Wind and Solar Power in Distribution Grids – Risk Management with a Distribution System Operator Perspective

Ludvig Carlman Bydén
Sara Persson

Division of Risk Management and Societal Safety
Division of Environmental and Energy Systems Studies
Lund University, Sweden

Riskhantering och samhällssäkerhet
Energi och miljösystem
Lunds tekniska högskola
Lunds universitet
Report 5027, Lund 2016

Wind and Solar Power in Distribution Grids
– Risk Management with a Distribution System Operator Perspective

Ludvig Carlman Bydén
Sara Persson

Lund 2016

Wind and Solar Power in Distribution Grids
– Risk Management with a DSO Perspective

Ludvig Carlman Bydén
Sara Persson

Report 5027
ISSN: 1402-3504
ISRN: LUTVDG/TVRH--5027--SE

Number of pages: 147
Illustrations: 48

Keywords
Risk, Risk management, Risk analysis, Distribution System Operator, E.ON, Wind power, Solar power, Generation
Sökord
Risk, Riskhantering, Riskanalys, Nätägare, E.ON, Vindkraft, Solkraft, Produktion

Riskhantering och samhällssäkerhet
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

http://www.risk.lth.se

Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Division of Risk Management and Societal Safety
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

http://www.risk.lth.se
Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

SUMMARY

The electric utility system is complex and dependent on all of its constituents for attaining a reliable distribution. The increase of solar and wind power adds a new dynamic element to this system. The functions of distribution grids and the requirements for operating under the new conditions are becoming increasingly complex. The role of distribution system operators (DSO) is central for achieving an energy system based on renewable energy sources. Distribution system operators need to adapt to the characteristics of solar and wind power generation and proactively ensure reliability of distribution. Risk management methodology can help in facilitating a safe and sustainable transition, achieving minimal negative impact on society, environment and economy. The process involves identifying risks, evaluating them and providing suggestions for reducing their likelihood and/or consequences.

The working process of the Thesis is constituted by a risk analysis of low and medium voltage grids that are subjected to an increased share of wind and solar power. The concept of reliability of distribution is assessed in the perspective of a distribution system operator in Sweden. Future risk scenarios are identified through a qualitative study in order to answer the three questions: What can happen? What is the change in likelihood? What are the consequences? Methods for mitigating the risks are sought and suggested. Economic and managerial issues were also identified as part of the qualitative study. These aspects were considered important to weigh into the risk analysis, as the role of the distribution system operator is affected also by the non-technical aspects of implementing renewable energy. The qualitative part of the Thesis is comprised of a literature study, interviews of experts within the electricity sector and a survey inquiring the same interviewees regarding the identified future risk scenarios. Out of the identified future risk scenarios, two were chosen for further investigation in a quantitative analysis. The goal of the quantitative study is to determine if the identified future risk scenarios have come close to, or have already been realized in the distribution grids in Sweden operated by E.ON. The choice of carried out qualitative studies are based on the feasibility of performing the analyses, the severity/likelihood determined in the qualitative study and availability of information from the DSO, E.ON Elnät.

The qualitative study resulted in the identification of six future risk scenarios. The survey ranked them from most to least problematic: Uncontrolled islanding, Undesired events due to unmanageable system, Harmonics on the grid, Overvoltage on the grid, Unacceptable levels of reactive power and Increased distribution losses. Increased distribution losses was classified as one of the least likely and least severe future risk scenarios. Over voltage was ranked as one of the more troubling future risk scenarios and therefore also chosen for further study. Most future risk scenarios were almost identically classified as moderately likely to increase in likelihood and moderate in severity of consequences. Furthermore, the identified consequences were mostly of an economic character. The economic/managerial issues were characterized by the common view of how the electricity system needs to function in the future, but that the responsibilities and standardized solutions for getting there are not clear.

In the quantitative part of the Thesis four medium voltage grid areas were studied in order to investigate the apprehension that wind power causes higher power losses on the grid. The analysis concludes that wind power has a varyingly large and sometimes contradicting effect when comparing different grid areas. Loss rate is the studied parameter i.e. the losses relative to the total electricity distributed on the grid. The two grids with the most installed wind power showed low loss rate during times of little or no wind power generation. After a certain percentage of wind power generation the loss rate starts to increase. In the studied grid which had the largest share of wind power, the loss rate at maximum wind power generation is 50 % higher than when no generation is present. The addition of a large wind power park during the studied period caused a remarkable increase in loss rate and spread of the observations. An incentive ruled by Energimarknadsinpektionen (EI) was closer looked into and deemed as feasible for reducing the economic impact of increased losses.

The second part of the quantitative study was meant to investigate Overvoltage on the grid, caused by solar power. The lack of solar power installations in the grids operated by E.ON in Sweden caused the study to shift focus, instead investigating the effects of wind power on voltage stability in low voltage grids. After asking several experts within the operation and maintenance division of E.ON Elnät, it was concluded that there should be no voltage problems due to wind power within the grids of E.ON, the low voltage grid of Påboda was however identified as a large net exporter of wind power generation and voltage stability in the transformer station was closer analyzed. Voltage deviation over a year at the station was compared to voltage and reactive power levels at the wind power connections. The analysis does not show any indication of wind power having detrimental effects on voltage stability. Conclusively, neither wind nor solar power is at current levels making voltage stability unmanageable in the grids operated by E.ON.

The findings presented in the Thesis will hopefully create an awareness of the most problematic effects of solar and wind power generation for the operation of distribution grids. The classification and evaluation of risks can be useful for prioritizing interventions for maintaining reliability of distribution. The overall conclusion from the Thesis is that most problems that arise due to solar and wind power are manageable. The initial presumption of the authors that problems might be both plentiful and potentially severe has changed into a belief that there is room for additional solar and wind power within the Swedish power system.

SAMMANFATTNING

Elnät är komplexa och vidsträckt system som förlitar sig på alla sina beståndsdelar för att bibehålla en god driftsäkerhet och stabilitet. Den ökade andelen vind- och solkraft utgör ytterligare ett dynamiskt element i de redan komplexa systemen. Nätägare spelar en avgörande roll i att hantera dessa förändringar i strävan mot ett energisystem baserat på förnybara energikällor. Nätägarna måste anpassa sig efter de nya förhållandena och egenskaperna som mer sol och vindkraft innebär och arbeta proaktivt för att trygga en god driftsäkerhet. En analys och behandling av riskerna kan bidra till en säker övergång, där påverkan på hälsa, miljö och ekonomi är minimal. Denna process utgörs av kartläggning av de risker som finns, värdera hotet dessa utgör samt bidra med förslag på åtgärder för att minimera deras sannolikhet och/eller deras konsekvenser.

Studien är utformad utifrån ett riskhanteringsperspektiv kopplat till driften av regionala och lokala nät med en högre andel sol- och vindkraftsproduktion i Sverige. I fokus står driftsäkerhet från nätägarnas perspektiv. Genom en kvalitativ delstudie identifieras riskscenarion. Denna del av studien ämnar besvara frågorna "vad kan hända?", "Hur troligt är det?" samt "Vad är konsekvenserna?". Även åtgärder för att reducera riskerna och/eller deras konsekvenser är undersökta och föreslagna. Ekonomiska problem och verksamhetsproblem identifierades också som en del av den kvalitativa studien. Dessa aspekter ansågs viktiga att inkludera i riskanalysen eftersom nätförvaltare även påverkas av icke-tekniska aspekter vid implementeringen av förnybar elproduktion. Den kvalitativa studien består av en litteraturstudie, intervjuer med personer inom energibranschen samt en enkät som skickades till intervjuobjekten. Av de riskscenarion som identifierats undersöks två mer ingående i en kvantitativ analys. Målet är att undersöka och fastställa om de identifierade riskscenariona redan idag påverkar driften av elnät förvaltade av E.ON Elnät i Sverige. Valet av undersökta riskscenarion baserades på möjligheten att utföra en analys, riskscenariots samlade vådlighet utgör enligt enkäten samt tillgängligheten av data från E.ON Elnät.

Den kvalitativa delstudien resulterade i sex identifierade riskscenarion. Enkäten rankade dem från mest till minst problematiska enligt: Ödrift, Oönskade händelser på grund av ohanterbart system, Övertoner på nätet, Överspänning på nätet, Oacceptabla nivåer reaktiv effekt samt Ökade transportförluster. Ökade transportförluster samt Överspänning klassades både som mindre troliga och med mildare konsekvenser än de andra riskscenariona. De andra riskscenariona var nästan identiskt klassade som "moderate" i sannolikhet och "medium" i allvarlighetsgrad av konsekvens. De flesta konsekvenserna var av ekonomisk karaktär. De verksamhetsmässiga/ekonomiska problemen karakteriserades av den gemensamma åsikten av hur energisystemet måste fungera i framtiden men att ansvar och standardiserade lösningar för att nå dit är oklara.

Fyra olika avräkningsområden av mellanspänningsnät undersöktes för att utreda huruvida vindkraft leder till större förluster i näten. Förlustandelen är den undersökta parametern, alltså förlusterna relativt den totala andelen inmatad elektricitet i nätet. Analysen resulterade i slutsatsen att vindkraftsproduktion har varierande effekt på förluster inom olika nät. De två nät som har mest installerad vindkraft visade låg förlustandel när lite eller ingen vindkraft producerades i näten.

Efter en viss andel av tillgänglig produktion så börjar förlustandelen öka, en brytpunkt verkar finnas. I nätet med störst andel vindkraftsproduktion så är förlustandelen vid maximal vindkraftsproduktion 50 % högre än när ingen produktion sker. När en till vindkraftsanläggning börjar producera syns en tydlig ökning av förlustandelen. Ett incitament för minskade förluster i nät av Energimarknadsinspektionen (EI) träder i kraft under nästa regleringsperiod. Detta undersöktes närmre för att se hur det skulle kunna påverka de kostnader som förnybar kraft medför till följd av ökade energiförluster i elnät. En nätförvaltare kan med hjälp av en klausul i incitamentet söka ersättning för de ökade förluster som förnybar kraftproduktion åsamkar. Slutsatsen är alltså att vindkraft kan öka förlusterna i ett nät, men också att de ekonomiska förlusterna av dessa förluster kan minskas med hjälp av incitamentets formulering.

Den andra delen av den kvantitativa studien ämnade undersöka Överspänning på lågspänningsnät till följd av solkraft. Avsaknaden av tillräcklig installerad solkraft i E.ON:s elnät gjorde att studien ändrades till att undersöka vindkraftens påverkan på spänningsstabilitet i lokalnät. Det ledde också till slutsatsen att solkraft ej verkar påverka E.ONs nät med avseende på riskscenariot Överspänning på nätet. Efter att ha frågat flertalet experter inom driftavdelningen på E.ON Elnät fastställdes det att inga spänningsproblem kunde knytas till vindkraft inom E.ONs nät. Ett lågspänningsnät (10,3 kV) valdes trots detta ut för en noggrannare analys av spänningsstabilitet då detta nät har en hög andel elproduktion från vindkraft. Spänningsvariationen vid överliggande transformatorstation under ett år jämfördes med reaktiv och aktiv effektöverföring från vindkraftanslutningarna. Analysen visade inte några indikationer på att vindkraften har någon skadlig inverkan på spänningsstabiliteten.

Resultaten som presenteras i denna studie kommer förhoppningsvis skapa en medvetenhet om de mest problematiska effekterna som sol- och vindkraft har på driften av elnät. Klassificeringen och värderingen av riskerna kan vara till hjälp vid prioritering av åtgärder för att upprätthålla en hög driftsäkerhet. Den generella slutsatsen i arbetet är de flesta problem som uppstår i samband med mer sol- och vindkraft är möjliga att hantera. Den tidigare uppfattningen från författarna att problemen kan vara både överväldigande och ha förmågan att försämra driftsäkerheten har förändrats till en tro på att det finns kapacitet och potential för vidare utbyggnad av sol- och vindkraft i det svenska elkraftsystemet.

ACKNOWLEDGEMENT

We wish to thank the employees at E.ON Elnät who have helped and supported us throughout our work. Your willingness to help and interest in our work have made us feel very welcome. We wish to give a special thanks to our supervisor at the Division of Grid Settlement, David Kostkevicius. Your comments have been honest and often spot on. Thanks to the other Thesis Students at E.ON for their input and advice, but foremost for all the fun breaks at work. We would also like to thank all the interviewees and survey respondents in Sweden as well as those in Germany and Denmark.

Also a special thanks is directed to our supervisors at the Faculty of Engineering at Lund University, Henrik Hassel at the division of Risk Management and Societal Safety and André Månsson at the division of Environmental and Energy System Studies. When we were confused and discouraged, you brought us clarity and belief.

I, Ludvig, thank my friends and family for taking such great interest in my studies. I would especially like to thank you all for changing the subject when asked to. There is a long list of people who have made my years in Lund a great experience. If you are reading this and feel you have had even the slightest positive influence, please give yourself my thanks many times over.

I, Sara, would like to thank my friend Cathrine Klingspor Harder, for everything you helped me with these past months and for all the invaluable advice and support you have been giving me. Foremost, I wish to thank my brother, Daniel Klugman, for always believing in me and telling me when I was younger that I could do whatever I dreamed of. Thank you for being my inspiration, without you I would not be where I'm at.

Thanks to all our friends and family who have supported us and listened to us in hard times. We wish to thank all of you who have been a part of this journey and Master Thesis. It has not been easy, but with your support and help it was possible!

Table of Contents

ABBREVATIONS

Some words and expressions are used frequently throughout the Thesis. Their abbreviations are presented here.

- ADL - Medium voltage grid in Ådalen
- DSO - Distribution system operator
- DG - Distributed generation
- EI - Energimarkandsinspektionen - Swedish Energy Markets Inspectorate
- GSO - Generation system operator
- IEC - International Electrotechnical Commission
- RA - Risk assessment
- PHA – Preliminary
- PV - Used for solar power, abbreviated from photovoltaic(s)
- SML - Medium voltage grid in Småland
- SUR - Medium voltage grid in Sundsvall
- SYD - Medium voltage grid in southern Sweden
- WP - Wind power

DEFINITIONS

- **Ancillary services -** Services for distributing electric power.
- **Coarse risk analysis –** A superficial risk analysis (see risk analysis below)
- **Consumption -** Transfer of electric power from the grid in question to a customer, typically to electricity intensive customers when connected to medium voltage grids.
- **Export –** Electric power transferred from the grid in question to another.
- **Distribution system -** The term for hardware and other components involved in distributing electricity e.g. transformers, lines and cables.
- **Generation -** "Production" of active and/or reactive power transferred to the grid in question.
- **Grid -** A defined section of an electric power distribution system.
- **Grid settlement area –** An area of concession, a defined section of an electricity distribution grid from which the volumes of electricity are reported to relevant actors and authorities.
- **High voltage grid -** Operated by Svenska Kraftnät, it is the largest dimensioned electrical distribution system through which electric power is transferred over long distances. Defined as voltages above 130. Levels used by Svenska Kraftnät are usually 220 - 400 kV.
- **Import -** Electric power transferred from one grid to the grid in question.
- **Inverter -** Electronic device converting direct current to alternating current.
- **Losses -** Electric power losses in a grid.
- **Loss Rate -** The losses relative to the total power on the grid during one hour. Defined as Losses / (Import + Generation).
- **Low voltage grid -** The smallest dimensioned part of the electricity distribution system, the grid infrastructure closest to customers. Defined as 20 kV and below by EON Elnät and therefore also throughout the thesis by the authors. In literature commonly defined as below 1kV.
- **Medium voltage grid -** A grid stretching over regions, connecting to low voltage grids, the high voltage grid, other medium voltage grids or directly to customers. Defined by EON and authors as 20 - 130 kV. In literature more commonly defined as 1 - 130 kV.
- **Regulatory reporting unit -** A collection of several grid settlement areas, for which a distribution system operator reports volumes of electricity to the Swedish Energy Markets Inspectorate.
- **Reliability of distribution -** The ability to deliver electric power to end users with the right quantity, quality and timing.
- **Revenue cap -** The maximum revenue a DSO is allowed to collect from its customers. Regulated by The Swedish Energy Markets Inspectorate.
- **Risk analysis -** Risks and their consequences that cause a deviation from the wanted scenario of the system are identified and evaluated.
- **Risk assessment -** Consist of risk analysis and risk evaluation.
- **Risk evaluation -** Evaluation of risks, where risks are established to be acceptable or unacceptable.
- **Risk management –** The process involving risk analysis, risk evaluation and risk reduction.

- **Risk reduction -** Reduction of risks and/or their consequences. If risks are found to be unacceptable in the risk evaluation, the next step is often risk reduction.
- **Risk Scenario -** An unwanted scenario or event that can occur in a system.

CHAPTER 1
INTRODUCTION

The following sections describe the background for writing the thesis and what the study aims to achieve. A thorough description of the methods for answering the research questions is also presented.

1.1 BACKGROUND

The increasing global demand for energy, supplied to 78 % by fossil fuels, antagonizes the ambitions to reduce climate impact and effects on human health. The continued replacement of fossil fuels with renewable sources of energy is a vital part of limiting the anthropogenic effects on climate change. Solar power (PV) and wind power (WP) have both started to compete economically and politically with traditional power generation (REN21, 2014). The European Commission (2016) has set target goals for its member countries to achieve overall 20 % renewable energy, 20 % increased energy efficiency and 20 % reduction of greenhouse gases by the year 2020 compared to 1990 levels. The composition of electricity generation types in Sweden has been relatively static during the latter part of the 21st century. However, the appointed goal of 50% renewables has in recent years been surpassed. The electricity certificate system has been effective in facilitating the expansion of renewable electricity sources and improving energy efficiency. The largest change is the increase of WP. It has gone from a more or less insignificant share of the total electricity generation in the beginning of the century to around 8 % in 2014. The installed capacity of PV increases at a rate of around 50-60 % per year. However, the total generation only corresponds to 0.04 % of the total electricity generation within the country. Parallel to the addition of renewable energy sources are plans for early phase out of several nuclear power plants (Energiläget, 2015).

The technical characteristics and the geographical distribution of generation of both PV and WP challenge the traditional structure and functions of electricity distribution systems. Stability of the electrical system, from generation to consumption, is a necessity for supplying power in the right quantity and quality at the right time (Söder, Dahlbäck, Larsson & Linnarsson, 2014). This concept is referred to as the reliability of distribution. In maintaining reliability of distribution, the overall process of the system needs to be robust. Magnusson, Nilsson, Hallin & Lenntorp (2000) defines robust as the opposite of vulnerable. Technical robustness is a cornerstone of a resilient society, together with social and ecological robustness. Having a robust electrical system is essential for the needs of a modern society.

As DSOs (distribution system operators) are granted concession for operating the utility infrastructure within a geographical area, they play a central role in maintaining the reliability of distribution. Much of the new additions of renewable energy sources are connected to the low and medium voltage grids. This implies that if any detrimental effects are caused by the generation, they need to be handled partly or solely by the affected DSO (D. Kostkevicius & R. Nylander, personal communication, November 6, 2015). In handling the effects of PV and WP, DSOs will have a harder time keeping operational parameters within acceptable bounds. Hence the DSOs role for achieving a reliable power system based on renewable energy (RE) is becoming increasingly important. The research of this Thesis aims to map the potential risks of an increased share of PV and WP within the low and medium voltage grids with a DSO perspective. In assessing the reliability of distribution, managerial and economic prerequisites for properly operating a grid are also important aspects for a DSO. The report will therefore not only treat the technical aspects, but how these prerequisites are affected by the change.

1.2 Purpose and Goal

This Master Thesis aims to answer how the trend of increasing implementation of WP and PV generation affects the distribution of electricity in medium and low voltage grids. More specifically, it intends to:

- Identify the potential future risk scenarios and their consequences that the distribution system operators (DSO) face with an increase of PV and WP
- Suggest measures for reducing the likelihood or severity of the risks or their consequences
- Investigate if the installed WP and PV already affects the operation and if so suggest solutions for dealing with the consequences

Through understanding the future risk scenarios and their consequences, DSOs can adapt their operations to address the most urgent problems. The conclusions drawn can hopefully be of use when planning for and implementing additional renewable electricity generation. In the larger perspective, the goal is to aid the transition to a power system based on renewable energy generation in a socially, environmentally and economically sustainable manner.

1.3 Research Questions

The research questions are based on the concept of reliability of distribution, i.e. the ability to deliver electricity to end users with the right quantity, quality and timing. The research questions aim to identify and evaluate the risks inferred on the reliability of distribution by the increased share of renewable electricity generation.

1. What are the risks affecting the reliability of the distribution system operation when implementing a higher share of PV and WP in Sweden's existing electricity grids; its ability to distribute electricity efficiently and safely?
    a. What future risk scenarios and other challenges can affect DSOs and ultimately the reliability of distribution for electricity consumers, with an increased share of PV and WP?
    b. What future risk scenarios will be the most challenging to manage?

c. What measures can be taken in order to minimize the likelihood of the risk scenarios and/or their consequences?

From the findings of the first research questions, a quantitative analysis of two future risk scenarios aiming to answer the questions in bullet point 2 below is performed. A more detailed description of the motives for choosing these can be found in section 4.2 Choice of Risk Scenarios, along with the delimitations that have been done.

2. Has the increase of WP or PV generation already affected the operation of the distribution grids operated by E.ON? Can conclusions be drawn in regards to future development?
   a. Has the increased share of WP lead to more distribution losses in the medium voltage grids?
   b. Is it possible to prove an increase of costs in the form of network losses caused by WP in order to apply for a reduction of the incentive ruled by EI?
   c. Has the increase of WP affected the ability to maintain voltage stability in the grid?

1.4 Project Boundaries

In the qualitative part of the Thesis, the risks that arise in regards to the operation of the grid with an increasing share of PV and WP have been identified and assessed. The risk analysis takes on the perspective of risks for the DSOs operation of the distribution grids. Since the authors are engineers, the study mainly treats technical risk scenarios. Economical and managerial issues are briefly treated, this only to give a slightly more holistic perspective. The interviewees were chosen by the authors in order to cover the many aspects of electricity distribution. Most were people from E.ON, others included people with specific technical expertise and some were from countries that have witnessed the transition to a large share of WP and PV. The focus in the qualitative study has been on both low voltage and medium voltage grids. Detailed technical descriptions of each risk event have been held to a minimum in order to keep the analysis stringent and concise.

Choices of risk scenarios for the second part of the Thesis are made from the conclusions drawn in the qualitative study. The decision to analyze distribution losses and voltage deviations was primarily based on feasibility to conduct the analysis within the scope of this thesis and the availability of relevant data. The few installations of PV within the grids of E.ON has made it impossible to study the effects thereof. The qualitative study has therefore only treated WP.

One of the quantitative studies analyses low voltage grids in regards to one risk scenario and the other analyses medium voltage grids. The conclusions drawn from low voltage grids cannot be applied to medium voltage grids and vice versa. Both parts of the quantitative study have been focused on the effects of WP, since the total installed capacity of PV generation within the grids of E.ON in Sweden is still too small.

In analysis of losses, section 4.3.1, only WP generation and loss rate are treated, although many other parameters affect losses. A statistical study on what parameters that affect losses has already been performed by other students. They studied the significance of e.g. wind, ambient temperature, production from other power sources and humidity. Furthermore, their study was performed on one of the grid sections analyzed in this part of the qualitative study. The focus of this analysis is rather on how different medium voltage grids are affected by WP specifically.

The voltage deviation analysis in section 4.3.2 does not in depth analyze the effects of WP on voltage. This analysis uses an investigative approach to assessing if WP has affected voltage stability within the grids of E.ON. The data visualized in the analysis only aims to get an insight into how the output of a single WP generation unit can influence voltage stability.

1.5 METHOD

The research questions are answered by a comprehensive risk assessment of the reliability of distribution of low and medium voltage distribution grids. The risk assessment consists of two main parts, a qualitative and a quantitative study. Below in figure 1 is an illustration of the work process.

Qualitative research can be used as a foundation for the quantitative research. As Bryman and Nilsson (2002) explain, the qualitative methods can result in ideas or hypotheses that can be tested with quantitative methods. This is the approach used in this Master Thesis. From the identified future risk scenarios in the qualitative study, two are investigated further in the quantitative.

