are stable but connecting renewable energy to the grid makes the whole system unstable. Being a big challenge this area has been continually tested at Ju Jeon substation after the project was finished.

For ‘Smart Transportation’ the biggest challenge were to make the batteries in the car smaller and lighter.

The project started 2009 and a big challenge at that time was to build up the infrastructure.

Many people participating in the project were old and did not really understand the project. They received a smart meter, special washing machine and an IHD, In Home Device, controller, making their home a ‘Smart Home’. They liked it because they got machines and home equipment for free as well as a lower electricity bill due to the ‘smartness’ of the system. However the respondent argue that they didn’t really actively participated in the test because they didn’t understand the system or they were not interested. The ‘Smart Home’ test were expanded to some living areas in Jeju City, were more young people live. The young people showed more interest in the smart grid solutions and adapted their behavior after the smart grid solutions.

Smart grid could be very handy in Korea as Korean people are very technology-updated and experienced in using smart devices such as smart phones. Education about benefits with smart grids and how they work could be an important factor in Korea when influencing people to a ‘smart consumer behavior.

Looking back at the project, perhaps five different study fields were too much and too ambitious. The focus of the test could have been smaller. The respondent thinks that it could have been beneficial if the test were directed to only battery storage technology and EMS, energy maintenance system in factories and homes.

The government will provide 400 Electrical vehicles to the public next year. The Korean government are very interested in smart grids and have made big investments. The next stage of Koreas smart grid plans is to implement smart grid in mainland cities.

Interview at Korea Electro-technology Research Institute 2014-02-17

This is a summary of the interview held at Korea Electro-technology Research Institute. The respondent were Kang Dong-Joo, Senior researcher and representative for South Korea in ISGAN (International Smart Grid Action Network). Some of the passages are very similar to earlier retailed information as the text is not a transliteration but rather a review of the important matters discussed during the interview.

As mentioned, the wind power on Jeju stands for 12% of the total energy production on the Island not to be confounded with the part of the Island which were part of Jeju Smart Grid Test-bed. During the test period 10 megawatt wind power were used, which is low compared to the full capacity, so capacity wise the wind power was not a problem.

Considering that the wind power stands for such a small part of the total energy there have not been any problem with the wind power integration from a system perspective.

However compared to the power system of mainland Korea the system is smaller and therefore more vulnerable to fluctuations. This is one reason why not all the wind power was used. More battery storage systems and power conditioning systems are needed. In electrical grid level the engineers need to consider both transmission and distribution level. For the entire system this kind of fluctuations is not a problem but in local aspect it can cause problems. The system has a rating limit for fluctuations. The local system needs more buffering capacity on a local basis. There is a need for buffering capacity between the wind power park and the grid. This buffering capacity system could be an energy storage or an energy conditioning system.

Korea will have a similar problem on a large (national) scale as they plan to build a large wind power park in the west sea side, between Korea and China. Many experts in Korea worries about the system impact when the large scale wind power park is connected to the mainland grid. The limit of wind power capacity, based on the grid structure of Korea is 20 % according to power system experts in Korea. The Korean grid of today does not have a high level of flexibility when it comes to incorporating more renewable energy.

The HVDC link were connected to the Island during the full test period and Jeju Island were supported with power 80-90 % of the time counted from 8760 hours per year.

Concerning the question about Operational reserves, voltage control and short circuit capacity, there are an independent EMS (Energy Management System) which schedules and controls the overall Jeju Island System.

In 2030 Jeju government has set up as a goal to be a carbon dioxide free Island. To achieve this ambition they will use wind power, small scale hydro power and wave power. They will also focus on the demand side. For example to replace all non-electric vehicles with electric vehicles in 10 years. Currently Jeju Island is heavily dependent on fossil fuel plants which is a dependence that will take time to transcend out of. There could also be problems with system stability with more renewable energy integrated in the grid. The power grid will need to be rebuilt as to have a bigger flexibility. More energy storage systems and super capacitors need to be installed.

During the test-period the role of the battery storage system was both to supply with power and to give stability to the system. The battery storage needs to act as a buffer in the power system and store the energy from renewable energy sources. Another reason why energy storage systems were used was that the companies are trying to create new business models based on energy storage. There is already a market for batteries and in the test site, companies were trying to create a market for demand response technology including energy storage technology.

Korea has a kind of unique situation as more than 60% percent of the residential sector consists of apartments. Therefore Korea has a high possibility to save energy by applying energy management systems in the buildings perhaps combined with energy storage systems.

The respondent had not heard about the fish farms which were showcased In the Jeju Smart Grid Information Center and did not see the relation between the fish farms and power generation.

Currently thermal units/fossil fuel generators cover the fluctuations from the wind power. Therefore energy storage systems are not that important. If the wind power output is higher than expected, the fossil fuel generators reduce their production and if wind power output is low, the output from fossil fuel generation plants is increased. So, there is a large capacity to make up for wind power. Also there is the HVDC-link which can level up and down the power transfer to the Island depending on how much electricity which is being generated on the Island. In the future, with more installed wind power, Jeju might face the same challenges as Gotland with bottlenecks in the system concerning the HVDC-link to mainland, but at the current situation there is no such bottle-neck concerning the HVDC-link.

Compared to Gotland, the smart homes had a different function where the people living in the Jeju Smart Homes had many choices on how to adapt their energy consumption. “That’s why we failed” says the respondent. Most people living in the smart homes of Jeju Island were old and they had a hard time to understand how to adapt their consumption after the variant pricing. Smart Grids in Korea are in the beginning stage and in the future the demand response solutions can be developed into automatically demand response solutions which does not need active participation of the people living in the smart homes. But in that kind of system, the automatically demand response system must understand the context of the individual person living in the home, because all people has different preferences, living pattern and behavior. In individual homes the system needs to learn to adapt to home owners behavior around energy consumption. It is a give and take between energy saving functions and convenience which later can be evolved into automatic functions. The system needs to reflect the human’s choice and adapt to it. The respondent talks about technology development within the field, for example swedish company Ericsson is working on “Internet of things” solutions. In the paradigm the machines needs to understand the human mind as a sort of artificial intelligence.