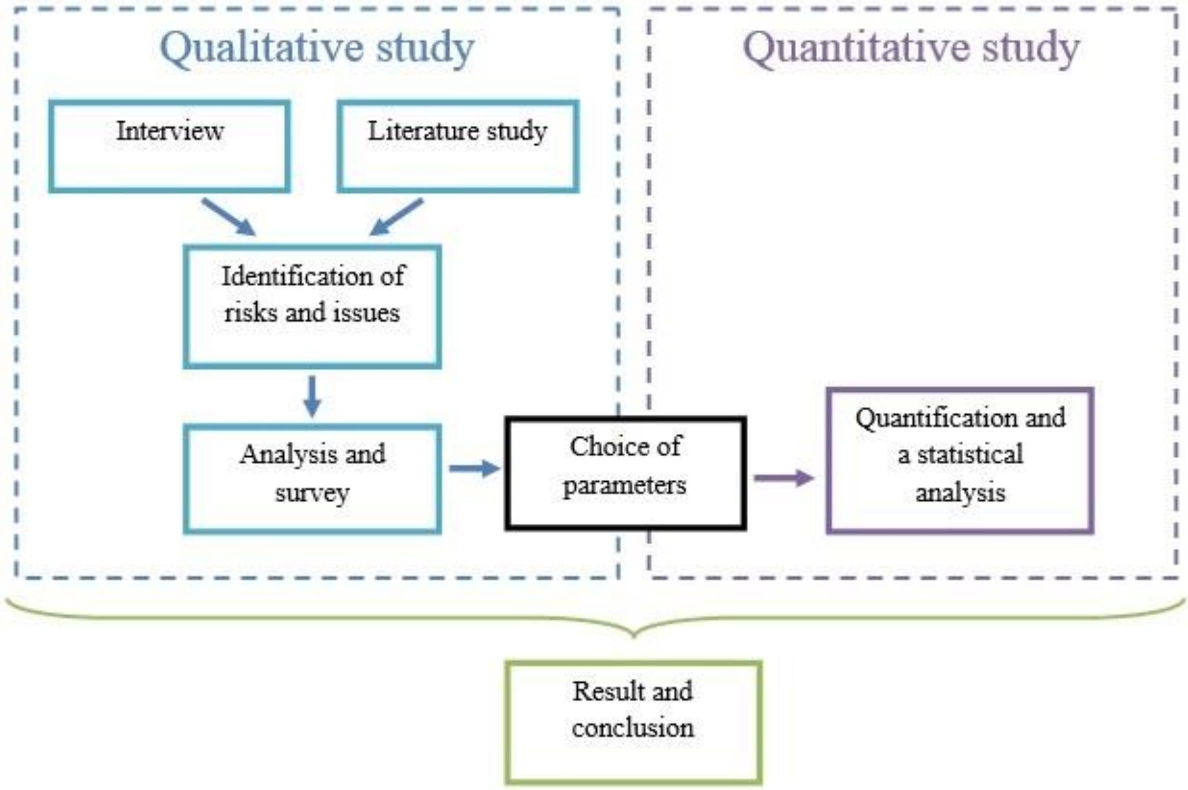

FIGURE 1. SCHEMATIC ILLUSTRATION OVER THE WORK PROCESS

1.5.1 Qualitative Study

The qualitative study aims to answer research question one "What are the risks affecting the reliability of the distribution system operation when implementing a higher share of PV and WP in Sweden's existing electricity grids; its ability to distribute electricity efficiently and safely?".

The qualitative study is designed as a coarse risk analysis inspired by a Preliminary Hazard Analysis (PHA). PHA is the most commonly used method amongst distribution system operators (DSOs) for identifying and evaluating risks and their consequences (Mörée, 2015). PHA is used to get an overview of the hazards and risks that exists in a technical system. Risks are identified and evaluated by inquiring people with experience of the system (MSB, 2011 and Nilsson, 2003). If risks are identified the method suggests investigating them further. A rating scale can be used for representation and comparison of the findings (MSB, 2011).

In this Master Thesis, the protocol of a PHA was not followed strictly. However, the overall methodology of the PHA as briefly described above was used. This because the authors had limited time and resources. Therefore only the overall methodology was used because it was considered enough for this study. The qualitative study consists of a literature study and interviews for identifying the future risk scenarios and their consequences, which are formulated in words. A survey was performed to categorize the severity and likelihood of the identified future risk scenarios.

The results of the qualitative study were used to determine which future risk scenarios were to be further analyzed in the second part of the research questions.

1.5.1.1 Literature Study

A literature study was performed in order for the authors to get a better understanding of the field of electricity distribution and potential problems caused by renewable electricity generation. The literature study also resulted in the background section, where notions of risk and methods are explained. Information has been studied regarding distribution grids, generation types and laws and regulations of the energy market. Surveys and interviews were planned and the relevant literature on methodology and interview theory was studied. Most sources were gathered from LUBsearch, the search engine for literature of Lund University. Some sources have also been provided by supervisors and new acquaintances at E.ON. Most references for identifying future risk scenarios come from personal communication with these helpful people.

1.5.1.2 Interviews

Since a specific field of research was investigated, interviewees were handpicked. The chosen interviewees can be seen in Appendix B. The composition of interviewees was assembled in order for the sources to complement each other in terms of their individual fields of knowledge.

- Several persons from E.ON were interviewed. People with different areas of expertise were chosen to get a comprehensive picture of the risks. The personnel working at a DSO company such as E.ON can provide firsthand information in terms of what problems can arise in the operation of a grid and how these problems can be dealt with.

- People within the energy sector from Denmark and Germany were contacted. The experience of people who have seen a similar development in other countries is of particular interest for identifying future problems. This might give an indication of what lies ahead for the Swedish DSOs.

- Other people with a broader overview of energy sources were chosen, such as professors in Sweden and Denmark and other specialists within the energy sector.

Kvale and Torhell (1997) explain that interviewing should be performed until you have answered the questions you want answered. In all 13 people were interviewed, which was considered enough as the last few interviews gave little new insight.

An open "in-depth" interview was considered appropriate. Interviewees can in that format identify risks and expand on their thoughts. The in-depth interview does not have a list with specific questions that are followed. The interview is interactive, rather like a discussion (Ritchie & Lewis, 2003). Issues and questions that need to be answered are written down beforehand by the authors, these can be seen in Appendix A. These work as a template of what topics the interview needs to cover. The interview was initiated by asking interviewee to identify the technical risks that arise with the increase of renewable energy generation. Subsequently they are asked how and why these are a problem and what consequences might they lead to. The questions are based on the three risk questions Kaplan and Garrick (1981) present, which are further explained in chapter 3. Supplementary questions were asked in order to find out more about a certain topic or to clarify. The interviewees were in the end of the interview asked about how they see the future role of DSOs and what they think needs to be done in order to maintain a reliable distribution of electricity.

Since the interviews were conducted in an open fashion, both authors asked questions. This type of interview requires the interviewer to analyze, understand and work out how to proceed with the discussion and interview. Richie and Lewis (2003) explain that it is important to listen carefully and that recording the interview along with taking notes can be helpful. The interviews were therefore recorded, which the interviewees were made aware of and their consent was given before the interview started. The interviews were transcribed, summarized and analyzed. The transcriptions were sent to the interviewees for approval and eventual clarification of what they actually meant. The transcriptions can be seen in Appendix B.

The reliability and the validity of the interviews were also evaluated questioned by the authors. Some of the interviews were held face to face whilst others were held over the phone due to lack of time and resources. As mentioned above the in-depth interview puts demands on the interviewer. It requires the interviewer to be able to read and analyze the interviewee. As Ritchie and Lewis (2003) mention the body language might indicate if the interviewee is uncomfortable. The body language, however, is not possible to read over the phone. More detailed reasoning of what might have affected the validity and reliability of this Master Thesis is attended in chapter 5, Discussion.

1.5.1.4 Identification of Future risk scenarios

Identification of future risk scenarios was done based on the information from the interviews. Complementing information was provided from the sources studied in the literature study. The identified future risk scenarios are presented in Chapter 4.1 Qualitative Study. The Future risk scenarios were presented as to answer the risk analysis questions that Kaplan and Garrick (1981) provided:

- *What can happen? i.e. the risk scenario*
- *How likely is it?*
- *What are the consequences?*

1.5.1.5 Surveys

The interviewees were also asked to take part of a survey regarding the identified future risk scenarios. This since they were involved in the work and already had knowledge about the study. A disadvantage with a survey is that it is not possible to clarify to the respondents or for the respondent to explain further if somethings if unclear. This is why the authors thought it was suitable for the interviewees to answer the survey and not send it to other persons. The purpose of the survey was to analyze the future risk scenarios in terms of likelihood and severity of consequences. The decrease or increase of likelihood and severity of the consequences are asked for on the scales of classes as described below.

Likelihood: Class 1 - Substantial decrease in likelihood, Class 2 - Decrease in likelihood, Class 3 - No change in likelihood, Class 4 - Increase in likelihood, Class 5 - Substantial increase in likelihood
Severity: Class 1 - Negligible, Class 2 - Low, Class 3 - Moderate, Class 4 - High, Class 5 - Extreme

A kind of risk matrices were constructed from the results, as seen in Chapter 4.1 Qualitative Study. Risk reducing measures were also asked for.

During the first interviews many new insights were dawned, resulting in additional perspectives of operational security. In assessing the risk for operational security, the role and difficulties of operating a grid are essential for understanding how the problems can be dealt with. The role of a DSO is growing increasingly complex. More functions are demanded of the grid and the related tasks are growing more sophisticated. Examples include higher resolution of measured volumes, ability to handle large fluctuations due to intermittent power and "smart grid" technology. Therefore, questions regarding economic and managerial issues relating to the operation of distribution grids were added to the survey.

The survey was constructed using SurveyMonkey, a web based tool for creating easily accessed inquiries. A link to the survey was sent to the interviewees via e-mail.

1.5.2 Quantitative Study

The quantitative study aims to answer part two of the research questions "Has the increase of WP generation already affected the operation of the distribution grids operated by E.ON? Can conclusions be drawn in regards to future development?".

From the conclusions drawn from the qualitative analysis, a selection of risk scenarios has been made for further analysis. The analysis performed aims to prove or dismiss the notion that certain risk scenarios have come closer to or have already been realized in the grids of E.ON.

The selections of risk scenarios have been made on the basis of:

- Overall feasibility of assessing the risk scenario, i.e. can it be assessed in practical terms?
- The availability of data from the cooperation with E.ON Elnät
- The likelihood and severity of the risk scenario evaluated in the survey
- The opinion of an expert within the field outweighed the other opinions. .

This resulted in Distribution Losses and Overvoltage being chosen. The motives for these choices are presented in section 4.2 Choice of Risk Scenarios. The risk scenario Overvoltage on the grid changed focus during the course of the analysis process, resulting in a study on voltage deviation problematics due to WP.

In choosing a tool for the analysis, the ability to duplicate the procedure in a future analysis was the most important factor. Keeping the statistical analysis simple was important for both making the findings easily conceivable and useful when comparing different areas to each other and over time. Microsoft Office's Excel 2013 proved sufficient for plotting data and performing simple statistical comparisons. The vast amounts of data provided by E.ON Elnät needed to be sorted and structured into manageable time series, which was made possible with the use of Excel. Other tools were considered, such as MATLAB and R, however, Excel 2013 proved capable in all aspects.

1.5.2.1 Distribution Losses due to WP

This method section aims to answer part two of the research questions, "Has the increased share of WP lead to more distribution losses in the medium voltage grids?"

Four medium voltage grid settlement areas operated by E.ON have been studied in order to establish what effect WP has on the losses within these subsections. Grid settlement areas are practical for the study, since all ingoing and outgoing electricity is hourly measured and aggregated in time series. The different areas were compared to see if there is any relationship between losses and WP generation. PV was not included as a parameter in the analysis, since it was not considered to be of large enough installed capacity to have a measurable effect on losses. Furthermore, most PV systems of today are connected to low voltage grids rather than medium voltage. In looking at some of the grid areas, other types of generation needed to be handled in order to isolate the effects of WP.

As described in section 2.2, Wind Power, the majority of WP is connected to medium voltage grids. The conclusive argument for choosing medium voltage grids as the main focus was the superior quality of data, as each transformer/distribution station measures the flow of electricity hourly, with good accuracy.

Data of ingoing and outgoing volumes, generated and consumed electricity are documented and sorted in the program Generis, a comprehensive cataloguing software for storing measurement data from measurement of transferred and generated power within the monitored electricity grid.

An extract from the program was made to six separate Excel sheets, with all settlement data for the year 2015. The data from the extract was compiled into columns sorted from the first of January to the 30th of December. In total 8736 hourly values each for consumption, WP generation, other generation, consumption, import and export exchanges between grids, losses and loss rate were sorted into one year vectors. Values from a dozen days in the end of the year were removed from SUR, as the loss data was deemed to be of poor quality. The final settlement report of grid volumes is quality assured and sent to relevant actors and authorities no more than 47 days after the last recorded value of the month (D. Kostkevicius, personal communication, January 18, 2016). The total daily volumes during one year were plotted to give an overview of the load fluctuations that the grids experience.

The losses within the settlement areas are automatically calculated in Generis from the aggregated time series of import, export, generation and consumption according to equation 1 below.

$$Losses = (Import + Generation) - (Export + Consumption) \quad \text{EQ. 1}$$

Import: kWh/h transferred from other grids to the grid settlement area.
Export: kWh/h transferred to other grids.
Generation: kWh/h transferred from a power plant to the grid.
Consumption: kWh/h transferred from the grid to customers connected to the medium voltage grid.

The unit kWh/h is used throughout the result section. It was concluded necessary to specify that the observations are hourly values of transferred energy, since some figures show daily values.

Some power plants are registered as import when generation system operators (GSOs) choose to manage the lines or cables connecting their power plant to the rest of the grid. Operating this small utility system, made up by a stretch of line or cable, makes the GSO a DSO. The practical operation of this small grid can be outsourced to a more experienced actor (S. Svensson, personal communication, April 8, 2016). The implication for the quantitative study is the risk of missing large volumes of electricity generated from WP. The volumes from the aforementioned connection will register in the settlement report as import from an adjacent grid instead of WP generation. This problem has been addressed with the help of S. Svensson and "hidden" generation identified. He was believed to be the person most familiar with the distribution of WP plants in the analyzed grids. SYD had 16 hidden WP time series. Two WP series in each SUR and SML were identified. These were added to the aggregated WP generation series in each grid settlement area.

Loss rate was considered suitable for determining the effect of WP on the magnitude of losses. It is defined as losses divided by all electricity fed to the grid, see equation 2 below. It is used at the division of Energy Controlling at E.ON as a measure of how big the losses are in relation to the total volume of electricity distributed by the grid. The absolute value of losses in itself is not interesting to compare directly to WP, as other flows of electricity are much larger in the examined grids. Distribution losses are a direct function of the total load on the line. The relative magnitude of losses can be compared by calculating a quote of the losses divided by the total power on the grid every hour. This is done at EON Elnät and is referred to as the loss rate (D. Kostkevicius, personal communication, February 1, 2016).

$$Loss\ rate = \frac{Losses}{Import + Generation} \qquad \text{EQ. 2}$$

(D. Kostkevicius, personal communication, February 1, 2016)

The loss rate was plotted against WP generation in order to investigate whether a relationship between the two parameters could be found. A value of correlation was also calculated in order to:

1. Establish a positive or negative relationship between loss rate and WP generation, i.e. is WP generation causing an overall increase or decrease within the studied grid?
2. Determine if the observations follow an increasing or decreasing linear trend.

The Excel 2013 function CORREL was used to calculate correlation. This results in a value of how much the two arrays correlate according to a linear relationship. The result is a number between -1 and 1. The closer the value is to -1 or 1 the stronger the correlation, 0 means no correlation. A positive value indicates a positive correlation, if the x array increases, so does the y array. If the y-values decrease when the x-values increase, the correlation coefficient will be negative (Microsoft, 2016). A positive value of correlation between the x-value (WP generation) and the y-value (loss rate) indicates that the losses increase with increased WP generation. A negative value of correlation indicates a decrease of losses with an increased WP generation.

The CORREL function is presented below in equation 3:

$$Correlation\ (X,Y) = \frac{\sum(x-x_{mean})(y-y_{mean})}{\sqrt{\sum(x-x_{mean})^2\sum(y-y_{mean})^2}} \qquad \text{EQ. 3} \qquad \text{(Microsoft, 2016)}$$

When plotting the loss rate and WP, the trend of some of the data series proved to be of a non-linear nature. Therefore, a second order equation was also fitted to the analyzed values. The values had in most cases a high variance that it would be hard to draw more detailed conclusions regarding the nature of the trend. Some of data also contained unexpected distribution of observations. These were more thoroughly assessed in order to isolate the impact of WP or determine the cause of the anomalous distributions.

1.5.2.2 Measure for Reducing Consequences of Increased Losses

Research question 2. of the qualitative study includes the question "Is it possible to prove an increase of costs in the form of network losses caused by WP in order to apply for a reduction of the incentive ruled by EI?".

The relevant laws have been studied, presented in Chapter 2, and the question brought up for discussion with representatives of the division of Energy Controlling at E.ON.

The analysis performed on losses aimed to prove or dismiss the thesis that WP generation increases the losses within a grid. Based on the conclusions from the study, the feasibility of successfully applying for a reduction of the incentive was also assessed.

1.5.2.3 Failed Attempt to Assess Losses in a Low Voltage Grid

Low voltage grids, which generally experience higher losses due to their higher impedance, were considered interesting in performing the same loss analysis on. The larger transformer substations of the low voltage grids are mostly hourly measured while some are less frequently measured. Consumption of individual customers within the low voltage grids is measured monthly in more than 90 percent of the cases, resulting in an unacceptably low resolution when calculating losses.

However, an attempt was made in cooperation with S. Svensson to isolate a low voltage grid subsection and study the losses thereof. Most measuring equipment below the 50 kV/10.3 kV transformer station in Påboda reports daily measured energy. A daily resolution was considered acceptable for a rough analysis and the time series were extracted with help from the division of Operations at E.ON. The generation of WP relative to consumption within the subsection is often several times higher. This makes the power flow "upstream" on the grid, exporting surplus generation to the medium voltage grid.

The task proved impossible to perform. A look at the data showed losses ranging from minus 15 % to 30 % of the total volumes. There were missing values during periods over several weeks at many measurement points. Around 2500 measured points in the grid made up the data, far too many to individually assess and estimate the missing volumes of. The analysis was therefore discontinued.

1.5.2.4 Voltage Deviations due to WP (Originally: Overvoltage due to PV)

Overvoltage on the grid and Unacceptable levels of reactive power were identified as future risk scenarios in the qualitative study as a result of numerous PV installations. Overvoltage on the grid was chosen for further investigation. Reactive power is closely related to voltage, as increased levels thereof cause elevated voltage, see section 4.1.1.4 Unacceptable levels of reactive power. It was therefore looked at as one parameter which influences voltage at the transformer station. This part of the qualitative study was more exploratory. Focusing first on PV, which causes overvoltage on low voltage grids in Germany (S. Schmidt, interview, January 13, 2016) it was concluded that the amount of installations present within the grids in Sweden was insufficient. The distribution of PV was also too scattered to locate an area with large enough generation relative to consumption under one transformer station. At this stage, we either had to start looking for data from other grids or change focus to another risk scenario. Quantifying the other risk scenarios was deemed unfeasible. Instead, focus was shifted toward the effects of WP on voltage stability in low voltage grids. In the interviews with representatives of Energinet.dk, T. Fonnesbæk & T. Skødt (interview, January 19, 2016), it was noted that old WP technology used to be poor in terms of voltage stability and reactive effect. The analysis shifted to function as a means of either confirming or dismissing WP as having a detrimental effect on voltage stability on the low voltage grids.

K. Berg, T. Lundgren and F. Roos, who work at the Operation Management division at E.ON Elnät were consulted. None of them could identify an area where WP was believed to have a detrimental effect in terms of voltage stability. Despite this, an interest remained within both parties in looking at a low voltage grid with large WP generation. Low voltage grids are of higher impedance and are often more geographically widespread, making them more susceptible to voltage deviation. This choice coincided with the failed attempt to study losses within a low voltage grid described in the previous section 1.5.2.4. Although that attempt failed, it did result in identifying a suitable low voltage grid (Påboda) with several WP generation units for the analysis of voltage deviation.

With help from K. Berg and T. Lundgren data during one year was studied. The maximum and minimum hourly values of voltage at Påboda transformer station were viewed in order to identify any values outside of the permitted range. The period with the most voltage deviation was examined closer. Hourly values of WP generation, transferred reactive power from WP, voltage at Påboda transformer station and load through the transformer was extracted from the program dpPower. The data was transferred to Excel 2013 where it was analyzed.

CHAPTER 2
ELECTRICITY - DISTRIBUTION & GENERATION

An overview of the Swedish power system is described in this chapter. The description is intended to give a general overview of the utility system - how electricity is generated and distributed. The necessary background on PV and WP is also presented.

2.1 THE SWEDISH POWER SYSTEM

This section presents the layout of the Swedish Power System, its generation sources, consumption and ownership.

2.1.1 SWEDISH ELECTRICITY GENERATION AND CONSUMPTION

Swedes consume around 14 000 kWh electricity per capita and year, making Sweden the sixth most electricity intensive country in the world. According to Energiläget (2015), the total electricity generation within the country has since the mid-eighties amounted to around 140 TWh per year, a figure well matched by domestic consumption. Recent years have shown decreasing electricity consumption and increasing levels of generation, resulting in record levels of export and low prices (Alaküla, Gertmar & Samuelsson, 2011). Figure 2 shows the relative shares of generated electricity from different power generation types and the total domestic consumption.

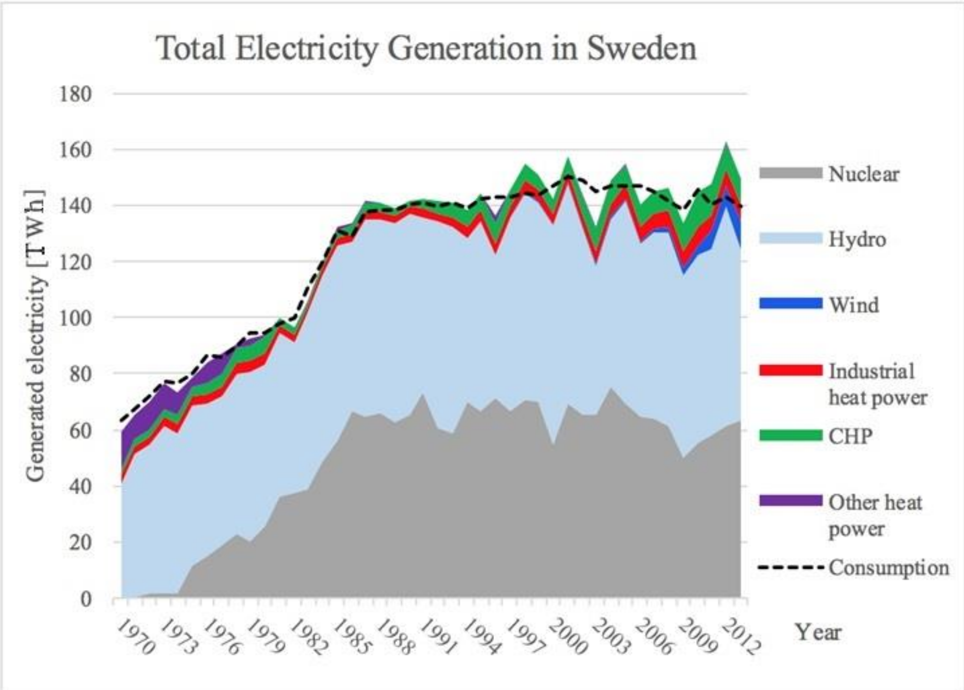

FIGURE 2. TOTAL ELECTRICITY GENERATION PER TYPE IN SWEDEN, YEARS 1970-2013. DATA FROM APPENDIX OF ENERGILÄGET (2015), FIGURE PLOTTED BY THE AUTHORS.

The two main power sources are hydro- and nuclear power. They have each constituted 40 % or more of the total generation every year since the mid-eighties. Some reserve generators that run on fossil fuels are still used as auxiliary power, included in the figure above in "other heat power". One of the later additions to the electricity mix is the use of biofuels, primarily used for combined heat and power generation. The most recent and largest change in installed capacity during recent years is the rapid increase of WP (Alaküla *et al.,* 2011).

2.1.2 The Electricity Distribution System

Large-scale electricity distribution has the same general characteristics throughout the world. Large power plants, the main source of electrical power, is normally fed to high voltage transmission lines or cables. This network transmits electricity over long distances from the place of generation to areas of consumption, such as a region with industries or cities. This general layout is present also in Sweden, where electricity from large hydro power plants in the north is transmitted to the rest of the country. High voltage, usually 220 - 400 kV in three phases, allows for large flows of electricity to be transmitted over several hundred kilometers, typically with only a few percent losses. High voltage grids are often extended across national borders, connecting to the grids of other countries. Connecting to other grid areas increases the redundancy of the system and its ability to handle fluctuations in demand and supply (Svenska Kraftnät 2015a). Electricity fed to the Swedish grid has a frequency of 50 Hz, with the exception of some high voltage direct current cables. Reaching a region of consumption, the high voltage is lowered in transformer stations and redistributed to grids of lower voltage (Alaküla *et al.,* 2011). See the illustration in figure 3 below.

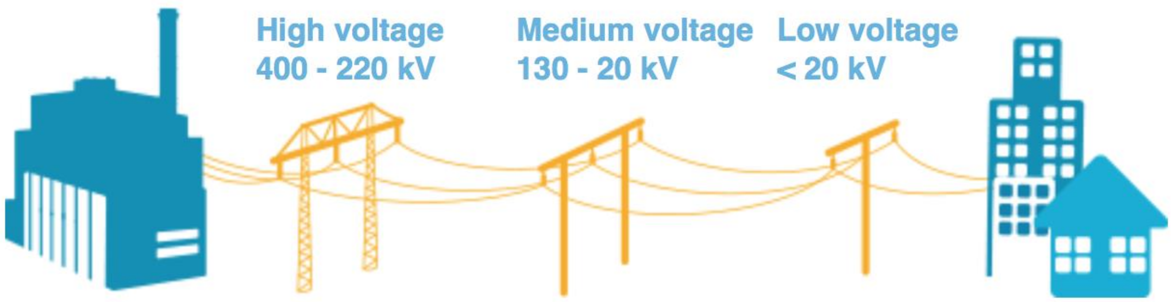

FIGURE 3. OVERVIEW OF POWER TRANSFER WITH VOLTAGE LEVELS. GRAPHICS BORROWED WITH PERMISSION FROM (KRAFTRINGEN, 2016), RANGES OF INTERVALS DEFINED BY THE AUTHORS.

The distribution systems with voltage ranging from roughly 10 - 130 kV and sometimes down to 1 kV are referred to as medium voltage grids. The definition provided by EON Elnät is 20 - 130 kV. They are used for distribution over shorter distances, for example between municipalities or for redistributing generated electricity closer to where it is consumed. Medium voltage grids connect the high voltage grid to the even finer low voltage grids. It is normal for electricity intensive industries to be connected to the medium high voltage grid, as their machinery and processes require high capacity and stable quality parameters (Svensk Energi, 2015).

The medium voltage grids feed not only large industries but primarily low voltage grids, which have an even lower voltage of around 1 kV and below. The definition of a low voltage grid is throughout the rest of the thesis, however, 20 kV and below due to the definitions provided by EON Elnät. Much of these are constituted by buried cable, making little aesthetic intrusion in the city landscape. At this point the electricity is either further converted to lower voltages for domestic consumption or transferred to other customers with limited consumption. During the very last distance of up to a few hundred meters in connection to small users, the voltage is transformed to only 400 V. Losses are large due to the low voltage making it necessary to keep the length of cable at a minimum (Aladküla *et al.,* 2011).

2.1.3 Ownership and Management

The high voltage grid in Sweden is owned and operated by Svenska Kraftnät (SVK), a state owned non-profit organization. They are ultimately responsible for the overall balancing of the system, compensating the deviances in supply and demand and ensures the quality of electrical power supply. As SVK does not own the entire electricity infrastructure, some of this responsibility is outsourced to other actors, whom answer to SVK (Svenska Kraftnät, 2015a).

Both the medium and low voltage grids in Sweden are owned and operated by around 160 companies of varying size and type of ownership. Private actors are allowed to own and operate a grid, they are referred to as DSOs. The market for grid ownership is divided into areas of concession, where only one DSO is allowed to operate the electric grid within the specified geographical area. The medium and low voltage grids within a defined geographic area can have different DSOs. The business of DSOs is regulated by EI (Energimarknadsinspektionen), which regulate revenue and ensures fair competition. They stipulate the income tariffs for DSOs aimed at ensuring that the grids are operated with both high efficiency and reliability. The medium voltage grids are owned almost exclusively by three companies; Vattenfall, E.ON and Ellevio. DSOs charge customers for the distribution of electricity, made possible by the use of their grids. This fee should not be confused with the cost for electricity, which is bought and sold by other electricity trading companies (Svensk Energi, 2015).

The Swedish electricity law states that it is the responsibility of the organization which has concession of a grid area (a DSO) to ensure electricity with high quality to the customers connected to the grid. They are also responsible a reliable distribution (SFS 1997:857).

The trade of electricity is administered by the energy market Nord Pool Spot, allowing for the electricity to be bought and sold by electricity trading companies in many of the northern European countries. DSOs have no authority over what type of electricity is passed through their grids, nor what types of generation that is connecting to it (Svensk Energi, 2015). Depending on size and type of generation they are allowed to charge a connection fee and the continuous grid fee for transferring power, which the generation system operator (GSO) pays for. DSOs are obliged to transmit electricity regardless of origin and are responsible for the losses that arise within their grid. The costs for operating a grid along with losses are included in the level of allowed revenue set by EI. However, an increased share of losses will not automatically be included in the granted revenue for DSOs in the next regulatory period. A new regulatory incentive will result in DSOs having to pay for the increase (Energimarknadsinspektionen, 2015). This incentive is more thoroughly treated in section 4.3.1.6, Measure for Reducing the Consequences of Increased Losses.

2.2 Wind Power

This section includes information necessary for the understanding of the risk scenarios regarding WP.

2.2.1 Prevalence and Future Trends

As of today, large scale wind turbines are almost exclusively of the horizontal axis wind turbine type with three blades, as seen in figure 4. They are placed, favorably, in wind rich areas either individually or in larger conglomerates commonly referred to as wind parks. A general trend is larger turbines and larger capacity per turbine, resulting in the need to connect to grids of higher transmission capacity, mostly medium voltage (Manwell, McGovan & Rogers, 2009).

FIGURE 4. HORIZONTAL AXIS WIND TURBINE. PHOTO BY AUTHOURS.

Wind parks in Sweden range in the tens of megawatts to those in the hundreds. Offshore WP has not had the same rapid expansion in Sweden as land based (Svenska Kraftnät, 2015a). Offshore WP is almost always arranged in wind parks. Things like sea bottom characteristics, shipping routes and existing wind parks limit suitable locations. The use of expensive high capacity transmission cables also limits the distance between of the individual turbine, and thus also the sprawl of the wind park as a whole. These parks are able to produce more land based wind parks, thanks to the more favorable wind conditions at sea. They are however more expensive to build, which is the foremost reason that land based wind power is built to a larger extent (Manwell *et al.,* 2009).

Figure 5 below illustrates the cumulatively installed power capacity of WP, how the generation of energy (GWh) has increased and the number of turbines in operation. It is only in the last few years that WP has made any significance in terms of installed effect and generation. WP generation in 2014 corresponded to around 8% of total generation in Sweden (REF). The reason for the generation increasing so rapidly relative to the number of turbines is due to the increasing size and capacity of the turbines, as well as advancements in the efficiency of the technology.

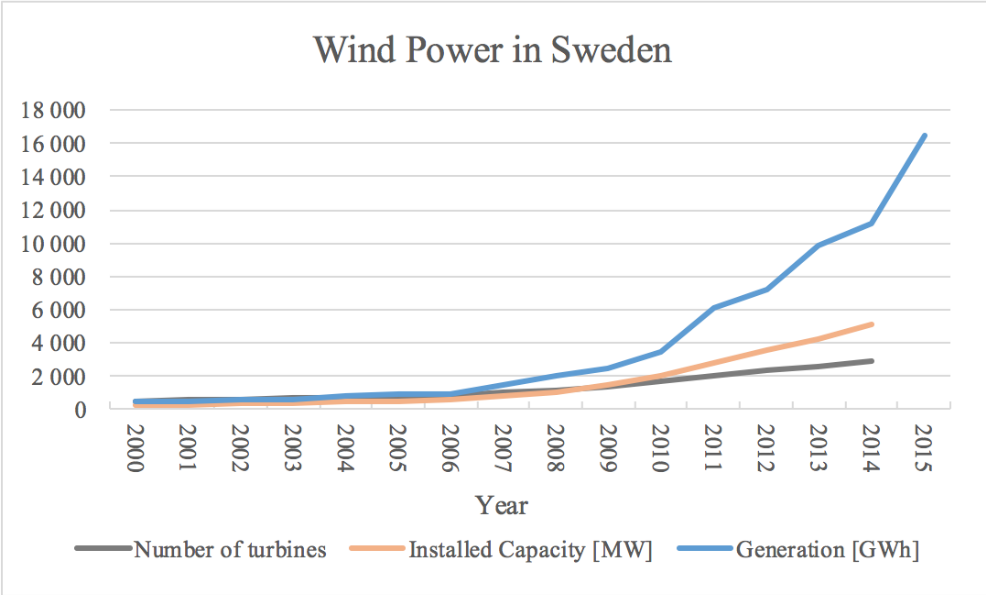

FIGURE 5. HISTORICAL DATA OF WP CAPACITY, NUMBER OF TURBINES AND GENERATION. DATA FROM APPENDIX IN ENERGILÄGET (2015)

Svenska Kraftnät (2015b) claims that the total applications for installation of WP roughly amounts to the total capacity of electricity generation installed within Sweden today. The realization of all those applications are in any scenario unrealistic, but it emphasizes the willingness to invest. Svenska Kraftnät (2015b) deem the incentives for future WP investments to be dependent on:

- The electricity certificate systems future contribution to the electricity price
- Investment cost of construction and components
- The electricity price

Their expected scenario for the continued development during 2016 - 2025 is a subsiding increase in WP installations, resulting in a total WP generation of 17 TWh year 2020 and 21 TWh year 2025. One contributing factor to this trend is the current framework of the electricity certificate system, which will not be efficient enough for continuous expansion. The certificate system is jointly used by Norway and Sweden. Norwegian GSOs are likely to claim much of the available subsidies for new hydropower installations (Svenska Kraftnät, 2015b).

2.2.2 Generation and Availability

Figure 6 shows how a conventional horizontal axis wind turbine of variable speed performs depending on wind speed. The generator will not be connected until the wind speed is high enough for both maintaining the velocity of the blades and being able to extract some of the energy from the wind without making the blades come to a stop. When wind speed is high enough for maintaining the desired speed for the generator, the blades are gradually deflected in order to avoid absorbing all of the winds energy. This is called to maintain the rated speed, for which the generator has an optimum power output. Deflecting the blades means losing generated power, but increasing the lifespan of the components and reducing the risk of malfunction and damages. At the cut-out speed, the physical integrity of the turbine is considered at risk. Therefore, the generator is disconnected and the blades brought to a halt. Continuing to work at speeds above this threshold would make the strain on internal components unacceptably high (Manwell *et al.,* 2009).

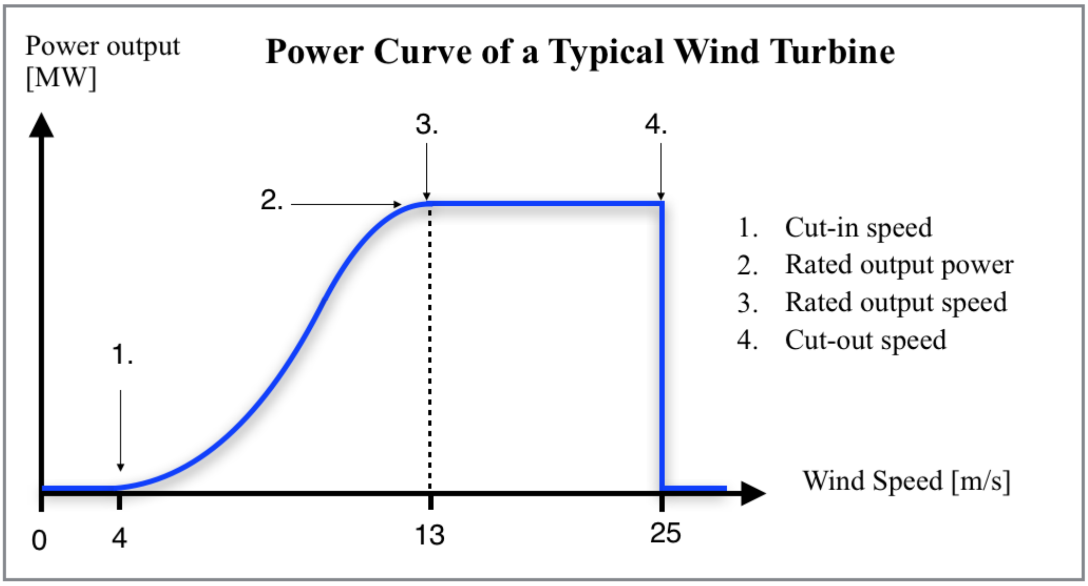

FIGURE 6. POWER CURVE OF A PITCH REGULATED TURBINE. AUTHOR'S INTERPRETATION AND ILLUSTRATION (MANWELL *ET AL.* 2009)

As wind energy is the primary limiting factor for WP generation only a small share of the total generation capacity is available on average over a year. Svenska Kraftnät (2015a) assumes the utilization of the total installed WP capacity to be 6% throughout a year and 9% during winter months, since wind conditions are better during winter. Wind conditions vary in both short and long term. The resulting generation of a WP system therefore looks more or less stochastic. Figure 7 shows the hourly generation of a WP turbine over two months. It shows the large variations that occur in the short term.

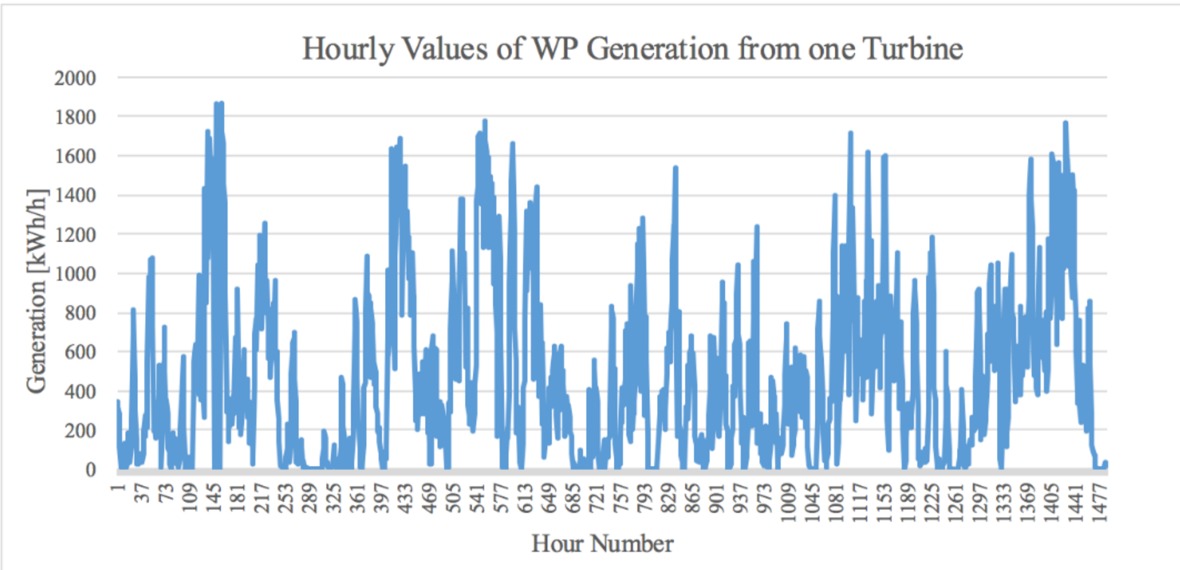

FIGURE 7. PLOT OF GENERATION FROM A WIND TURBINE. DATA FROM E.ON ELNÄT.

2.3 Solar Power (Photovoltaics)

This section includes information necessary for the understanding of the risk scenarios regarding photovoltaics, PV. In figure 8 below an example of a photovoltaic installation can be seen.

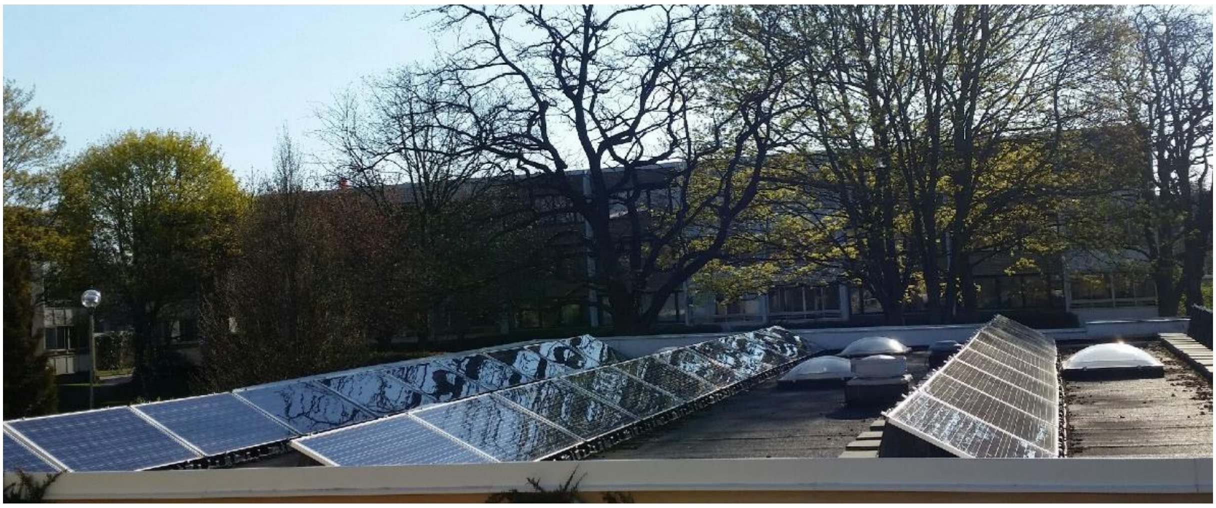

FIGURE 8.PHOTOVOLTAICS. PICTURE BY AUTHORS

2.3.1 Prevalence and Future Trends

The initial costs of the system is the single largest cost for operating a PV system. The Swedish government has since 2009 subsidized the installation of PV systems, which has made the technology more popular (Energiläget, 2015). Most systems installed are connected to the grid, allowing for the owner to sell their surplus of electricity, though not the generation exceeding the total domestic consumption. As seen in figure 9, this is the most commonly installed type of PV-system. The owner selling surplus electricity receives the same grant per kWh from the electricity certificate system as WP (Lindahl, 2014).

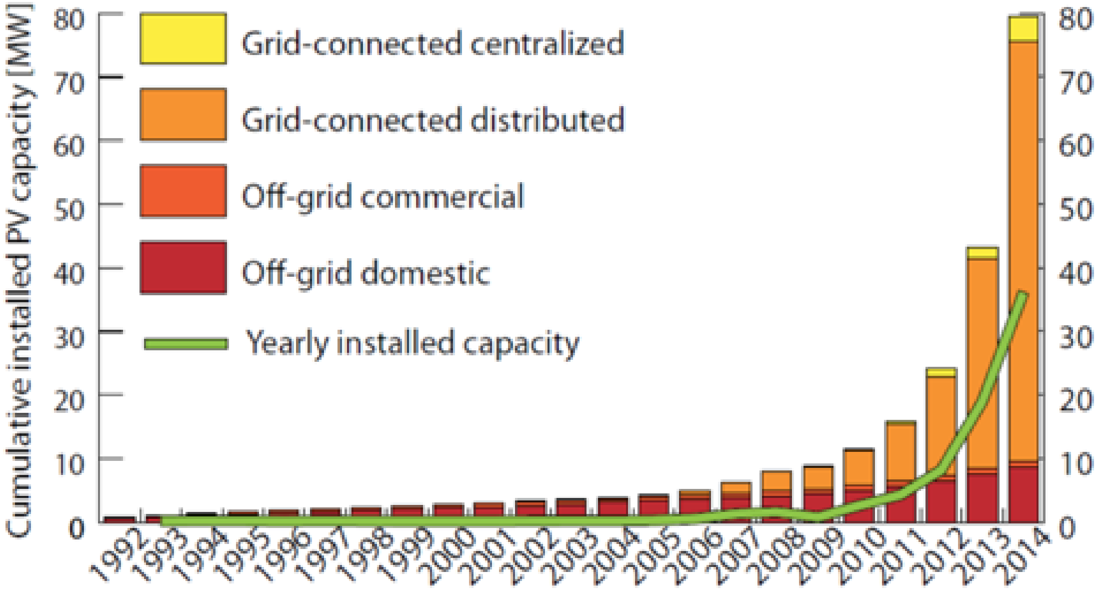

FIGURE 9. INSTALLED CAPACITY OF PV SYSTEMS IN SWEDEN ACCORDING TO TYPE. SOURCE: (LINDAHL, P. 4, 2014)

The total generated electricity in Sweden during 2014 was 62.9 GWh, a mere 0.04 % of the total electricity generated during 2014. No detailed data over the total generation over a year is available, only the sum of the total generation. As seen in figure 10 the orange bars, representing grid connected systems, have nearly doubled three years in a row (Lindahl, 2014).

Svenska Kraftnät (2015a) points out PV's small contribution to the electricity system in Sweden. They stress PVs reliance on subsidies to be economically viable and the fact that its use would be more beneficial in parts of the world where solar irradiation is more abundant. The fact that PV produces most of the electricity in the summer further deteriorates the already stressed situation of the power system during the summer, when supply tends to be larger than demand. They do however predict that as a generation type, it is likely to be economically competitive sometime in the near future (Svenska Kraftnät, 2015a).

2.3.2 Generation and Availability

The generation of solar cells is directly related to the amount of incoming radiation. It also implies no generation in the absence of solar radiation. The two main limiting factors for generation are the earth's daily varying alignment to the sun and cloud coverage. The solar cells, when shone upon, create a field of electric potential between two sheets of semi-conductive materials. This potential is measured as a voltage and creates a current of electrons from the illuminated side of the material to the one beneath. The current generated is a direct current, approximately proportional to the amount of irradiation times the efficiency of the solar cell. The direct current is converted with the use of an inverter to an alternating current and fed to either a grid, a storage device such as a battery or used to power domestic appliances (Alaküla *et al.,* 2011). The hourly generation of a PV system connected to the grid of E.ON is plotted in figure 10 below. The period is July and August of 2015. The plot clearly depicts the daily pattern of generation.

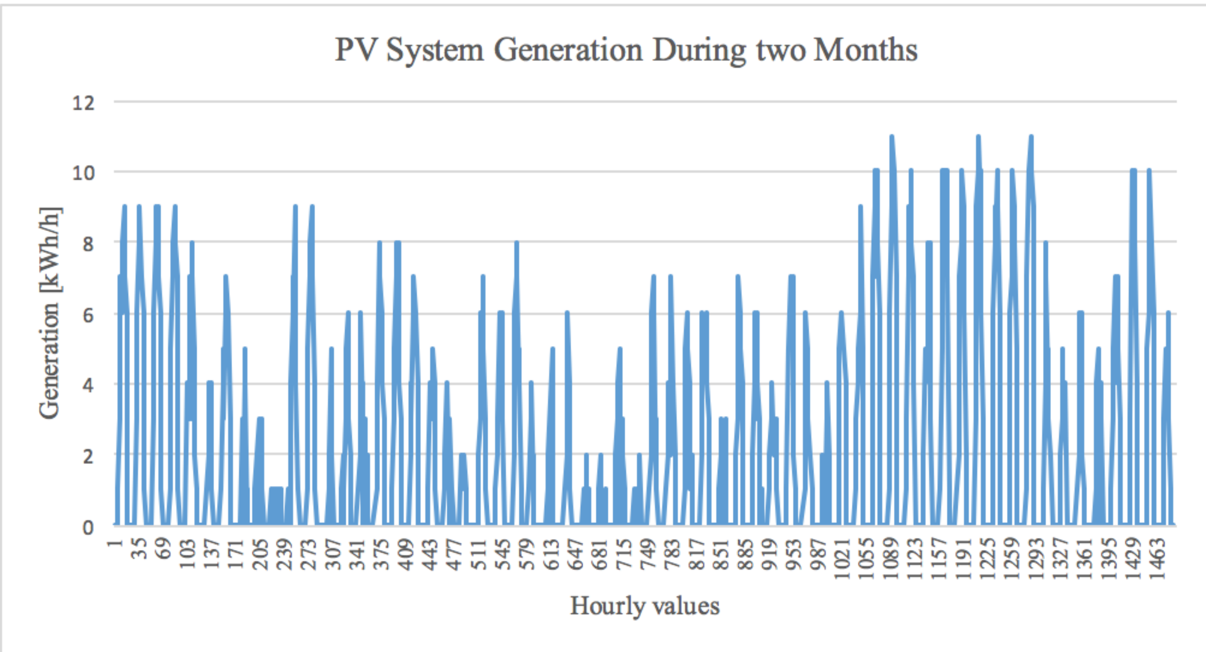

FIGURE 10. THE GENERATION EXPORTED TO THE GRID FROM A PV SYSTEM IN SOUTHERN SWEDEN. FIGURE BY AUTHORS, DATA FROM E.ON

A typical solar cell system is fixed to an angle of around 45 degrees, facing south. The generation of such a system during a day, without clouds or other shading, is illustrated in figure 11 below. The peak of generation is reached when the panels, during noon, face the sun in the south.