Kang Dong-Joo agrees that consumer engagement been a big challenge during the test period since the people in the area were old and had difficulties understanding the concept of smart grids and demand and response.

The respondent thinks that it would have worked better if there were less choices for people and more automatically functions. “People are too busy” so it is almost impossible for them to care about their energy usage at all times.

Jeju Island is kind of a country side in Korea and the population there consists to big proportion of old people. However this is changing as Jeju Island is a famous tourist attraction in Korea and young people go there to work with the tourists. Still the population is mainly old.

Concerning prosperities and failures of the Jeju Island project the respondent points out that the project failed to create an effective demand response model which was the main failure of the project. It was a test for technical and economic feasibility around smart grid solutions and the results are relevant on a global basis, not only for Jeju Island.

The economic impact of smart grid solutions is very limited in an Island Such as Jeju Island or Gotland. This is because the population is small and therefore the economic impact is small as well. When Smart grid technology is deployed in city areas there can be more economic benefits and stronger business models can be created. The city is a kind of platform with many business models. In that sense Jeju Island was not a good site for testing the Smart grid as it was not an ideal spot for business models.

Due to the smart grid project in Jeju. Korea has been recognized as one of the first developers of smart grid in the world. In marketing perspective it was a very successful project as Jeju Island is a famous sight-seeing location and got many people’s attention. Many people travel to Jeju Island for vacation and while at the Island got to know of the smart grid. The project meant smart grid technology became known too many people.

Because of the Jeju project, many Korean companies became engaged in smart grid technology and did research about smart grid solutions. There were many trial and errors but at least Jeju project was a starting point for many companies to invest in green technology and in smart grids.

Considering the entirety of the project, the national road map of smart grids has a benefit of having many smart grid areas. Dong-Joo does not agree that there were too many focus areas because the Jeju project were only the starting point of the road map for smart grids in Korea, and therefore it was good that it consisted of many different areas. However, it was a pilot project which is why it had limited economic impact and perhaps why companies had difficulties to create business models.

On a national scale, to create a market for renewable energy in Korea, one option would be to raise the taxes for coal, oil and nuclear power. However, that would lead to a higher energy price in Korea and to social resistance. The respondent argues that the Korean people would not appreciate that kind of tax-raise. Electricity price is currently a strong political issue and it would not be easy for politicians to enforce a tax-raise. There is though the renewable portfolio standard which is a standard that shall secure renewable power generation in relation to other installed capacity. This standard is currently at 2%.

Another issue concerning the national road map for smart grids in Korea is that there just isn't enough renewable energy sources in mainland Korea to supply the country. This is an argument for why Korea also in the future will use nuclear power.

Further Interviews at Korea Electro-technology Research Institute 2014-02-17

This is a summary of the interview held at Korea Electro-technology Research Institute. The respondent were Seojong Soo, Senior researcher with focus on HVDC-technology. Some of the passages are very similar to earlier retailed information as the text is not a transliteration but rather a review of the important matters discussed during the interview.

The HVDC link from the mainland supplies the island with active power but not with reactive power. If there is a big transfer of active power from the mainland to Jeju Island there could be a shortage of reactive power as there are many switches and devices on the Island which are in need of reactive power. There are synchronizing condensers and Statcoms installed on the Island to help with reactive power however in some scenarios they are not enough. Jeju Island are also supplied by thermal units. The thermal units have some contingencies which could lead to loss of generation. So when the thermal units for some reason are down, there can be problems with keeping up the frequency. In these situations Jeju Island needs to gain more power from the mainland to keep up with the load. But as the HVDC line transfers more power the need for supplying with reactive power is also bigger and thereby the problem with not enough reactive power support on the Island. The bottle neck of the system is therefore not the HVDC-link but rather the system as a whole, or the reactive power generation units on the Island.

Excel tables

The excel tables showcased below is a cutting with the topmost rows from the Excel tables which were used in the investigation. All the tables relates thereby to data measured on 2000-05-19 time: 09:30 for the first row. 2000-05-19 time: 09:40 for the second row and so on.

Table 1.

Wind speed 10m	38m	54m	75m	96m	120m	145m
3,97	4,01	4	4,02	4,07	3,95	3,82
4,92	5,64	5,93	6,17	6,46	6,53	6,45
4,73	5,64	5,99	6,32	6,78	7,18	7,38

Table 1. A cutting from the excel sheet used in the investigation.

Table 2.

Watts10m	38 m	54 m	75 m	96 m	120 m	145 m
28969090	29260970	29188000	29333940	29698790	28823150	27874540
35901240	41155080	43271210	45022490	47138620	47649410	47065650
34514810	41155080	43709030	46117040	49473660	52392460	53851860
39476770	46554860	48087230	47941290	49692570	51443850	52246520
38674100	40790230	42833390	43854970	45825160	48014260	49838510

Table 2. A cutting from the excel sheet with different power outputs from different heights.

Table 3.

Total power output percentage·height
29310940
45261635
47036345
48866499
44535831

Table 3. Percentage multiplied by power output at different heights.

Table 4.

kWh
4885,157
7543,606
7839,391
8144,416
7422,639

Table 4. Energy output from successive ten minute intervals.

Table 5.

Difference between subsequent values in kWh
-2658,45
-295,785
-305,026
721,7779
907,6909

Table 5. Difference in energy between successive ten minute values.