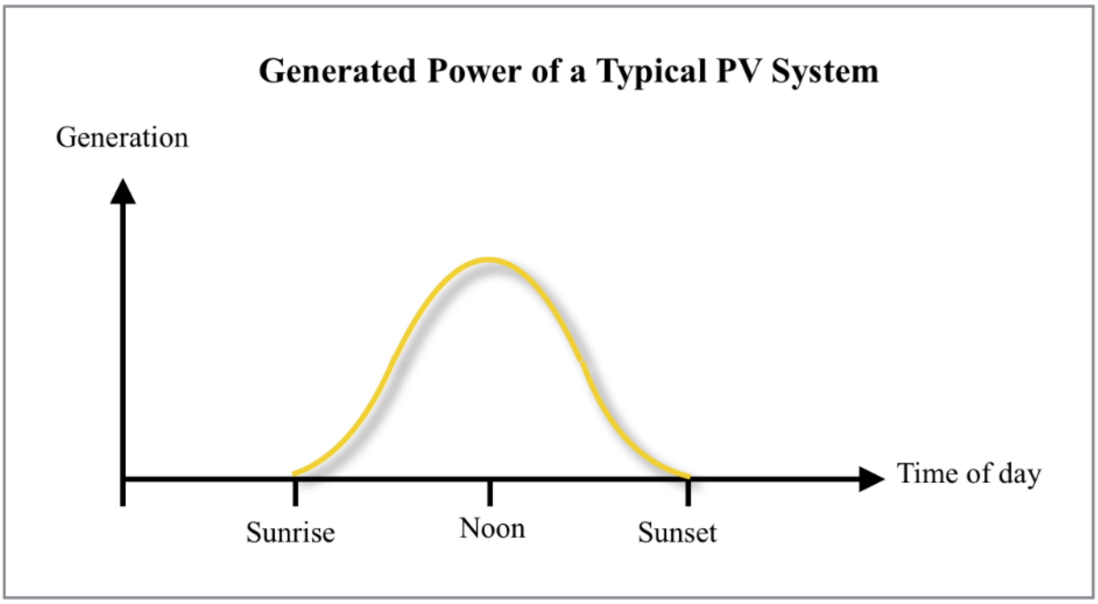

FIGURE 11. AUTHOR'S SKETCH OF ELECTRICITY GENERATED FROM A TYPICAL ROOF MOUNTED PV SYSTEM

2.4 Losses in Power Grids

Losses in all parts of the electricity distribution system will be described in this chapter, but only the losses related to the purpose of this study will be described more thoroughly. The amount of losses reflects the efficiency of the distribution system and how it's managed. Electrical losses in transmission and distribution grids amount to 7.5% of the total energy supplied to the grids in Sweden, a number held relatively constant during the last 15 years (Svenska kraftnät, 2015a). The rough categorization of losses can be done as in figure 12 below. The different categories will be described separately.

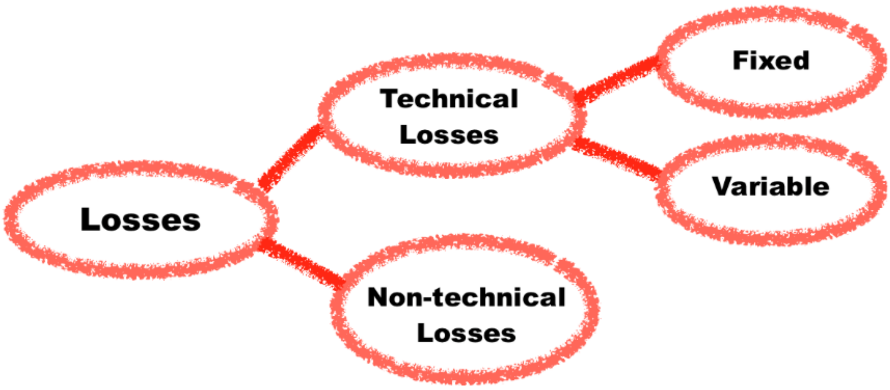

FIGURE 12. CATEGORIZATION OF LOSSES IN THE POWER SYSTEM. DEPICTED BY THE AUTHORS WITH INSPIRATION FROM (JIMÉNEZ, SEREBRISKY & MERCADO, 2014)

2.4.1 Non-Technical Losses (Administrative losses)

Non-technical losses, also known as administrative losses, depend on how the electricity system as a whole is managed and utilized. Due to intentional or unintentional mismanagement, both consumers and distributors contribute to this category. Non-technical losses include:

- Electricity theft from users who are not legally connected to the grid.
- Fraudulent modification of measuring equipment.
- Mismanagement by distributors; faulty or poorly conducted accounting, calculations, record keeping or registration of electricity volumes (Jiménez, Serebrisky & Mercado, 2014).

2.4.2 Technical Losses

The utility infrastructure; transmission lines, transformers and other components have physical properties which ultimately allow electrical power to be used where it is needed. The efficiency of the distribution depends on the technical qualities of the components the system consists of and the circumstances under which they operate (Jiménez *et al.*, 2014). The following section aims to distinguish and describe the most relevant types of technical losses.

2.4.3.1 Fixed Losses

As the name suggests, the fixed losses can be considered constant. The fixed losses depend mainly on the voltage level. Throughout the system voltage levels are ideally kept constant at the desired level. At the intervals in which voltage varies, its total effect can be considered constant in a larger perspective. They tend to account for 20-40 % of the technical losses (Jiménez *et al.*, 2014). Some of the constant losses include:

- Losses in transformers
- Corona losses - Electrical discharges from the electric field around transmission lines
- Losses due to measuring equipment (Jiménez *et al.*, 2014)

2.4.3.2 Variable Losses (Joule Effect)

These are the types of losses primarily focused on throughout the Thesis. Firstly, a short explanation on electricity transfer is required. In a distribution system, electricity is transferred through a conductor e.g. hanging line or buried cable. The amount of conveyed energy is described by Ohms Law, based on voltage (U), current (I) and resistance (R), see equation 4 below. Equation 4 combined with Joules law of effect, equation 5, gives equation 6.

$$U = I * R \qquad \text{EQ. 4}$$

$$P = U * I \qquad \text{EQ. 5}$$

$$P = \frac{U^2}{R} \qquad \text{EQ. 6}$$

In order to transfer the maximum amount power with minimal losses, the current is ideally kept as low as possible, the voltage as high as possible and the resistance of the material to a minimum. In order to transfer more power over the same line, either I or U needs to be raised. This physical relationship, as shown in equation 5, is the reason for using high voltage for long distance transmission. Higher voltage means that less current is needed for transferring the same amount of power. The current, or "flow of electrons", collide with the material it passes through, generating heat. Depending on the molecular characteristics of the material, it is more or less conductive. Higher conductivity implies less resistance and therefore smaller losses. According to Joules first law, an electric current passing through a resistive material generates heat according to equation 7 below (Aläküla *et al.,* 2011).

$$Q = I^2 * R * t \qquad \text{EQ. 7}$$

$$Q = Heat\ loss\ [Watt]$$
$$I = Current\ [Ampere]$$
$$R = Resistance\ [Ohm]$$
$$t = time\ [s]$$

Energy dissipates as heat due to the resistance. The squared current implies higher losses relative to the transferred energy during times of high generation/consumption. High peaks of current contribute significantly more to creating losses than if the energy had been transferred evenly during a longer time. This emphasizes the importance of keeping current low, which is either done by raising voltage of improving the qualities of the conductor. The ladder can be done by increasing the cross sectional area of the conductor changing the replacing the material with something less resistive. Some parameters that strongly influence Joule losses include:

- Length of conductor. Losses occur along the lines and cables. A longer distance creates larger losses due to higher resistance (proportional to length).
- Temperature. Increasing temperature results in higher resistance and therefore higher losses per meter.
- Cross sectional area of conductor. Larger cross sectional area allows for electricity to be conducted more easily, which reduces heat generation and as a result also the resistance and losses per meter (Aläküla *et al.,* 2011).

2.4.4 Reactive Power and its Effect on Losses

The electricity distributed on the Swedish grids is kept at the alternating frequency of 50 Hz. It is distributed in a three-phase system, where each phase is conducted on a separate line. The current (I) is transported over a voltage (U). On a conductor, current and voltage vary in a sinusoidal fashion, see figure 13 below. Note also ϕ, which is a phase shift between the voltage and current (Aläküla *et al.,* 2011).

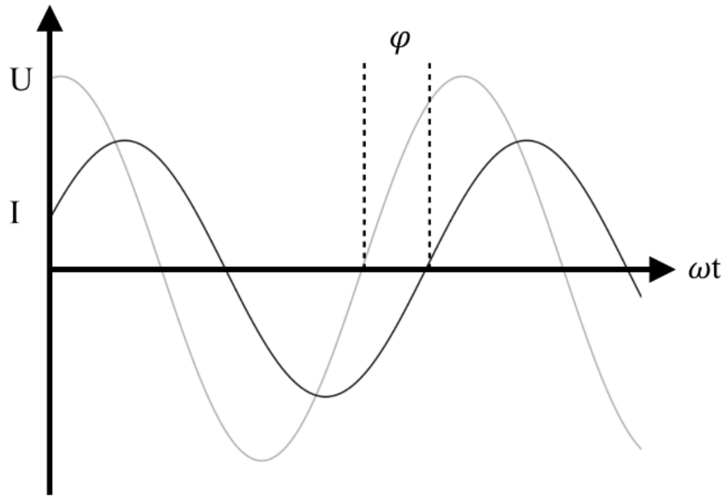

FIGURE 13. ILLUSTRATION OF A PHASE SHIFT BETWEEN CURRENT AND VOLTAGE. DRAWN BY THE AUTHORS WITH INSPIRATION FROM (ALAKÜLA *ET AL.*, 2011)

The apparent power (S) is the product of current and voltage, see equation 8.

$$S = U * I \qquad \text{EQ. 8}$$

Apparent power is the vector sum of active and reactive power. Active power (P) is the product of the momentary value of voltage and current, according to equation 9 below. It is the "useful" energy that can be used to power electrical equipment (Alaküla *et al.,* 2011). As seen in the equation, a larger ϕ causes the available active power to decrease.

$$P = I * U * \cos(\varphi) \qquad \text{EQ. 9}$$

The variable ϕ is a phase shift, a mismatch of current and voltage from being completely synchronized. The phase shift is a result of inductance or capacitance posed by e.g. a component of the distribution system, an electricity generation unit or load. Inductance is a storage of magnetic energy, which is the case in figure 13. The energy is not lost from the system, but is not able to be utilized as active power. A capacitive load, on the other hand, makes the voltage lag behind current. In an illustration similar to figure 13 where the reactance is capacitive, the current would peak before voltage. When ϕ is zero, the phases of current and voltage are perfectly matched and all of the power in the conductor can be used to power electrical equipment. The conductor is in that case purely resistive. (Alaküla *et al.,* 2011).

The part of the apparent power which is not active power is referred to as reactive power, expressed in equation 10 below. No phase shift between current and voltage implies no reactive power, a conclusion which also can be drawn from the sin(ϕ) part of the equation.

$$Q = I * U * sin(\varphi) \qquad \text{EQ. 10}$$

Reactive power presence in the distribution system reduces the efficiency of energy transport. Out of the total energy, only the active energy can be used for powering electrical equipment. Having much reactive power present on the grid means that either current or voltage needs to be increased in order to transfer the same amount of useful energy. Voltage is kept at relatively constant levels in a distribution system and hence current is the variable changing depending on the magnitude of transferred energy. This has negative implications for both efficiency of the distribution and the electricity system as a whole (Alaküla *et al.,* 2011) since:

- More current has to be transported to achieve the desired energy delivery
- Larger current causes higher losses due to the joule effect

Modern power technology is used to regulate reactive power and in turn regulate voltage. Capacitor banks are used for generating reactive power, increasing voltage when needed. Shunt reactors are used for consuming reactive power and decreasing the voltage. (T. Lundgren and K. Berg, personal communication, February 24, 2016).

CHAPTER 3
RISK

Risk is a well-debated concept (Barbu & Capuşneanu, 2011) and risk might be perceived differently. It is therefore described below along with other notions regarding risk management in order to clarify how risk is defined by the authors.

3.1 DEFINITION OF RISK

When working with risk management one of the most difficult things is to define risk (Magnusson, Nilsson, Hallin & Lenntorp, 2000). The differing views on risk can be divided into two categories, technical and social constructive.

The technical view of risk

The technical view is presupposed as objective where the risks can be quantitatively defined. Barbu and Capuşneanu (2011) define risk as the probability of an event where the result is unwanted. Kaplan and Garrick (1981) define risk qualitatively as a combination of uncertainty and damage. They explain that since a risk analysis is used to foresee the future regarding the impact of our decisions and actions, the analysis should answer three questions:

(i) What can happen? (I.e. what can go wrong?)
(ii) How likely is it that that will happen?
(iii) If it does happen, what are the consequences?

To describe the risk quantitatively Kaplan and Garrick (1981) presents following equation:

$$R = [(S_i, L_i, C_i)] \qquad \text{EQ 11.}$$

S_i is a defined risk scenario, L_i is the likelihood of the risk scenario and C_i is the consequence or the appreciation of the potentially inflicted damage. They claim that this definition is more accurate, that risk should be viewed as likelihood and consequence rather than likelihood times consequence. The latter definition equates low-likelihood and severe-consequence with high-likelihood and negligible-consequence, which is obviously not the same. Renn (1998) states that a technical view on risk alone is too narrow. The definition of risk as either the sum or product of likelihood and consequence is not enough to comprehensively describe the concept of risk. He points out that the technical view has shortcomings such as personal values can affect how risks are estimated and perceived. Hence, an objective risk analysis is not possible.

The social constructive view of risk

The social constructive view implies that risks are perceived subjectively, based on perception and social relations (Magnusson *et al.*, 2000). It is not optimal to assess risks only from what people see and feel is a risk. This is because former experience and anecdotal evidence affects our perception and hence we as humans might focus on and fear the "wrong" risks (Renn, 1998). Nilsson (2003) brings up some examples of what affects our acceptance of risk negatively, including involuntary exposure, lack of experience with the risk, lack of control over the situation and uncertainty regarding the likelihood and/or result of an unwanted event.

To summarize, it is practical and more accurate to use a mix of the technical and social view on risk. Magnusson *et al.* (2000) states that combining the two views gives a holistic and full covering risk analysis. Since the qualitative part of the risk assessment in this report is based on interviews, the outcome of the risk evaluations have probably been affected by social values.

3.2 Risk Scenarios and Consequences

In the qualitative study future risk scenarios are identified. This section explains the notion of a risk scenario and how it relates to consequences. Categorization of consequences is also explained. This will contribute to a better understanding of the results in Chapter 4.

3.2.1 Risk Scenarios

When performing a risk or vulnerability assessment it is common to use either a scenario based perspective or a system based perspective. The scenario based focuses on scenarios that might occur in a system and investigate these, whereas a system based perspective focuses on the system and describing it (Johansson & Jönsson, 2007, and MSB, 2011). Risk or vulnerability assessment methods using the system based perspective are detailed and not always possible to perform on complex systems. One advantage of using scenarios based methods is that they are easy to understand by people without risk experience (MSB, 2011). When performing a risk analysis using risk scenarios, one should look at the unwanted scenarios that can occur in the system i.e. the scenarios that cause a deviation from the wanted scenario of the system. The wanted scenario i.e. the system remaining in the preferred state, is often called S_0. The unwanted scenarios are S_i where i is the number of the unwanted scenario (Kaplan, Haimes, & Garrick, 2001).

The wanted scenario in regards to an electrical distribution system is defined by the authors as: a good reliability of distribution, i.e. the ability to deliver electricity to end users with the right quantity, quality and timing. Hence, the risk scenarios in this report are scenarios that might affect the distribution of electricity negatively.

3. 2. 2 Consequences

The consequence will vary depending on the perspective used in the assessment. A wanted result for one actor might be an unwanted result for another. For every risk scenario there is at least one consequence, it is also possible that different scenarios lead to the same consequence (Johansson & Jönsson, 2007). This can be seen in Chapter 4, Results and Analysis, where several future risk scenarios lead to the same consequence.

There are four practical ways to describe consequences according to MSB (2011):
- Solely qualitatively
- Qualitatively using a rating scale
- Solely quantitatively

- Quantitatively using a rating scale

The authors have chosen to describe the consequences qualitatively using a rating scale when answering the first part of the research questions. In answering the second part of the research questions, the consequences of two risk scenarios are studied quantitatively.

The direct consequences are often identified first. This constitutes the base for an evaluation of the environmental, economic and human related consequences (Davidsson, Postgård & Hardestam, 2003). The authors have chosen to define both the direct consequences of the risk scenarios as well as having a social, economic or environmental impact.

3.3 Risk management

Risk management consists of risk analysis, risk evaluation and risk reduction. This section aims to explain what risk management is and what approach the authors have chosen for the study.

3.3.1 A Qualitative Approach

Risk assessments can be performed in several ways depending on the character of risks that are involved. Risk management is typically approached in three different ways.

- Quantitatively
- Semi-quantitatively
- Qualitatively

This categorization is based on the degree of quantifiability. Quantitative methods define risks and consequences numerically. The semi-quantitative method contains to some extent quantification of likelihood and consequences. This could be classifying likelihood or consequences into intervals or categories (Nilsson, 2003).

However, in identifying risks a qualitative method is preferred (Magnusson *et al.* 2000 and Nilsson 2003). It is used to describe scenarios and events and to compare risks (Kaplan & Garrick, 1980). Likelihood and consequence is not quantitatively determined but instead compared and roughly appreciated. Therefore a qualitative coarse risk analysis was used during this Master Thesis to identify the future risk scenarios.

Nilsson (2003) has compiled a structural scheme over the different parts of risk management, using the standards from the International Electrotechnical Commission, IEC. This has resulted in a three step process, see figure 14 below.

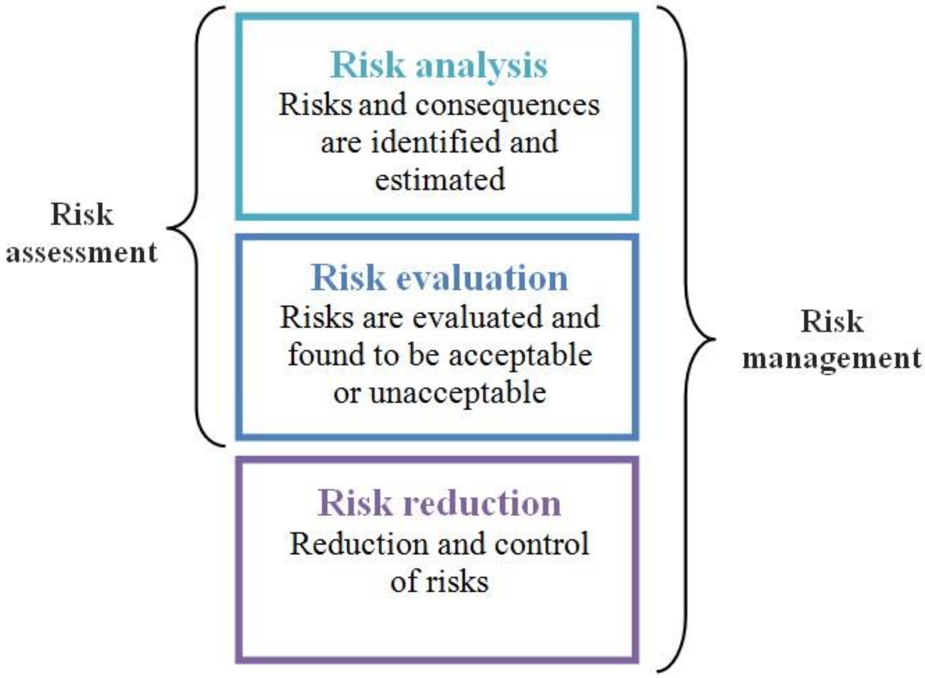

FIGURE 14. AN OVERVIEW OF THE PROCESS OF RISK MANAGEMENT. AUTHOR'S INTERPRETATION AND DEPICTION (NILSSON, 2003)

The three steps are explained further in the upcoming sections.

3.3.2 Risk Analysis

The first step is risk analysis where the risks and consequences are identified and evaluated (Nilsson, 2003).

3.3.3 Risk Evaluation

The second step is risk evaluation where the identified risks are evaluated and found to be acceptable or unacceptable (Nilsson, 2003). There are no clear guidelines for what is acceptable or not. The benefits and the disadvantages of the risk reducing measures are weighted in order to establish whether they should implemented or not (MSB, 2011).

Risk analysis and risk evaluation are together referred to as the risk assessment (Nilsson, 2003), see figure 16 above.

The evaluation of risks is done only in order to rate the urgency of addressing the identified risks and not the estimated likelihood of the risks. The evaluation is based on both likelihood and severity. No evaluation of what measures need to be taken is done.

3.3.3.1 The Risk Matrix as a Risk Evaluating Tool

One tool that is useful when performing risk evaluation is the risk matrix. One axis represents the likelihood of the occurrence and the other the severity of the consequence. The consequences can be either on a qualitative or quantitative scale. The probability and the consequence can be weighted together, giving an overall evaluation of the risk. An example of a qualitative risk matrix can be seen below in figure 15. Both axis are rated on a conceptual scale. Colors like in the figure 15 are commonly used to represent e.g. an acceptable risk (green) or unacceptable (red). The risk matrix is a simple tool but is useful to get an overview of the risk scenarios (MSB, 2011).

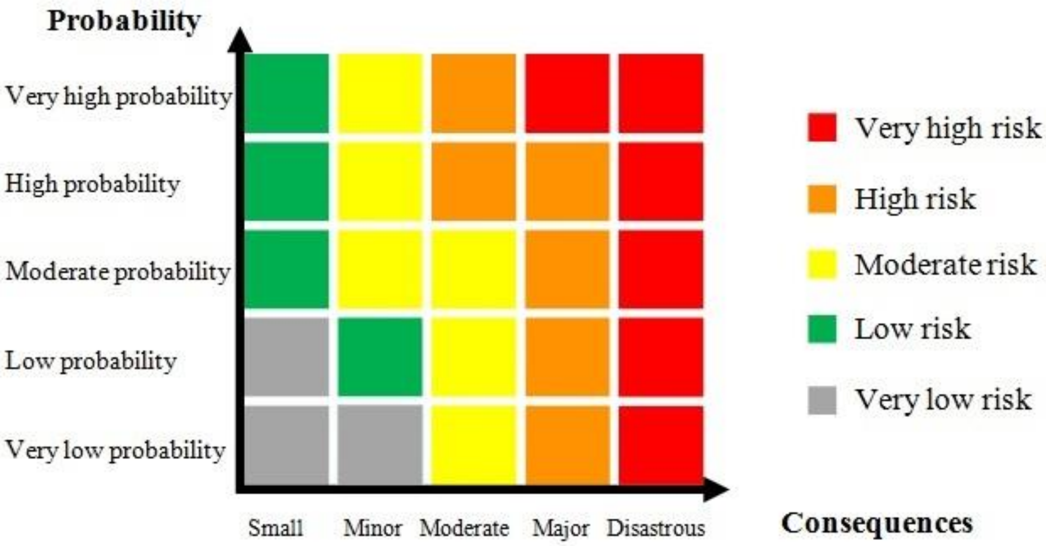

FIGURE 15. EXAMPLE OF A QUALITATIVE RISK MATRIX (MSB, 2011 AND JOHANSSON & JÖNSSON, 2007). AUTHORS' DEPICTION.

3.3.4 Risk Reduction

The methodology in this section is described in accordance with the literature. Only suggestions of risk reduction measures are included in section 4.1.6.2.

If any of the risks are found to be unacceptable in the risk evaluation, risk reducing measures should be suggested. Attempts to control or reduce the likelihood or severity of the consequences are made in the last step of the risk management process (Nilsson, 2003). Magnusson *et al.* (2010) explains that there are no clear principles regarding risk reducing measures since every risk and situation is unique and therefore requires its own assessment and solution.

CHAPTER 4
RESULTS AND ANALYSIS

In chapter 4 the results of the qualitative and the quantitative study are presented. The two studies are connected through the section 4.2 Choice of Risk Scenarios. The results in the qualitative study are analyzed and commented. The analysis borders on a discussion, but is kept in the same section as results in order to keep the reasoning stringent.

4.1 QUALITATIVE STUDY

The qualitative study is based on interviews, a survey and a literature study. This part of the Thesis aims to identify and assess the risk scenarios that the DSOs face in following an increasing share of WP and PV generation. In the sections The Risk Analysis, The Risk Evaluation and The Risk Reduction the technical risk scenarios are treated. Managerial and economic issues are presented in its section. They are more speculative and relate to business strategy in a broader perspective.

4.1.1 THE RISK ANALYSIS

The main technical aspects identified in the interviews and surveys are presented in this chapter. They have been identified by the interview subjects as the most challenging aspects for DSOs. The outline of the next chapters is divided up in order to answer the questions suggested by Kaplan and Garrick (1981):

> (i) What can happen? (i.e., What can go wrong?)
> (ii) How likely is it that it will happen?
> (iii) If it does happen, what are the consequences? (s. 13)

However, since the change in likelihood is treated question (ii) was changed to:

> (ii) What is the change in likelihood?

When further explanations are necessary, additional literature sources are provided. In order to maintain stringency throughout the analysis, technical explanations of the phenomena will be kept to a minimum. Chapter 2 provides the necessary technical background. Six technical future risk scenarios have been identified. An overview of the identified future risk scenarios and their consequences can be seen below in figure 16.

Risk Scenario / Consequence	Uncontrolled Islanding	Increased Distribution Losses	Overvoltage on the Grid	Unacceptable Levels of Reactive Power	Undesired Events due to Unmanageable System*	Harmonics on the Grid
Electrocution of People and Animals	X					
Fire Hazard	X					
Damage to Utility Equipment	X		X	X		X
Damage to Customer Equipment/Property	X		X			
Decreased Efficiency		X		X	X	X
Lower Competitiveness			X			X
Blackouts/ Disturbances			X		X	

FIGURE 16. AN OVERVIEW OF THE IDENTIFIED FUTURE RISK SCENARIOS AND THEIR CONSEQUENCES. A BLUE DOT INDICATES ECONOMIC IMPACT, GREEN ENVIRONMENTAL AND PURPLE SOCIAL IMPACT. *UNDESIRED EVENT DUE TO UNMANAGEABLE SYSTEM ALSO HAS UNFORESEEN CONSEQUENCES

4.1.1.1 UNCONTROLLED ISLANDING

What can happen?

Uncontrolled islanding can occur when a portion of the grid, for any given reason, loses electrical contact with the rest of the distribution system. During normal operations, the connection to the rest of the grid provides power and regulatory capacity in order to match supply with demand. The island phenomenon arises when power is provided from within the isolated subsection, which has no internal capability to regulate operational parameters. Uncontrolled islanding becomes a problem when one or more protective mechanisms fail, or have not been put in place (M. Andersson, interview, December 11, 2015). An example of this is when frequency derivative protection system, which modern wind tubes are equipped with to help detect islanding, fail (P. Thuring, survey, March 29, 2016). Even a small amount of net output on the grid will result in an increasing voltage in the components of the electrical system. Everything from lines, to transformer stations and the electrical sockets of consumers become charged (M. Andersson, interview, December 11, 2015).

As long as generation and consumption is matched and the voltage and frequency is kept within the right intervals, the islanded grid will run independently of the rest of the grid. This balance is however extremely rare without proper automatic regulation. If too much power is generated, the voltage and frequency will increase, the opposite happens when too little is generated. (M. Andersson, interview, December 11, 2015).

What is the change in likelihood?

Sgarbossa, Lissandron, Mattavelli, Turri & Cerretti (2014) identifies the increase of distributed PV as the main concern for increased likelihood of uncontrolled islanding. Generally speaking, the increasing number of generation units spread out on foremost low voltage grids increases the risk of faulty or absent protective devices. Furthermore, existing automatic reclosure functions at substations may also be a risk, as the system would try to re-close its circuit during a time when the islanding effect has distorted the frequency on the system. M. Andersson (interview, December 11, 2015) stresses the importance of following standards for protective devices, the importance of which might not be prioritized or known by the owner of a non-registered generation unit.

The survey indicates that the respondents believe that there will an increase in likelihood for Uncontrolled Islanding when more WP and/or PV is implemented, see table 1 below. A. Andersson (Survey, March 22, 2016) also stated that the likelihood is largely dependent on how well the standards of protective devices are implemented. A. Larsen (Survey, April 1, 2016) highlighted the importance of having a well-functioning system for controlling individual units remotely.

TABLE 1. CHANGE IN LIKELIHOOD OF UNCONTROLLED ISLANDING

	Class 1 *Substantial decrease in likelihood*	Class 2 *Decrease in likelihood*	Class 3 *No change in likelihood*	Class 4 *Increase in likelihood*	Class 5 *Substantial increase in likelihood*	**Weighted Average**
Uncontrolled Islanding	0 %	0 %	29 %	71 %	0 %	3.71

What are the consequences?

- *Damage to utility equipment.* Some utility equipment cannot handle an elevated voltage. Overvoltage in relation to equipment means operating outside of their span of tolerance, resulting in electrical overstress (P. Thuring, personal communication, April 29, 2016). Hence overvoltage can damage transformers and other electrical components of the grid, either reducing efficiency, putting them out of service, or shortening their life expectancy (M. Andersson, interview, December 11, 2015). Uncontrolled generation of electricity within the disconnected grid distorts frequency and voltage, which is mismatched with the rest of the grid. This makes reconnection problematic, potentially further damaging utility equipment when reconnecting (S. Schmidt, interview, January 13, 2016). Re-connecting without matching frequency or level of voltage is known as out of phase reclosure. That can severely damage substation equipment both within the affected grid section and "upstream" in the system. Damaging more of the equipment also prolongs blackouts and possibility to restore the functions of the grid (Ding & Crossley, 2005).

- *Damage to customer equipment/property.* Also customer components can be damaged due to "out-of-phase reclosure" and elevated voltage. Many industries and other electricity intensive operations require a stable voltage, as not to damage their equipment and ongoing industrial processes (Short, 2004).

- *Fire hazard*. When too much power is fed to the disconnected grid it can cause electrical discharges and thereby fire (M. Andersson, interview, December 11, 2015). Fire hazard is a potential danger to people, the environment and property.

- *Electrocution of people and animals*. Charged household appliances and other conducting objects are a danger to people and property. It is perhaps most dangerous for the technicians working on the actual distribution hardware. There are routines for checking for electrical charge of the equipment being worked on, as well as double checking the registered generation units connected to the grid. The likelihood of accidents increases in stressed situations during e.g. massive infrastructure failure. Situations have occurred where technicians work around the clock to restore the functions of the grid, in both light and dark. Such working conditions increase the risk of making mistakes or making hasty decisions (A. Andersson, interview, January 11, 2016 and M. Andersson, interview, December 11, 2015).

4.1.1.2 Increased Distribution Losses

What can happen?

The losses referred to in this section deal with the heat losses due to the Joule effect. Losses occur also in e.g. in transformers, but such losses will not be thoroughly assessed. In short, the distribution losses in a one phase system increase in a squared relationship with the current times resistance as described in section 2.4. The implication of this relationship is that losses are much higher at times of large currents.

The interview subjects describe the relationship between distribution losses and DG as duplex, i.e. installation of DG can either increase or decrease the losses in a grid (S. Schmidt, interview, January 13, 2016, P. Sørensen, interview, January 15, 2016 and P. Thuring, interview, December 17, 2016). How much energy is saved or lost is not simply a function of how much is installed, but also on the installations e.g. location, to what voltage, type of generation and adjacent consumption patterns (M. Andersson, interview, December 11, 2015).

First off, shorter distribution paths decrease losses. DG systems connected to individual consumers and with a production less than the domestic use, e.g. roof mounted WP or PV, will decrease losses because less transport is needed to the facility. DG connected to areas of high consumption can also eliminate some of the distribution losses, as electricity is provided from nearby (S. Schmidt, interview, January 13, 2016, and P. Thuring, interview, December 17, 2016). When DG generation matches consumption within an area, many of the lines have low net transport, as some of the power is supplied from within a small subsection of the grid. The net exchange with the closest overlying substation will be near zero, eliminating also some of the losses in the transformer. Placing large scale WP can also have the same effect if placed in proximity to areas with correspondingly large consumption to use the generated power. Interviews (S. Schmidt, interview, January 13, 2016, P. Sørensen, interview, January 15, 2016 and P. Thuring, interview, December 17, 2016) conclude that distributing WP and PV with location in mind can reduce losses.

It is when generation exceeds consumption in a section of a grid that the relationship is reversed. Large surplus cannot be consumed, making it necessary for either transport to other areas of consumption or in extreme cases having to stop the generation (S. Schmidt, interview, January 13, 2016 and P. Sørensen, interview, January 15, 2016). The generation of both PV and WP varies stochastically and favorable weather conditions often occur simultaneously for units within a smaller geographic area, resulting in spikes in generation.

The placement of WP is often rural, where land is cheap and wind plentiful, resulting in wind parks far from consumption. N. Broman (interview, January 18, 2016) explains that the prevailing factors for wind park placement is availability of affordable land and the wind conditions at the site. Consideration for the grid placement is not regarded as important in the eyes of an investor. Today much of the large WP plants are connected directly to the medium or high voltage grids, due to the increasing capacity of individual turbines. The high voltage at these levels cause relatively low losses over long distances, however the effect can be present on a larger system level as well.

As PV is primarily installed as small scale DG in Sweden, the low voltage grids with higher impedance have to transport the surplus. These lines experience higher losses due to the low voltage level (i.e. high current) and high impedance of the lines. They are generally of a radial structure, which results in long transport distances when surplus is generated in an area (Aláküla *et al.,* 2011). Enough generation results in volumes having to be transferred up to higher voltage grids in order to reach other areas of consumption. This means losses increase in transformers and also due to the extra transport distance. An example from Germany is given in the next section.

The relationship is further complicated by the fact that installations of DG makes additional reinforcements to the grid necessary. Lines, cables, transformer substations and other distribution components might need to be reinforced in order to handle the potential maximal currents that additional generation infers. The reinforcements in Sweden are always dimensioned to handle 100% of the added generation capacity plus the previous peak load. These reinforcements provide the grid with overcapacity at normal loads, decreasing transport losses when loads are normal (S. Schmidt, interview, January 13, 2016 and Abo-Khalil, 2013). So, although DG can cause higher losses in the grid, the enhanced capacity of the grid that their implementation requires might help decrease the overall losses (S. Schmidt, interview, January 13, 2016).

What is the change in likelihood?

The effects of DG on losses is documented and acknowledged by the Swedish Energy Market Inspectorate (EI). Several reports verify the increase in losses due to PV and WP (Energimarknadsinspektionen, 2015).

If enough peak power is installed within the country, as in the case of Denmark, large volumes of WP generation have to be transported over long distances and often exported outside country boundaries. T. Fonnesbæk and T. Skødt (interview, January 19, 2016) explain that Denmark is dependent on transferring surplus to neighboring countries in order to maintain their power balance. Typically, when favorable wind conditions occur in one northern country, the bordering countries with WP also experience good conditions. That creates surplus generation within a larger geographical area, making it necessary to transport large volumes even further. Long transport distances and large flows contribute to creating high losses (P. Sørensen, interview, January 15, 2016).

The same type of situations occur with conglomerates of decentralized PV generation. S. Schmidt (interview, January 13, 2016) stressed this problem with PV in the Bavarian part of Germany, where ca 250 000 PV plants are connected to the grid operated by Bayernwerk. Demand is rarely matched with peak generation, making it necessary for distribution over the weak low voltage grids up to the higher voltage grids and further on to where the electricity can be used. The mismatch of consumption and generation is present in both the short and long term. Yearly peak generation occurs in the summer, whereas peak demand occurs during the colder months in the winter. Peak generation during the span of a day occurs around 12:00-13:00 pm, mismatching peak consumption which occurs during mornings and evenings. As of yet, consumption flexibility of the market is low, making it necessary to either export electricity to where it can be used or reduce generation. Negative prices that have started occurring in Denmark during peak generation have created a willingness among customers to make their consumption more flexible (T. Fonnesbæk and T. Skødt, interview, January 19, 2016).

The survey indicates that the respondents believe that there will probably be an increase in likelihood for Increased Distribution Losses when more VP and/or PW is implemented. See table 2 below. As seen the opinions vary.

TABLE 2. CHANGE IN LIKELIHOOD FOR INCREASED DISTRIBUTION LOSSES

	Class 1 *Substantial decrease in likelihood*	Class 2 *Decrease in likelihood*	Class 3 *No change in likelihood*	Class 4 *Increase in likelihood*	Class 5 *Substantial increase in likelihood*	**Weighted Average**
Increased Distribution Losses	0 %	14 %	43 %	29 %	14 %	3.43

What are the consequences?

- *Decreased efficiency*. Electricity that could have been used goes to waste. This results in a system with an overall decreased efficiency (S. Schmidt, interview, January 13, 2016, P. Sørensen, interview, January 15, 2016 and P. Thuring, interview, December 17, 2016). The consequence for the DSO is having to compensate for the lost energy through purchasing or generating the equivalent amount. The cost of losses is covered in the revenue granted by EI, but an incentive is being put in place, which will make DSOs responsible for 50% of the increase (A. Larsen, interview, February 11, 2016 and R. Nilsson, interview, February 2, 2016).

4.1.1.3 Overvoltage in the Grid

What can happen?

The traditional situation in a grid is that voltage decreases from the place of generation down to the place of consumption. It is the impedance of lines or cables that causes voltage to fall during the course of transport. To compensate for this the voltage is slightly raised at the transformer substations, raising it to a level that is predicted to decrease during the course of the transport distance. With small scale DG in the end of lines, voltage is elevated where it previously was at its lowest. This causes a rise in voltage in the periphery of the grids, affecting also the overlying transformer stations where it is regulated.

On a medium voltage grid, the voltage is more easily regulated. The system is more stable on medium voltage grids, where large power plants provide stability and regulatory power. Large WP power plants connected to high voltage grids have strictly set demands on the influence on voltage. The norm for installing new generation units is that they should have little or no influence on voltage (Larsson & Larsson, 2006). Voltage support with reactive power is becoming a common feature in WP, which is installed in agreement with the affected DSO (F. Roos, interview, January 15, 2016).

The main concern with PV is its placement in low voltage grids with high impedance. One difficulty with voltage in regards to DG lies in the limited monitoring and regulation within the low voltage grids, making it difficult to properly compensate for DGs effect on voltage. The fluctuations on the lower grids are greater, as consumption in a small section of the grid varies more than the aggregated fluctuations of several grids. This means that the regulation on low voltage grids need to be more responsive, able to cope with larger relative fluctuations. (Schmidt, interview, January, 2016)

What is the change in likelihood?

S. Schmidt (interview, January 13, 2016) explains that in Bavaria, high PV generation coinciding with low consumption creates serious problems with elevated voltage. A subsequent problem is the sudden cut out of generation that intermittent power sources such as WP and PV often experience. The availability of both solar radiation and wind varies in the short term with abrupt changes. A stop in generation reduces the voltage during a short period of time until it can be compensated for. The challenge is maintaining the ability to cope with faster and larger variations. Regulation in the short term has become increasingly difficult with the rurally concentrated PV in Bavaria. The ability to regulate voltage in the very short term is possible within a limited range.

A. Andersson (interview, January 11, 2016) does not believe that the voltage limits have been a priority for PV installed within the grids of Sweden. The almost negligible capacity installed has not caused any reason for concern and E.ON has rather encouraged the installations of PV.

Large scale WP is today well-regulated and the demands for voltage fluctuations put out on the grid strictly set (P. Thuring, survey, March 29, 2016). The question now is to what extent they should be able to help regulate voltage on the grid instead of having little or no influence at the point of connection. Fonnsbæk and Skødt (interview, January 19, 2016) explain that WP used to cause problems with voltage back when the asynchronous generators of old WP were poorly regulated. Neither of the aforementioned interviewees can recall any unmanageable problems with voltage due to WP in the grids of Energinet.dk or E.ON.

The survey indicates that the respondents believe that there will be an increase in likelihood for Overvoltage on the Grid when more VP and/or PW is implemented. See table 3 below. However, no change in likelihood is also often responded.

TABLE 3. CHANGE IN LIKELIHOOD FOR OVERVOLTAGE IN THE GRID

	Class 1 *Substantial decrease in likelihood*	Class 2 *Decrease in likelihood*	Class 3 *No change in likelihood*	Class 4 *Increase in likelihood*	Class 5 *Substantial increase in likelihood*	**Weighted Average**
Overvoltage on the Grid	0 %	0 %	43 %	57 %	0 %	3.57

What are the consequences?

- ***Damage to utility equipment.*** Damage due to elevated voltage, see uncontrolled islanding
- ***Blackouts.*** Damage to utility components causes the grid to malfunction, leaving customers without electricity.
- ***Damage to customer equipment/property.*** Damage due to elevated voltage, see Uncontrolled islanding.
- ***Lower competitiveness.*** Worsened electricity "quality" in terms of voltage stability creates lower competitiveness for attracting energy intensive industries panning to connect to the grid (F. Roos, interview, January 15, 2016).

4.1.1.4 Unacceptable Levels of Reactive Power

What can happen?

The concept of reactive power is not easy to grasp. The capacity of the lines is designed for apparent power, the vector sum of active and reactive power. This is a physical limiting factor for the transport of electricity on the grid. The most common problem with reactive power is that it occupies the capacity of lines and cables, which could have been used for transporting active power. In short, presence of reactive power flow means that not all of the power delivered to the grid can be converted to useful energy at the place of consumption. High apparent power means that more current needs to be transported in order to achieve the same amount of useful power. The increased current causes higher heat losses due to the joule effect, see section 2.4. Reactive losses also occur in transformers, where it heats the transformer.

Reactive power added to the grid generally causes voltage to rise. This feature is used for regulating voltage on the grid by utilizing capacitor banks. It also means that too much reactive power added to the grid can cause voltage to rise to unacceptable levels (T. Lundgren and K. Berg, personal communication, February 24, 2016).

Some electrical equipment requires reactive power for startup and operation. Hence, the lack of reactive power support can also be a problem. Electricity intensive customers are the biggest contributors to reactive power flow. Their power demand on the grid is continuously measured. DSOs charge these customers according to their contribution. F. Roos (Interview, January 15, 2016) explains: DSOs take care of the problems generated within the facility, the phase shift created from their electrical equipment. If customers take reduce their reactive power put on the grid, they can reduce the cost charged by their affected DSO.

What is the change in likelihood?

The old models of both WP and PV had poor qualities in regards to reactive power. The old WP plants generated reactive power on startup and neither had the ability to actively control it (M. Andersson, interview, December 11, 2015). It is standard for WP installed today to have a net zero exchange of reactive power with the grid it is connected to (Larsson & Larsson, 2006). Figure 17 below shows the reactive power from a modern wind turbine that is exported to a low voltage grid. The red lines are the grid code acceptance levels.

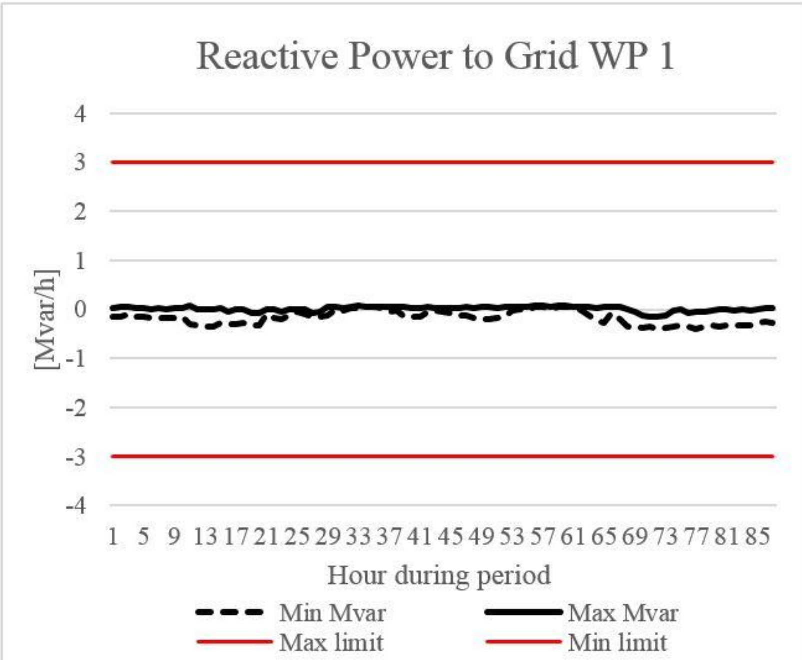

FIGURE 17. REACTIVE POWER FROM A WP PARK TRANSFERRED TO A LOW VOLTAGE GRID. PLOT BY AUTHORS, DATA FROM E.ON.

According to F. Roos (Interview, January 15, 2016) WP has not detrimentally impacted the levels of reactive power flow on the grids of E.ON, despite many large installations. T. Lundgren (Personal communication, February 24, 2016), a systems operation manager at E.ON Elnät, has a hard time recalling problems in regards to reactive power in the grids operated by E.ON. He adds that an effect of building better capacity in the grid (larger dimensioned cables) is that they also create more reactive power during low load situations. The possibility for DG to support reactive power could in those situations help to consume it.

K. Berg (Personal communication, February 24, 2016) points out that the rule of little or no reactive power contribution from generation units might not be the best option for creating a stable grid in terms of voltage control. Being able to not contribute is in itself a good thing, but if troubling levels of reactive power is present on the grid to which the generation is fed, the possibility to compensate with reactive power from WP might be beneficial for the system. DG could in that way help support voltage and reactive power on the grid where it is connected.

According to A. Andersson (Interview, January 11, 2016), the norms for reactive power exchange have not yet been followed as strictly when connecting PV. The regulation described in the previous section can also be used for PV system, as the technology has become both cheap and effective. The problems with reactive power are most accentuated on weaker grids with high capacitance, which is why the problem is more serious for the small PV systems. The capacitance on the lines and cable raises voltage. S. Schmidt (Interview, January 13, 2016) stresses the voltage issues created from distributed PV plants in Bavaria, which are mostly connected to low voltage grids.

The weighted average in the survey indicates that there will probably be an increase in likelihood of Unacceptable levels of reactive power when more WP and/or PV is implemented. See table 4 below. No change in likelihood has been responded more often than increase in likelihood.

TABLE 4. CHANGE IN LIKELIHOOD FOR UNACCEPTABLE LEVELS OF REACTIVE POWER

	Class 1 *Substantial decrease in likelihood*	Class 2 *Decrease in likelihood*	Class 3 *No change in likelihood*	Class 4 *Increase in likelihood*	Class 5 *Substantial increase in likelihood*	**Weighted Average**
Unacceptable Levels of Reactive Power	0 %	0 %	57 %	43 %	0 %	3.43

What are the consequences?

- ***Damage to utility equipment.*** Consuming or generating reactive power to the grid reduces or increases voltage. Voltage deviations in turn can cause damage to grid components (P. Thuring, interview, December 17, 2016).

- ***Decreased efficiency.*** Decrease in distribution capacity throughout the system. Reactive losses, including overcurrent and heating of transformers (P. Thuring, interview, December 17, 2016).

4.1.1.5 Undesired Events due to Unmanageable System

The effects on an increasingly complex system can be summed up in two rough categories.

Management of a more complex system

This aspect relates to the practical issues regarding the vast amounts of data and variables that is necessary for controlling the distribution system. New functions for monitoring and regulation of distributed generation are desired, active generation and voltage regulation for example. Responsibility for power balance, electricity quality, and controlling individual generators etc. is assigned to different actors using different forms of communication, methods and personnel for conducting their tasks. The overall management can prove dysfunctional, as the number of tasks and parts of the system increase. Also the data volumes handled grow larger with more generation units and more monitored parameters. This concern was raised when interviewing A. Andersson (interview, January 11, 2016). The increased amounts of data and the desire to control the generation demands more autonomous communication and regulation technology. This remote management of numerous generation sources is commonly referred to as smart grid technology (4C Strategies, 2013). Also A. Larsen (Survey April 1, 2016) expresses the need for a more comprehensive grid management system to cover all monitoring and regulation. (4C Strategies, 2013) identifies risks associated with the "human factor" as the most severe threats to the operation of smart grid technology. Furthermore, they identify the following risks due to more autonomous regulation and larger volumes of data in distribution systems:

- "Malicious intent and acts of terror
- Competency shortage
- Behavior not in line with automation and regulation
- Lack of standardization, hampering communication
- Unclear apportion of responsibilities"

Author's translation of the cited text (4C Strategies, 2013, p. 13).

Also F. Roos (interview, January 15, 2016) highlighted the unclear responsibilities for regulating small generation units. The uncertainty regards whether the active regulation technology of voltage and reactive power is to be placed within the bounds of the generation system or not. The alternative would be placing it on the DSO side, assigning all responsibility for regulation and its costs to the DSO. The decision can have adverse effects on the system, if for example numerous units independently regulate voltage. That could e.g. cause feedback loops between generation clusters that accentuate oscillations of voltage as they take turns in compensating up and down. Such unforeseen effects belong to the next paragraph.

Unforeseen effects and synergies

This second aspect of the increased complexity is of a more speculative variety. The distribution system is managed by various actors, technologies, regulation systems etc. With such a vast operation, the possibility for overview and large scale coordination becomes increasingly difficult, especially generation market in an extensive structural change. With this comes the possibility of unforeseen effects on operational security. Heylighen, Cilliers & Gershenson (2007) explain that a complex system does not only consists of its different parts but also on how the parts relate to each other. Some parts work independently and others are dependent on each other. The system is often more than simply the sum of its parts. This means that there are risks and events that are not possible to foresee or to estimate in regards to their extent (Heylighen, Cilliers, & Gershenson, 2007).

What is the change in likelihood?

The survey indicates a belief that there will probably be an increase in likelihood for Undesired Events due to Unmanageable System when more WP and/or PV is implemented. See table 5 below. However, no change in likelihood is also often responded.

TABLE 5. CHANGE IN LIKELIHOOD FOR UNDESIRED EVENTS DUE TO UNMANAGEABLE SYSTEM

	Class 1 *Substantial decrease in likelihood*	Class 2 *Decrease in likelihood*	Class 3 *No change in likelihood*	Class 4 *Increase in likelihood*	Class 5 *Substantial increase in likelihood*	**Weighted Average**
Undesired Events due to Unmanageable System	0 %	0 %	43 %	57 %	0 %	3.57

What are the consequences?

- *Blackouts/disturbances.* P. Thuring (Survey, March 29, 2016) explains that Undesired events due to unmanageable system can cause blackouts.

- *Decreased efficiency*. When the apportion of responsibility is unclear problems might be left unsolved for longer time periods (4C Strategies, 2013).

- *Unforeseen Consequences.* There could be relations that are not possible to foresee in a "new" system and as a result cause unknown consequences (Heylighen, Cilliers, & Gershenson, 2007).

4.1.1.6 HARMONICS ON THE GRID

What can happen?

The harmonics problem has been a concern for some time, since household appliances which generate harmonics and renewable energy sources have constantly been increasing during the last decades (F. Roos, interview, January 15, 2016). The inverters of both PV and WP, which convert direct current into alternating current do not function perfectly, but are continuously improving (M. Andersson, interview, December 11, 2015). The conversion to alternating current can have the side effect of producing harmonics, which are multiples of the fundamental frequency of 50Hz. Harmonics affect the voltage frequency, which becomes distorted, not following the wanted sinus curve.

What is the change in likelihood?

Bollen (2009) claims that harmonics is an increasing problem, but none of the interviewed have mentioned harmonics as a significant problem. Surprisingly enough, the same people evaluated it as one of the risk scenarios that is more likely to increase in likelihood. Within grids operated by E.ON, the presence of harmonics has not reached unacceptable levels. When asked specifically about it, F. Roos (Interview, January 15, 2016) says that there have been some, but no large influences as a result of the installations of WP or PV that the grid has been subjected to. M. Andersson (Survey, April 4, 2016) explains that the limits set for harmonics is well regulated and enforced for new generation units.

The survey indicates that the respondents altogether expect an increase in likelihood of Harmonics on the grid when more WP and/or PV is implemented, see table 6 below. However, many also expect no change.

TABLE 6. CHANGE IN LIKELIHOOD OF HARMONICS ON THE GRID

	Class 1 *Substantial decrease in likelihood*	Class 2 *Decrease in likelihood*	Class 3 *No change in likelihood*	Class 4 *Increase in likelihood*	Class 5 *Substantial increase in likelihood*	**Weighted Average**
Harmonics on the Grid	0 %	0 %	43 %	43 %	14 %	3.71

What are the consequences?

- ***Damage to utility equipment.*** Damage to transformers and other electrical components. Harmonics stress generators and transformers which shortens their service expectancy. If too much harmonics are present in the distribution system, generators and other equipment may be damaged (F. Roos, interview, January 15, 2016). Equipment such as capacitors are overstressed, shortening their service expectancy or causing them to break down (Berglund & Åkerlund, 2004).

- ***Decreased efficiency.*** The presence of harmonics heats up transformers, causing losses and straining the equipment. (F. Roos, interview, January 15, 2016 and Berglund & Åkerlund, 2004).

- ***Lower competitiveness.*** "Quality" of electricity worsened, see chapter on overvoltage.

4.1.2 Risk Evaluation

The risk scenarios are compared using a matrix, similar to a risk matrix, to give an indication of which constitute the biggest threat. Respondents of the survey are asked to rate the future risk scenarios according to change in likelihood and the severity of its consequences. Figure 18 shows change in likelihood and severity plotted in order to establish what future risk scenarios are overall most problematic. The scale goes from least problematic furthest down to the left and most problematic furthest up to the right.

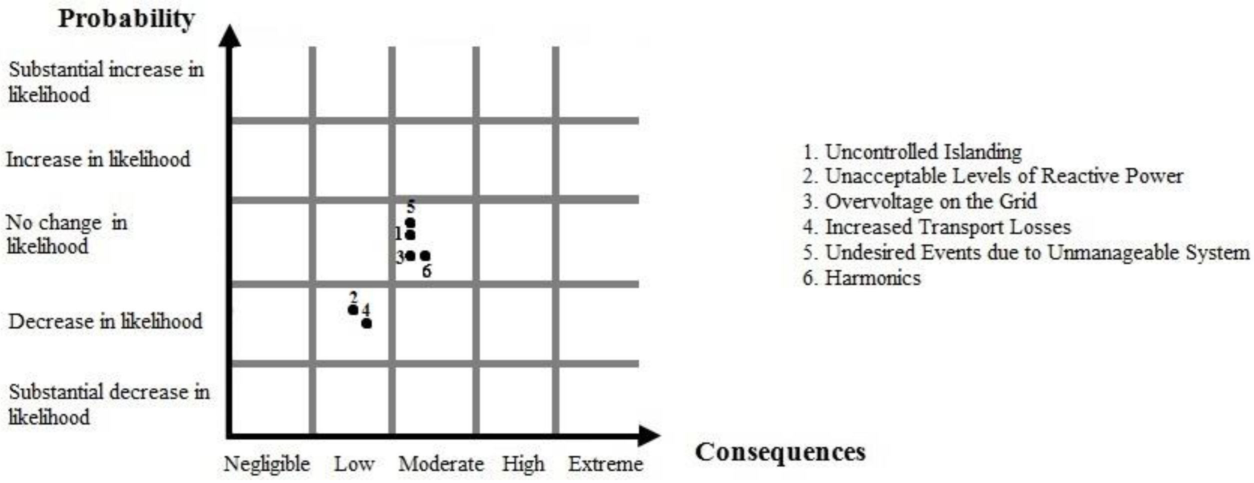

FIGURE 18. WEIGHTED CHANGE IN LIKELIHOOD AND SEVERITY OF THE MOST LIKELY CONSEQUENCE

Conclusively, the overall appreciation of change in likelihood and consequences by the respondents does not identify any of the future risk scenarios as particularly problematic. The four future risk scenarios Uncontrolled Islanding, Undesired Events due to Unmanageable System, Harmonics on the Grid and Overvoltage on the Grid are the most problematic according to their position in the matrix. The resolution of the matrix does not allow for distinguishing one as more problematic than the other. The answers in the survey often show a wide spread, making the average a rough estimation, See appendix D.

The change in likelihood of Unacceptable Levels of Reactive Power and Increased Transport Losses is expected by the respondents to decrease. The consequences of these risk scenarios are also considered low.

In the survey the respondents were asked to rank the future risk scenarios taking into account both the change in likelihood and severity of the consequence, see Appendix D for details. This resulted in the ranking presented in table 7. This ranking gives an indication of which future risk scenarios are overall most problematic and need the most attention. The average responses of the respondents ranked Uncontrolled Islanding as the biggest threat, followed by Undesired Events due To Unmanageable System. This way of ranking also shows Unacceptable Levels of Reactive Power and Increased Distribution Losses as the two least problematic risk scenarios.

TABLE 7. RANKING OF THE RISK SCENARIOS.

Rank	Risk Scenario
1	Uncontrolled Islanding
2	Undesired Events due to Unmanageable System
3	Harmonics
4	Overvoltage on the Grid
5	Unacceptable Levels of Reactive Power
6	Increased Distribution Losses

4.1.3 Risk Reduction

Below, suggestions for risk reducing measures are presented for each future risk scenario. These are identified from the information gathered in the interviews, the survey and the literature study.

4.1.3.1 Uncontrolled Islanding

Risk treatment/reduction

- *Documentation and communication.* Thorough documentation and communication routines before the installation of DG and connection to the grid. In case of a disruption where a grid is cut of, knowing where generation might be present and what units to turn off can help avoiding islanding problems. It will also make it easier to perform safe repairs in the grid during potential islanding situations (M. Andersson, interview, December 11, 2015).

- *"Microgrid" solutions - increased control.* Real time monitoring and regulation of grid subsections. Dividing up low voltage grids into smaller subsections and installing control mechanisms within these could allow for controlled islanding when loss of mains occurs. (Luu, N.A. 2014) Using only renewable energy, this option is on the research stage outside of Timrå (A. Larsen, interview, February 11, 2016). This type of solution could allow for some areas to not only avoid uncontrolled islanding, but be able to run independently of the rest of the electricity system when preferred (Short, 2004). A. Larsen (Survey, April 1, 2016) emphasizes the need for a better and more comprehensive control system.

- *Relay protection and voltage sensing equipment.* Installing proper over- and undervoltage relays to generators is fundamental for avoiding islanding. That means following the stipulated requirements when installing new generation units (A. Andersson, survey, March 22, 2016). A proper connection of any power source includes relay systems that sense voltage or frequency deviations on the line to which it is connected responding by disconnecting or regulating down generation. This is referred to as "passive protection". "Active protection" tries to alter the frequency output from normal levels and thereby detects loss of mains. The inertia on the grid will not allow an alteration during normal operation (Short, 2004).

4.1.3.2 Increased Generation Losses

Risk treatment/reduction

- *Location.* Steer investments in DG towards favorable locations. Preferable placement is in proximity to areas of high consumption, since shorter transport distance reduces the losses (P. Sørensen, interview, January 15, 2016).

- *Apply for increased revenue cap.* By establishing that higher losses are a consequence of RE, a DSO can apply for a higher revenue cap in accordance with the new regulations for the period 2016-2019 (Energimarknadsinspektionen, 2015). The losses within a grid will be further analyzed using data from the grids operated by E.ON. The possibility to prove WP as the cause of increased losses will there be further assessed.

- *Consumption flexibility.* Create incentives for flexible consumption to make use of local generation or identify new uses for peak generation (Söder *et al.*, 2014).

- *Storage.* Implementing storage capacity decreases the peak loads and the need to export generation surplus over long distances.

- *Increased voltage control.* Helps keep voltage stable and thereby losses (A. Larsen, Survey April 1, 2016). Can be done through reactive power compensation (M. Andersson, survey, April 4, 2016).

4.1.3.3 Overvoltage on the Grid

Risk treatment/reduction

- *Voltage regulation functions*. Voltage regulating equipment can be installed on generation units for both reducing individual impact and for helping the grid in compensating for fluctuations. Foremost the low voltage grids would benefit most from having voltage regulation in connection to DG (Vikesjö & Karlsson, 2013). The ability to communicate with and control individual units is technically viable, but hard to achieve with the numerous entities in use. Responsibility for the cost of this eventual regulation is not clearly established (P. Sørensen, interview, January 15, 2016). Voltage problems can also be assessed by increasing the capacity of regulating on secondary substations, as done in Germany (S. Schmidt, interview, January 13, 2016).

- *Consumption flexibility.* Consuming some of the energy where it is generated instead of exporting it to the grid reduces the eventual voltage elevation it would otherwise create (A. Andersson, interview, January 11, 2016 and S. Schmidt, interview, January 13, 2016).

- *Strict Requirements.* Strictly set limits for influence on the grid will minimize the aggregated influence of numerous generation units. New EU network codes are soon to be implemented, setting standards that F. Roos (Interview, January 15, 2016) believe will help avoid much of the problems associated with DG.

4.1.3.4 Unacceptable Levels of Reactive Power

Risk treatment/reduction

- *Reactors consuming reactive power.* Reactors placed at strategic points in the grid, consuming reactive power and leaving capacity for active power transport (P. Thuring, interview, December 17, 2016).

- *Reactive power regulation from DG.* The ability to have DG regulate reactive power can be beneficial for maintaining voltage level and compensating for irregular levels of reactive power on the grid. Reactive power support would have positive effects for both voltage stability and reduction of reactive losses. This regulation function can, in agreement with the affected DSO, be installed in connection to individual wind turbines and WP parks (M. Andersson, interview, December 11, 2015 and K. Berg, personal communication, February 24, 2016). Some WP systems are able to support with reactive power regulation even at zero wind speed. (P. Thuring, interview, December 17, 2016). PV can today also be fitted with reactive power support (S. Schmidt, interview, January 13, 2016).

4.1.1.5 Undesired Events due to Unmanageable System

Risk treatment/reduction

- *Control system.* A. Larsen (Survey, April 1, 2016) emphasized the need for a comprehensive and well-functioning control system for communicating with and regulating the different constituents of the power system.

- *Well tested, standardized solutions.* One way to avoid an unmanageable system is to only install well tested technology (F. Roos, survey, April 4, 2016).

- *Testing and monitoring.* It is important to perform load simulations (site acceptance tests) when connecting new generation and continuously monitor vital parameters of distribution (F. Roos, interview, January 15, 2016 and P. Thuring, survey, March 29, 2016)

4.1.1.6 Harmonics In the Grid

Risk treatment/reduction

- *Harmonic overtone filters.* Filters can be installed downstream of equipment producing harmonics, as well as placed in the grid, where they smooth out the frequency (F. Roos, interview, January 15, 2016).

- *Requirements*. Harmonics might be avoided with strictly followed technical requirements for the connected equipment (A. Larsen, survey, April 1, 2016)

4.1.4 Managerial and Economic Issues

The identified managerial and economic issues for DSOs due to a larger share of WP and PV generation are treated in this chapter. The risks are presented as future risk scenarios and are followed by suggestions of risk reduction measures. No evaluation of the change in likelihood or severity has been done.

4.1.4.1 Risk Identification

What can happen?

- *New solutions making old investments redundant.* Grid reinforcements such as larger transformers and bigger dimensions of lines due to increased installation of PV and WP make peak flows manageable. As the reinforcements are dimensioned to 100% of maximum load flow, they are designed for the highest possible loads. New solutions dampening the peak flows could make large parts of the capacity redundant. The possibility of energy storage or consumption flexibility could smoothen out the variations and reduce peak loads. That would leave overcapacity, with higher annual maintenance costs and an unnecessarily large initial investments. S. Schmidt (interview, January 13, 2016) added that reinforcements following PV installations are only dimensioned to 85 % of the PV maximum capacity in Germany.

- *Customer independence.* With the increasing feasibility of microgrids, it is likely that utility services will not be needed to the same extent in the future. Individual customers or communities might prefer being independent, able to supply their own consumption. Smart microgrid systems with the ability to store, generate and regulate their own power balance could make the connection to the rest of the grid necessary only during times of shortage in internal generation or other disturbances. The utility service would then function as more of a backup. Those types of customers will probably not be willing to pay the same amount only for backup power, however, the costs of maintaining the grid remain the same for the DSOs (R. Nilsson, interview, February 2, 2016 and A. Larsen, interview, February 11, 2016).

- *Threshold situations and unfair apportion of costs.* If a customer wishes to install generation and connect this to the grid, DSOs are obliged to enable the connection. Typically, small additions of generation can be handled by the existing transfer capacity of the grid. However, if one generation unit creates a situation where additional "downstream" reinforcements become necessary, those costs need to be covered. Two identified situations are hard to fairly assess. First off, previous investors which have connected to the grid without making additional reinforcements necessary have been allowed to connect without these future costs in mind. They cannot be charged with additional connection fees after their installment (R. Nilsson, interview, February 2, 2016). Should the new costs be covered by the new investor, by the recent investors or to the customer collective within the rest of the grid? This isolated problem is present on a larger scale, well-illustrated in Bavaria. There, most PV is installed in rural areas where rooftops are big and plentiful, but most customers live in cities where there is less possibility to install PV. The costs for reinforcements due to PV connections are evenly distributed amongst the customer collective. This makes customers without the possibility to install PV pay for the expansion of the generation in other regions. The fact that they also help to subsidize the feed in tariffs for renewable energy further redistributes funds to the owners of PV systems (S. Schmidt, interview, January 13, 2016).

- *Undefined responsibility for financing of new regulatory functions.* Some of the identified problems with DG, such as overvoltage and reactive power, require interventions from the DSO in order to maintain stability. Instead of regulating on a transformer substation level, or using on-line regulation, a possible solution is having the technology installed within the customer's generation system (S. Schmidt, interview, January 13, 2016 and Short, 2004). This would ensure better operational stability at the customer end and reduce the influence of individual generation units on the rest of the grid (Vikesjö & Karlsson, 2013). The equipment can be placed within the bounds of the customer's generation unit or on the grid side of the installation. The latter would infer costs are to be covered by the DSO. The appropriation of costs and responsibility for such interventions are as of today unresolved. The rules on how much and what the DSOs can charge their customers are set by the EI. Much of the new regulation equipment has not yet been approved, or granted extra revenue (R. Nilsson, interview, February 2, 2016).

- *New regulatory directives.* The EU has a hard time uniting over the formulation of a common energy policy, due to conflicts of interest between member countries. The regulations and laws also have a hard time keeping up with the new technological solutions. (A. Larsen, interview, February 11, 2016) exemplifies that there is no clear legislation regarding storage. As of today, DSOs are not allowed to store surplus generation. That exemplifies how development can be hampered due to the fact that laws are often enforced retroactively (R. Nilsson, interview, February 2, 2016).

What are the consequences?

- *Economic losses* e.g. DSOs not being able to charge their customers for necessary investments, reinforcements and technology. (A. Larsen, Survey, April 1, 2016).

- *Bound Capital.* Capital is bound in investments that become redundant, resulting in alternative costs. Both capital for the initial investment and future maintenance is bound. (R. Nilsson, interview, February 2, 2016).

- *Hampered development.* Legislation and regulation can hinder the development and changes in the energy market. As legislation often comes as a response to a change, rather than preemptively, the implementation of new technical solutions could be impeded. The oil price, geopolitics and power play controls the market. The speed and process of development is dependent on this since "money makes the world go round" (G. Bolin, interview, February 17, 2016).

4.1.4.2 Risk Reduction

Risk treatment/reduction

- *Planning, development and testing of new solutions.* Testing of both technical solutions, business models and services (A. Larsen, survey, April 1, 2016). A. Larsen (interview, February 11, 2016) says that it is important to not be idle in the change and work to create suggestions for solving the problems.

- *Stricter grid codes.* Effective grid codes on power quality need to be put in place and standardized (P. Thuring, survey, March 29, 2016).

4.2 Choice of Risk Scenarios

The identified future risk scenarios were Uncontrolled Islanding, Unacceptable Levels of Reactive Power, Overvoltage on the Grid, Increased Transport Losses, Undesired Events due to Unmanageable System and Harmonics on the Grid. It was not deemed possible to quantitatively investigate Uncontrolled Islanding or Undesired Events due to Unmanageable System. They were concluded as the two most troubling risk scenarios in the qualitative study, but unfortunately hard to assess. No islanding events have occurred, leaving no empirical data to study. Undesired Events due to Unmanageable System is a risk scenario that acknowledges the possibility of unknown risks and consequences. Due to the characteristics of that scenario a study of it would only be speculative.

Harmonics was pointed out as the third biggest possible future risk. However, its severity was thought to be exaggerated due to outdated and subjective views of the respondents. F. Roos (Interview, January 15, 2016) explained that harmonics were expected to become a problem, but have not increased enough to cause significant problems. Harmonic overtone filters can be used to reduce the problem and both PV and WP technology is rapidly improving in regards to harmonics (M. Andersson, survey, April 4, 2016). The opinions of these two, who to some extent both work with issues regarding harmonics, were regarded more credible than those of other respondents. It was believed by the authors that the notion of harmonics as a big problem is a view that has stuck with the respondents, despite the development in recent years. Harmonics were not investigated further.

The risk scenario Distribution losses was pointed out as likely to increase, but also as the least threatening of the six scenarios. E.ON Elnät, specifically the division of Grid Settlement, could provide relevant data over a year. As such this risk was therefore possible to assess empirically and also relevant considering the conclusions in the risk identification. T. Fonnesbæk & T. Skødt (interview, January 19, 2016) confirmed that WP has an effect on losses and so Distribution losses were chosen as relevant for further assessment.

The risk scenario Overvoltage specifically referred to elevated voltage on low voltage grids due to PV generation. This scenario was stressed as a big problem in Germany during the interview with S. Schmidt (Interview, January 13, 2016) and therefore considered important for more in-depth studies. It turned out that no low voltage grids with sufficient PV generation could be identified in grids operated by E.ON in Sweden. Unfortunately, PV generation is still at negligible total generation capacity within the studied grids. The focus was therefore shifted toward studying the effects of WP generation on voltage in low voltage grids. Reactive power contribution from the studied WP plants was also looked at, since it contributes to increasing or decreasing voltage. To be clear, reactive power is only included in the study of voltage deviations due to WP as a parameter that affects voltage, not as the risk scenario Unacceptable levels of reactive power.

The lack of sufficient PV installations and empirical data made it impossible to assess research question number two in regards to PV. It does however dismiss the notion that PV generation is currently significantly affecting the reliability of distribution within the grids operated by E.ON in Sweden. This answers one part of the research question number two. The dismissal of one parameter (PV) as currently detrimentally affecting operations is in itself a valuable conclusion. However if PV would to be installed in much larger quantities in Sweden the risk should be revisited. Fortunately for the Thesis, this means that the focus can be shifted to WP, which is installed in much greater capacity. Unfortunately for the Thesis, it means that the quantitative study focuses only on WP.

4.3 Quantitative Study

In this section the results from the quantitative study are presented. The study aims to investigate if the installed WP and PV already affects the operation of the grids operated by E.ON and if any conclusions can be drawn regarding future development. Identified in the qualitative study, the risk scenarios Distribution Losses and Overvoltage have been chosen for further investigation. Overvoltage was changed to "Voltage deviation due to WP", since no sufficient data could be found regarding PV.

The grids chosen for the analysis were selected on the basis of.

- Availability of data
- Load profile of the grid
- Installed capacity of WP

The grid settlement areas of SUR (Sundsvall), ADL (Ådalen), SML (Småland) and SYD (Southern Sweden) were chosen for the study. See figure 19 below. They are all medium voltage grids where different stretches of cable or hanging wire is set to levels ranging from 20 – 130 kV.

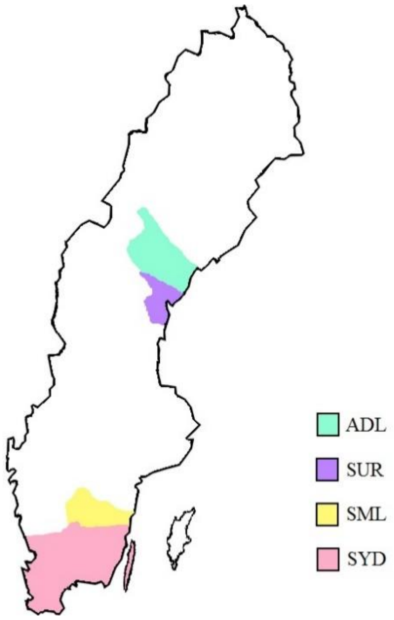

FIGURE 19. THE EXTENT OF THE MEDIUM GRID SETTLEMENT AREAS STUDIED.

4.3.1 Losses in Grids Due to Wind Power

Increased losses due to WP and PV have been identified as a future problem, given a continued increase in installed capacity in the grid. EI has decided on an incentive for reducing losses (Energimarknadsinspektionen, 2015). The incentive creates an economic risk for DSOs. By studying several different grid settlement areas, this chapter aims to determine how WP is affecting losses. Data from four medium voltage grids operated by E.ON have been studied. PV is not installed in sufficient capacity for performing the same analysis on. Since most PV is installed to the low voltage grids where most consumption is measured only monthly, the analysis thereof is made even more unfeasible.

4.3.1.1 Ådalen (ADL)

The medium voltage grid of Ådalen (ADL) is almost exclusively used as a means of distributing the electricity generated from the wind- and hydropower plants connected to it. The total power supplied to ADL is around 5037 GWh per year, out of which 104 GWh (2 %) is import and 4932 GWh (98 %) is generation. See figure 20 below for more detailed shares of generation types. An addition of ca 40% of total installed WP was added in the middle of the studied year, making for a larger share had the values been extracted later. Figure 21 shows that most power on the grid is exported to other grids.

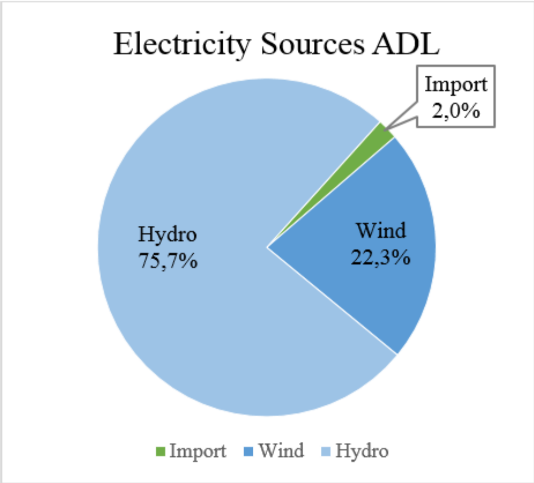

FIGURE 20. THE ELECTRICITY SOURCES SUPPLYING ADL

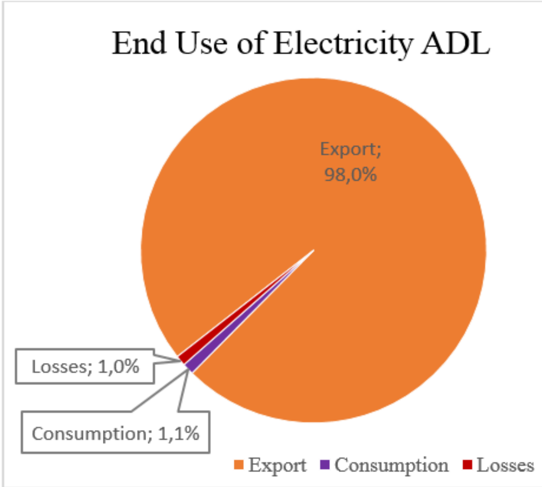

FIGURE 21. THE END USE OF THE ELECTRICITY SUPPLIED TO ADL

Figure 22 is a plot of the daily energy balances in ADL. The losses are plotted on a second axis in order to distinguish a visual relationship between the losses and the generation within the grid. To some extent, the losses line can be seen following the movements of the export, which in turn is more or less the sum of wind- and hydropower.

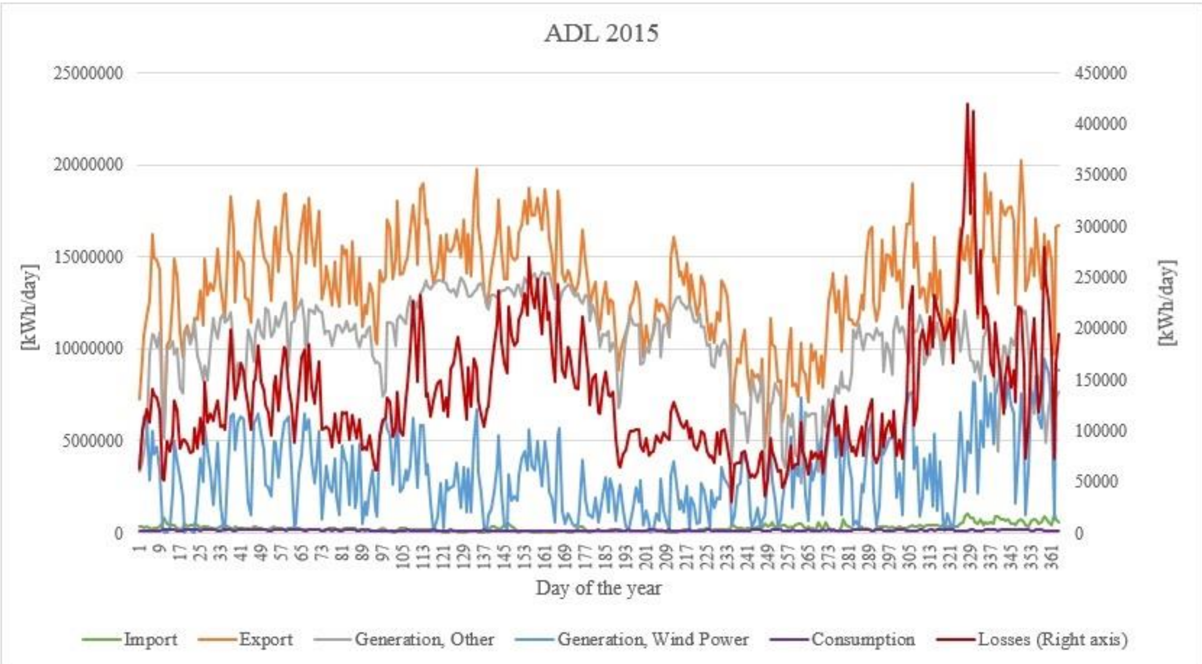

FIGURE 22. DAILY ENERGY BALANCE DURING ONE YEAR IN ADL.

Figure 23 below show the values of loss rate plotted against WP generation. As seen, an increase of WP generation causes the loss rate to increase. Out of the four studied grids, it is the most accentuated trend. The loss rate is approximately 50% higher when WP generating with full capacity than when no WP generation is present. High losses when WP is not generating is likely the cause of the approximated curve having a somewhat downward slope in the beginning. According to S. Svensson (Personal communication, April 8, 2016), the reason for these observations could partly be explained by the absence of WP generation during high pressure weather in winter months. Such climate situations during winter create stagnant wind conditions and low temperatures, increasing demand for electrical power. Large demand in turn creates the need for large generation from hydropower, which starts generating. That would cause hydro power to contribute to losses whilst WP is inactive, creating high loss rate at times of no WP generation.

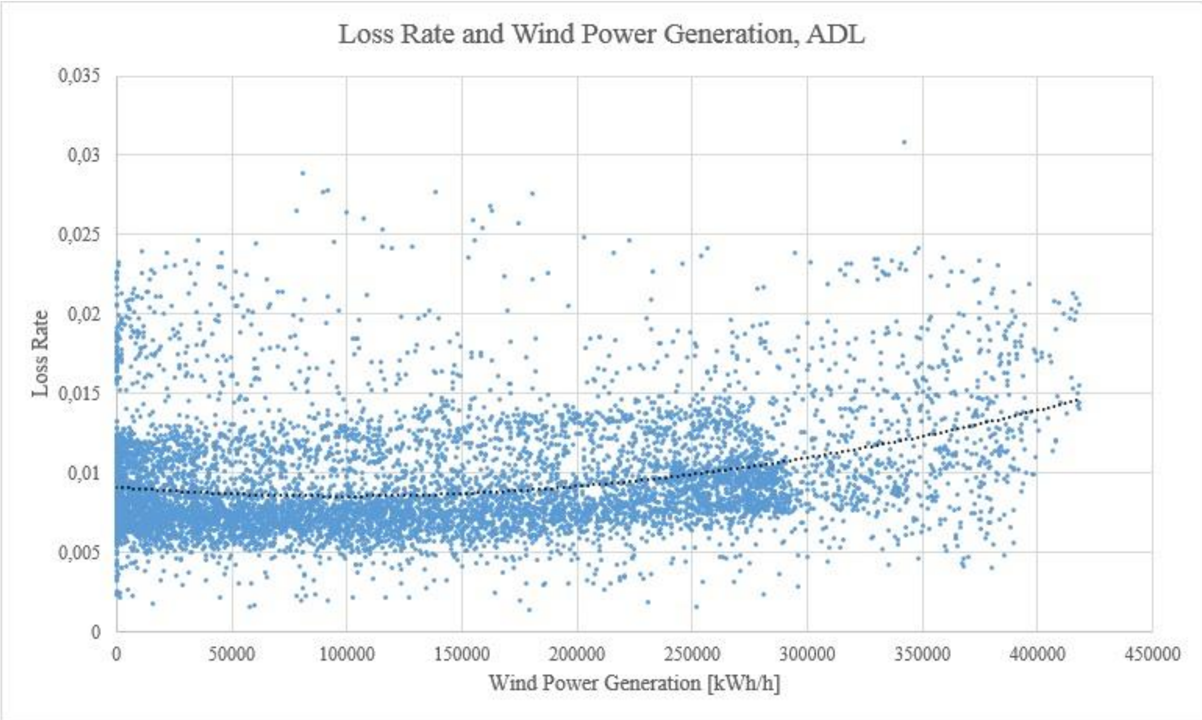

FIGURE 23. LOSS RATE PLOTTED AS A FUNCTION OF WP GENERATION AND APPROXIMATED SECOND DEGREE FUNCTION.

The spread of values in figure 23 was suspected to have another influence. When further investigating the values it was discovered that an additional wind park was connected to the grid, and started generating electricity, on the 27th of July. The generation provided by this park corresponds to an addition of around 40% extra WP capacity. In figure 24 below, the same data as in figure 23 above was divided into two data series, the prior values are plotted in light green and the latter in light blue. The two data sets have each been provided with an approximated second degree function. The spread of observations show a surprisingly large spread after the 27th of July. The green first half of the year shows loss rate values kept in the range of around 0.006 and 0.015. The second half show a spread between 0.002 and 0.03 in loss rate. It is unclear whether this addition of WP is the only reason for the increased variation of loss rate values, but it does seem to have a profound effect.

The average value of losses between the two periods increased by 4 % and the approximated function shows a much more accentuated increase after the 27th. The means of both periods are statistically differentiated with >99 % certainty. The increased losses during one year cost roughly 570 000 SEK, if the price of one MWh is assumed to be on average 300 SEK/MWh and the overall losses 4 % higher throughout the year.

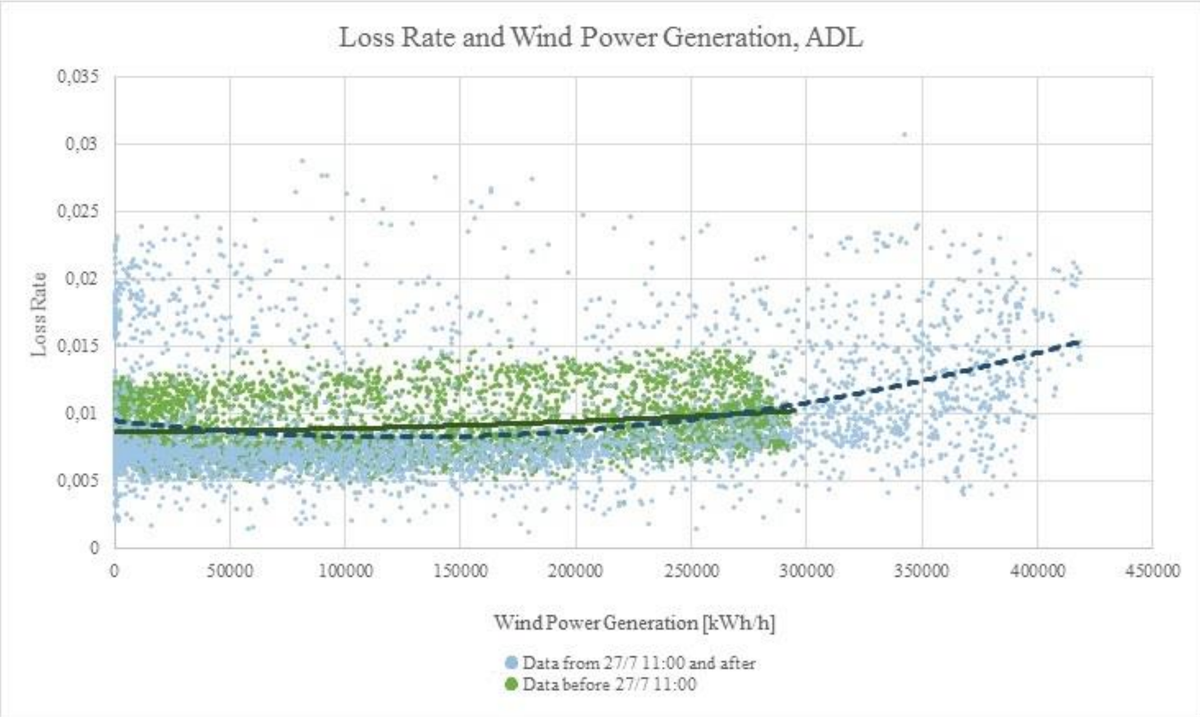

FIGURE 24. LOSS RATE PLOTTED AS A FUNCTION OF WP GENERATION. THE DATA SERIES FOR ONE YEAR IS SPLIT IN TWO, WITH THE OBSERVATION POINTS FROM BEFORE THE 27TH OF JULY IN GREEN AND THOSE AFTER IN BLUE

The increased spread of losses is a problem for DSOs in prognosticating the total cost of covering the losses within their grids. Prognoses work as a basis for keeping the economic fallout of losses to a minimum. Losses are secured at a certain price through a third actor, ensuring the agreed upon price for the total losses during a month. The losses are billed to the DSO monthly. The compensating for losses is done hourly and the final bill is calculated as the total hours during the month times the price of electricity during each hour. The difference is settled to the previously mentioned third party, which in retrospect compensates for or gets compensated for the final difference in price. The problem with an increased spread of losses is that it becomes harder to predict the final price for the losses per month. The short term losses can prove more expensive, as the spot prices of electricity vary in the short term. Electricity prices tend to be highest at hours of peak load on the system, when demand an electricity flow is the greatest. The result could be securing the price higher than necessary (D. Kostkevicius, personal communication, 2 May, 2016).

The intermittency of WP could however, have an alleviating effect on the cost of hourly losses. As WP generates indifferently to demand, electricity prices during hours of generation may correlate negatively with the price. This relationship could cause the increased transport losses of WP to be cheaper, as the high losses due to WP coincide with generally lower prices (D. Kostkevicius, personal communication, 2 May, 2016).

4.3.1.2 SMÅLAND (SML)

Below are the sources of electricity for Småland (SML) grid area, depicted in figure 25. The total power supplied to SML is around 4557 GWh per year, out of which 1967 GWh (43 %) is import and 2589 GWh (57 %) is generation. WP only provides ca 2.5%, whereas the nuclear power plant of Oskarshamn provides 54% of the total electricity in the grid area during 2015. It should be noted that Oskarshamn is connected to the easternmost part of SML, feeding half of the power to SML and the rest to SYD. SML was chosen because it had little WP and the fact that it serves to supply mostly local grids. (S. Svensson, personal communication, April 8, 2016)

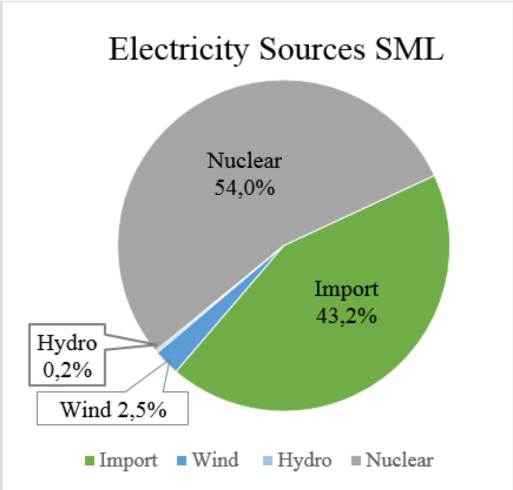

FIGURE 25. THE ELECTRICITY SOURCES SUPPLYING SML

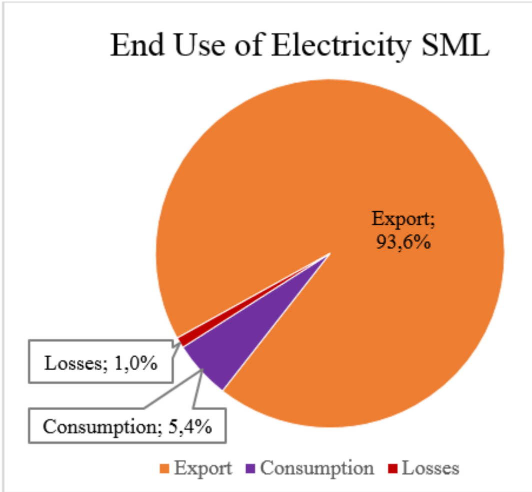

FIGURE 26. THE END USE OF THE ELECTRICITY SUPPLIED TO SML

Figure 27 below shows that the grid is dependent on import from adjacent grids to match its export, presumably exporting to underlying low voltage grids. However, much of the power is provided from the nuclear power plant when it is generating. At such times, the nuclear generation causes export to increase and import to decrease. Losses are the most accentuated during winter. The two periods during summer when nuclear power is generating does not exhibit elevated losses compared to the periods right before and after. The explanation given from Svensson. S (Personal communication, April 8, 2016) is that most electricity generated there is exported a short distance after its generation site. That makes the generation look big, but most is exported directly after. This makes the relative losses appear smaller than if the electricity had been transported over longer distances on SML, causing distribution losses there.

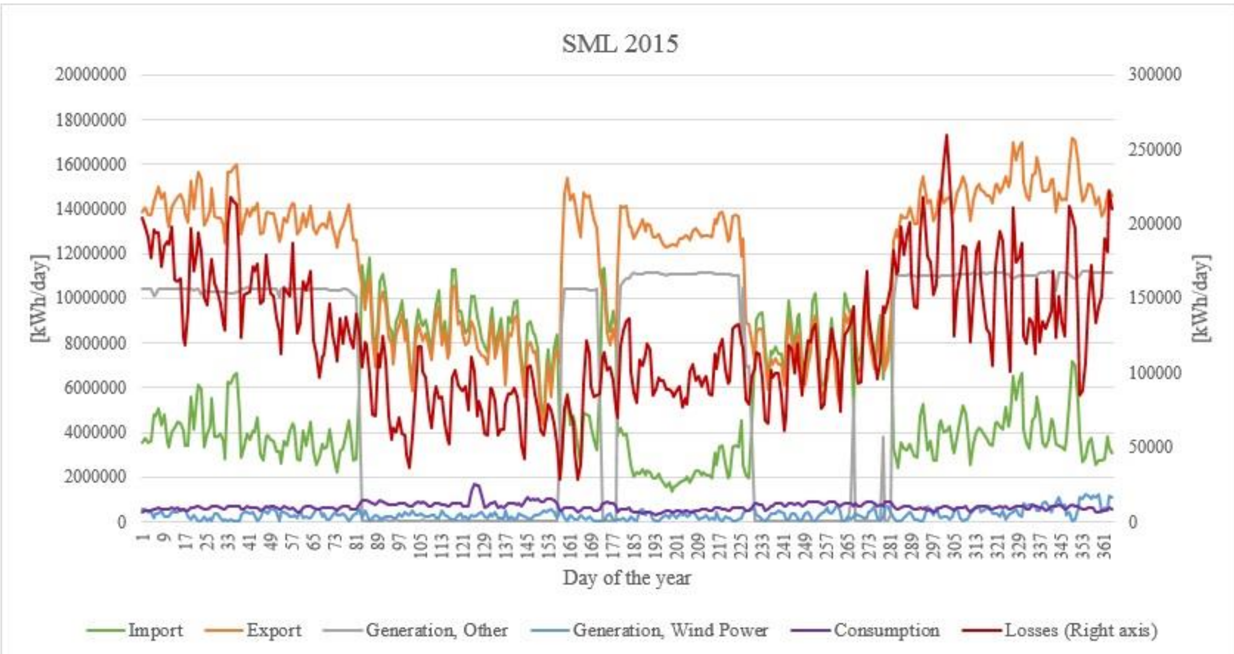

FIGURE 27. DAILY ENERGY BALANCE DURING ONE YEAR IN SML

Loss rate plotted against WP generation can be seen in figure 28 below. It should be noted that only a very small percentage of the total electricity flow in this area is from WP generation. The linear correlation is 0.0275, if any, a very weak correlation. The conclusion drawn from this plot is that there are other factors more significantly impacting the loss rate. The plot shows little or no resemblance to those of the other grids.

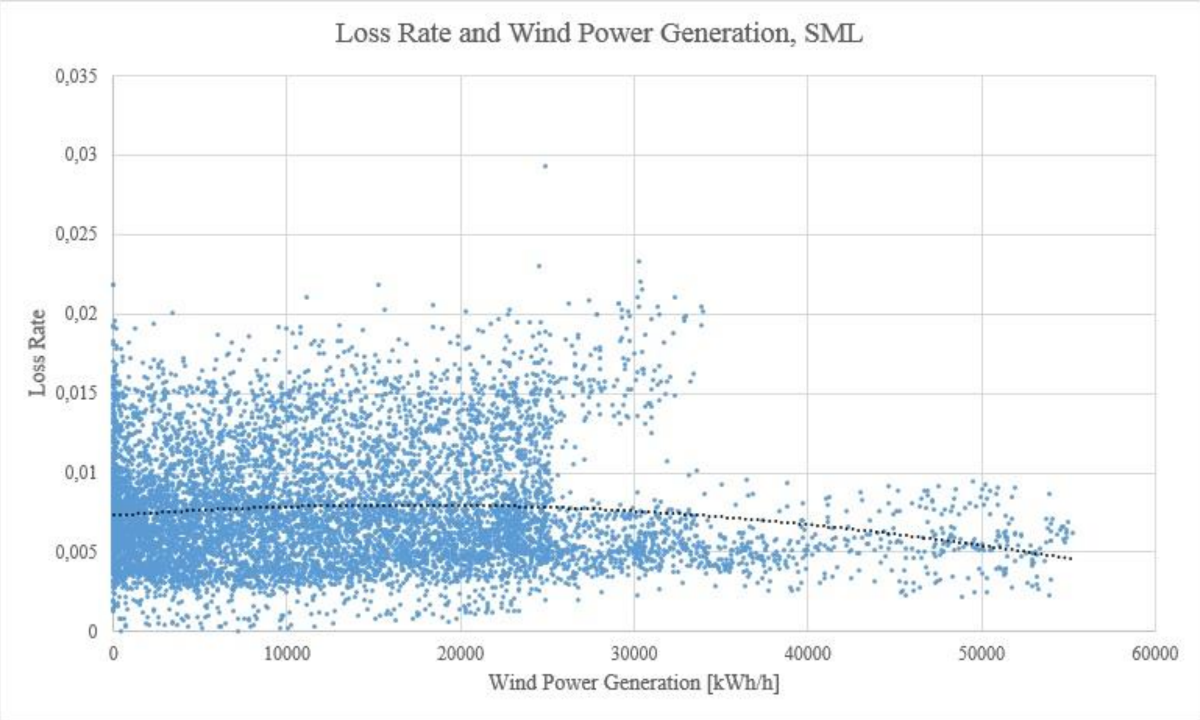

FIGURE 28. LOSS RATE PLOTTED AGAINST WP GENERATION IN SML

The odd disposition of the plotted values in figure 28 was further investigated, resulting in figures 29 and 30 below. The first, figure 29, has loss rate plotted against "other generation". As other generation in this area is to >99 % nuclear power, the data series will henceforth be referred to as nuclear generation. When in operation the nuclear generation is held constant at ca 43 000 and 46 000 kWh/h, which can be seen in the plot of values over a year in graph 28 above.

Figure 29 below shows a decreasing loss rate when nuclear generation is present. The linear correlation for this set of data is 0.72, the strongest correlation observed. The decreasing loss rate suggests that the losses are small relative to the total volumes passing through the grid when nuclear generation is present. Together with S. Svensson (Personal communication, April 8, 2016), the suspected explanation was confirmed. Around 50 % of nuclear power is exported after a very short distance to adjacent grids, making it easy to misinterpret the figure. The exported power is not distributed on the grid of SML more than for a few meters contributing little to creating transport losses. It does however register as generation imported to the grid. The definition of loss rate makes it look like nuclear generation is greatly reducing the relative losses.

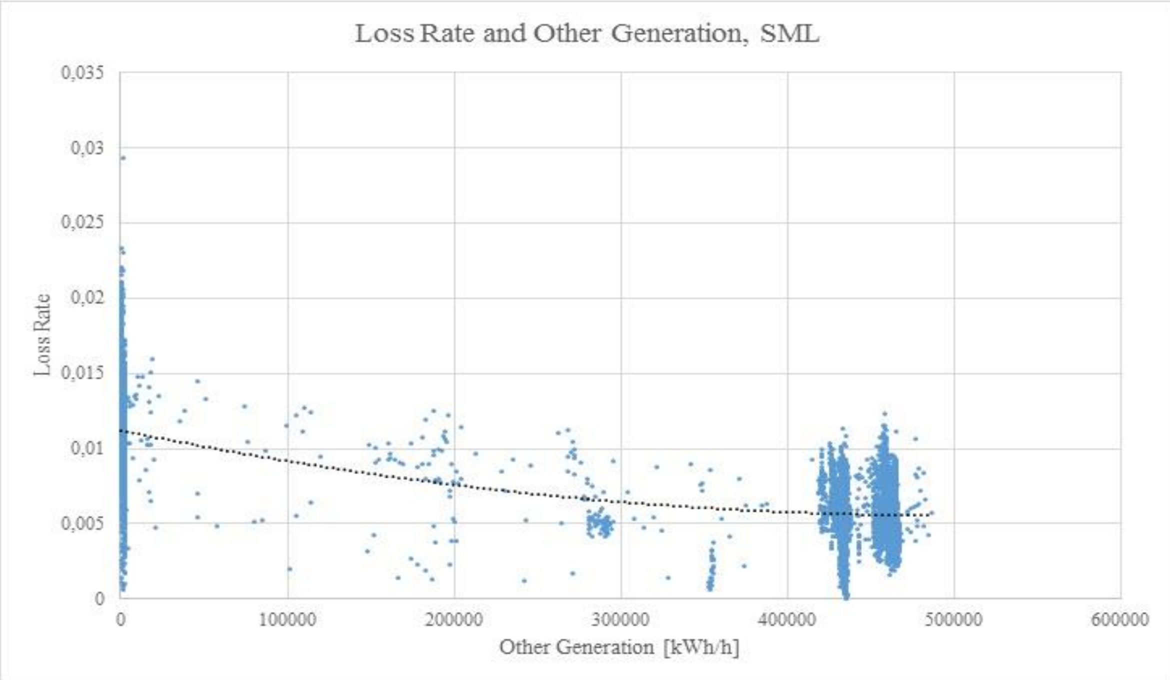

FIGURE 29. LOSS RATE PLOTTED AGAINST OTHER GENERATION IN SML, WHICH IS >99 % NUCLEAR POWER.

The second, Figure 30, shows loss rate plotted against WP generation during times when nuclear generation is above 100 000 kWh/h. There is no increase or decrease of loss rate in this set of data to suggest a trend and the correlation is a very weak -0.0378. In this set of data the large contribution of electricity from nuclear generation is likely drowning the effect on losses that the comparatively small WP generation has.

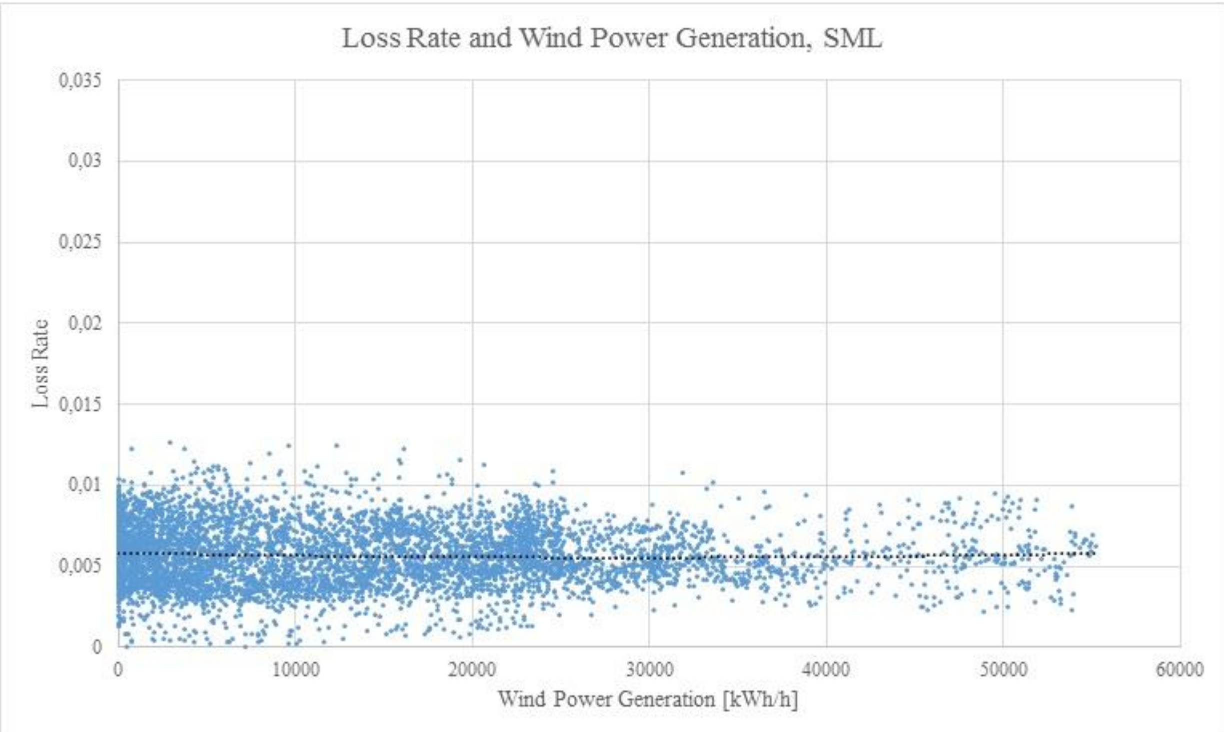

FIGURE 30. LOSS RATE PLOTTED AGAINST WP GENERATION IN SML. VALUES FOR WHEN NUCLEAR GENERATION IS ABOVE 100 000 KWH/H

Figure 31 below shows a correlation of 0.257 between loss rate and WP, which is one of the stronger correlations observed. In this plot, only observations of when nuclear power is not generating are included. The loss rate in SLM seems to increase with WP generation when nuclear generation is absent. If any conclusion can be drawn from the data in SML, it is that the small generation of WP generation in SML seems to increase the loss rate. The validity of these results can be questioned, as 2.5 % WP out of the total volumes on the grid is small. Compared with figure 36 of SUR in the next section 4.3.1.3, the results are contradicting. It would be necessary to perform a comparative analysis of more parameters to draw any further conclusions as to what might be affecting the losses.

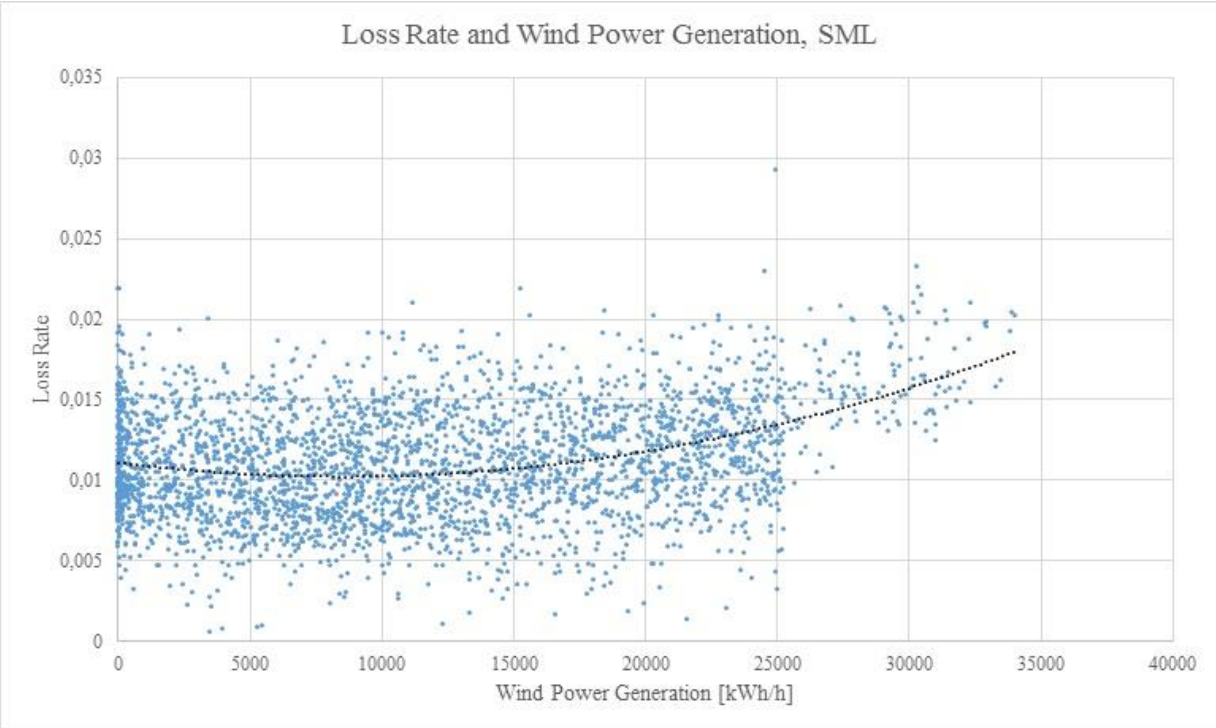

FIGURE 31. LOSS RATE PLOTTED AGAINST WP GENERATION IN SML. ONLY OBSERVATIONS FOR WHEN NUCLEAR POWER GENERATION IS LESS THAN 100 000 KWH/H ARE INCLUDED

4.3.1.3 SUNDSVALL (SUR)

The total power supplied to SUR is around 6283 GWh per year, out of which 4219 GWh (67 %) is import and 2064 GWh (33 %) is generation. See figure 32 below for more detailed shares of generation types. As shown in Figure XXX, the end use of electricity in the Sundsvall grid area (SUR) shows that most electricity on the grid is distributed to consumers connected directly to the medium voltage grid. These are mainly two large industrial complexes with a stable power consumption (S. Svensson, personal communication, April 8, 2016). The losses over a year are 0.7 %, which is lower than that of the other grids. More than half of the electricity supplied comes from import, Figure 32 shows around 30 % hydropower and a mere 1.5 % WP.

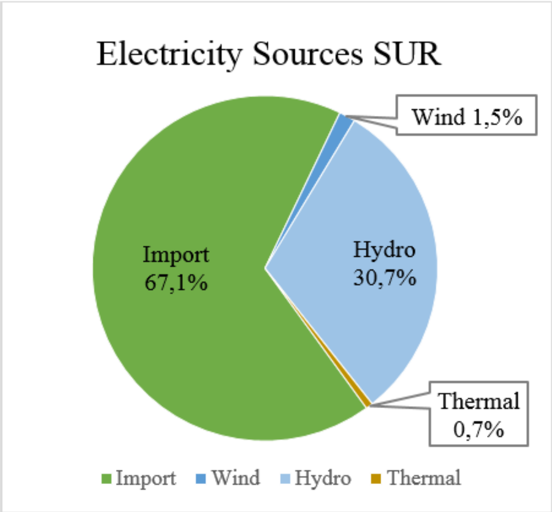

FIGURE 32. THE ELECTRICITY SOURCES SUPPLYING SUR

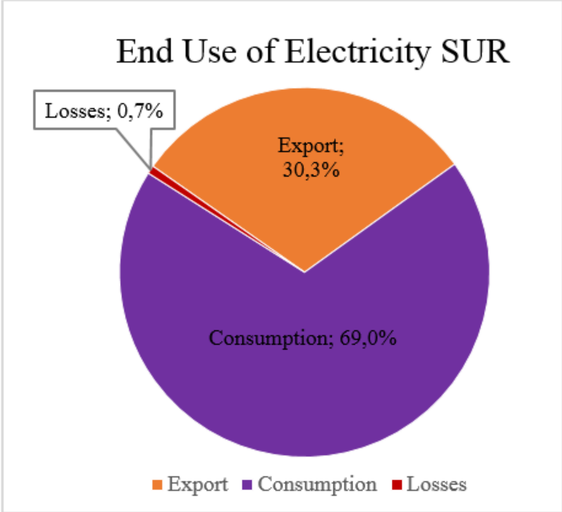

FIGURE 33. THE END USE OF THE ELECTRICITY SUPPLIED TO SUR

Notably, figure 34 below shows a fairly constant overall level of consumption, which is almost three times larger than export. The export curve seems to follow the curve of other generation, suggesting that much of the hydropower is exported off the grid instead of used for the consumption connected to the grid. Import and consumption seem to follow each other throughout the year. Not much can be distinguished as to what might affect losses, other than that it seems to somewhat follow the line of export.

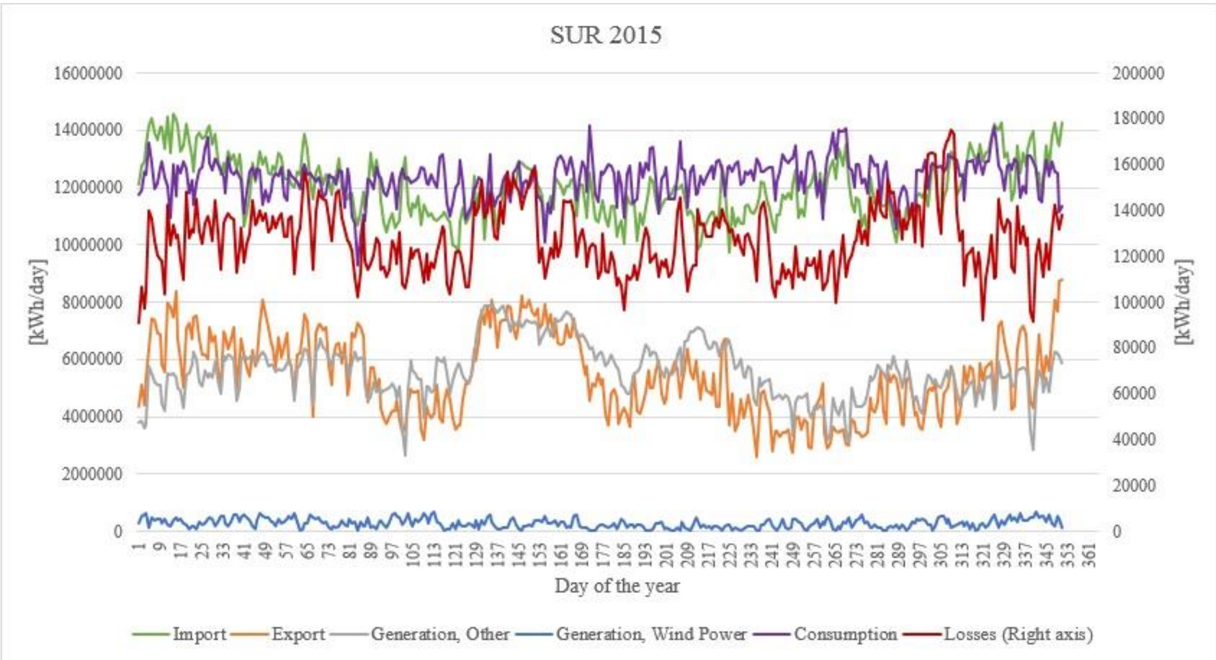

FIGURE 34. DAILY ENERGY BALANCE DURING ONE YEAR IN SUR

The loss rate does not exhibit any clear relationship with WP generation. Figure 35 below shows a scatter of loss rate much more concentrated than of the other analyzed grids. If anything is to be said about an eventual trend, it is that the approximated line shows a weak slope toward lower losses when WP is at close to maximum generation.

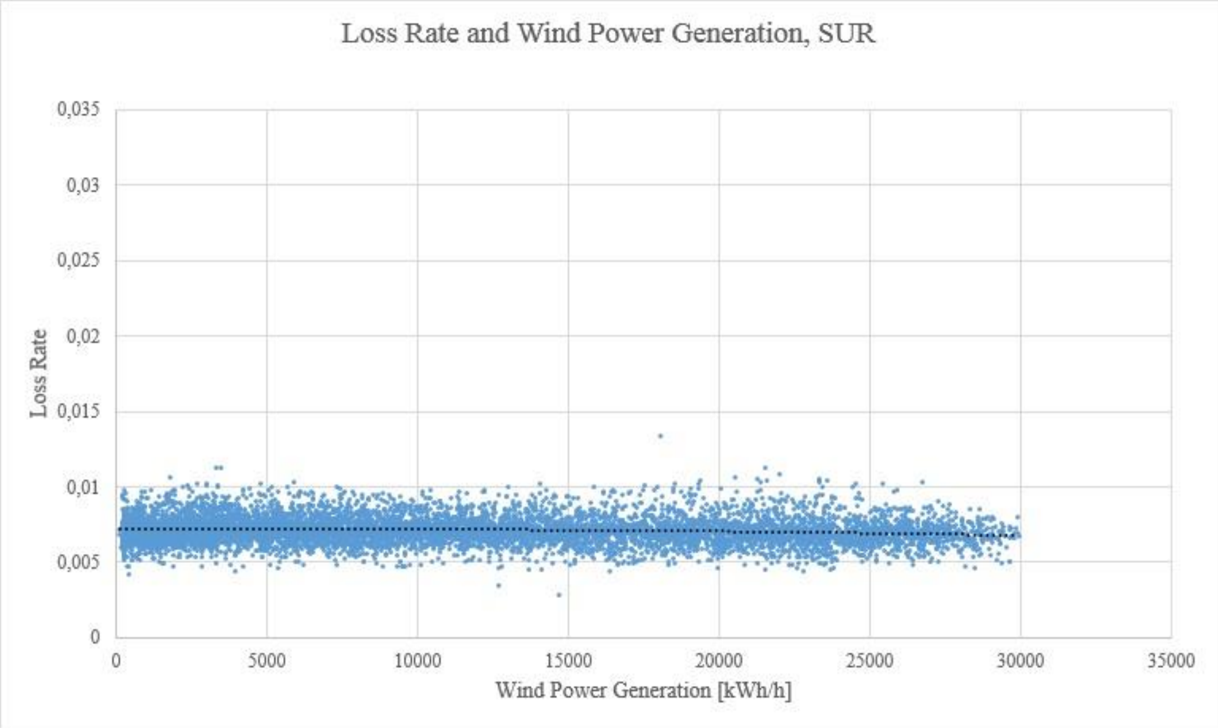

FIGURE 35. LOSS RATE PLOTTED AGAINST WP GENERATION IN SUR.

4.3.1.4 SYDSVERIGE (SYD)

As seen in figure 36, the medium voltage grid of the Sydsverige grid area (SYD) is largely dependent on import. The total power supplied to SYD is around 22075 GWh per year, out of which 18259 GWh (83 %) is import and 3815 GWh (17 %) is generation. See figure XXX below for more detailed shares of generation types. Favorably for the analysis of loss rate, the dominant source of internal generation is WP. Figure 37 shows 1.5 % in losses which is high compared to the other grids.

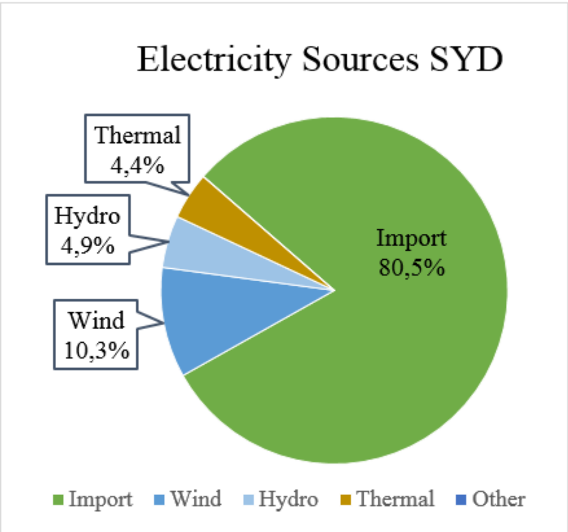

FIGURE 2. THE ELECTRICITY SOURCES SUPPLYING SYD

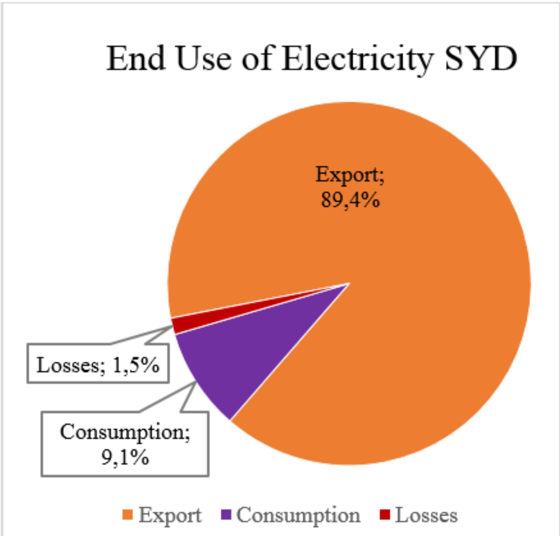

FIGURE 37. THE END USE OF THE ELECTRICITY SUPPLIED TO SYD

Export following the line of import in figure 38 below is expected. The medium voltage grid of SYD exports electricity to the underlying low voltage grids. The curve follows the normal seasonal variation of electricity consumption, with lower consumption in the summer and higher in the winter. Also losses follow this general trend. Unfortunately for the analysis, other generation peaks during these coldest months, when WP tends to produce the most. The geographical distribution of the other electricity generation is unknown, making any conclusions hard to draw.

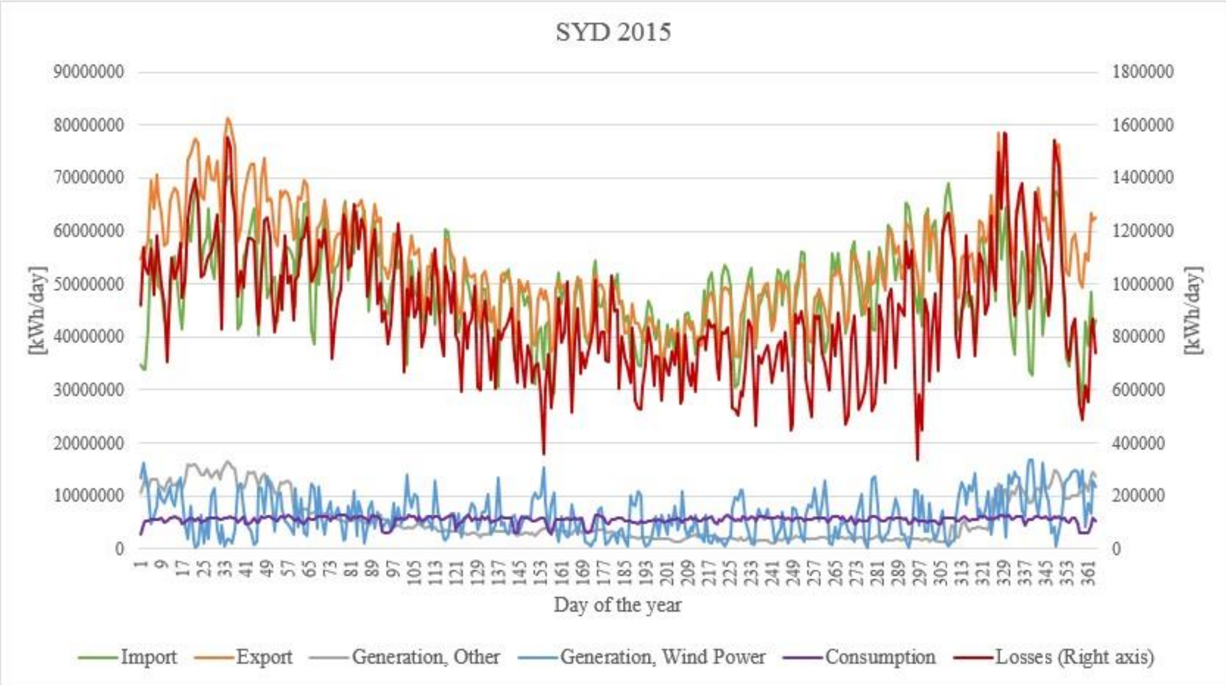

FIGURE 383. DAILY ENERGY BALANCE DURING ONE YEAR IN SYD

The loss rate in SYD is the overall largest, implying high losses per transported unit of energy. Although scattered within a wide range, the observations in figure 39 do seem to show a trend of decreased losses with low to medium level of WP generation. The trend is reversed when WP generation is around 50 %, reaching the same mean at maximum generation as when no WP generation is present. It is not reversed enough to cause higher overall loss rate at maximum WP generation. The correlation calculated from the linear regression -0.073 is weakly negative. It should be noted that calculating correlation of linearity is not optimal when examining data which shows an overall trend more akin to a parable. It only reveals how well the values follow a linear trend.

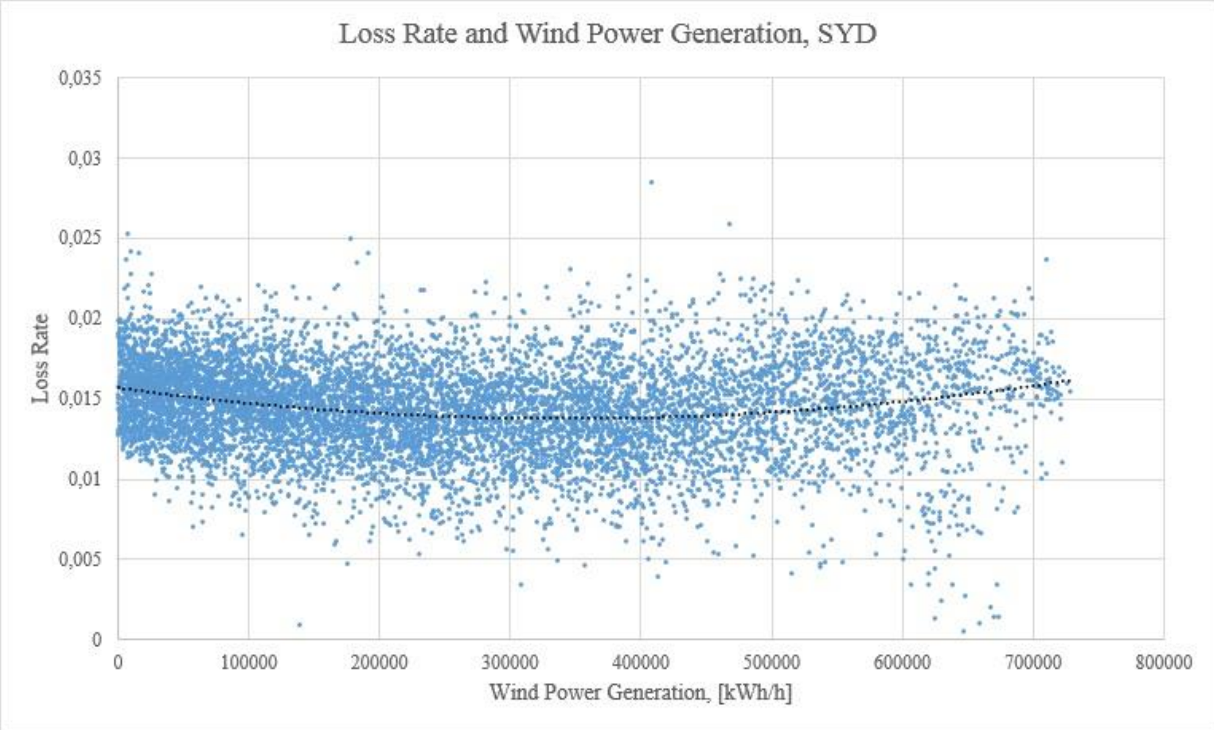

FIGURE 39. LOSS RATE PLOTTED AGAINST WP GENERATION IN SUR

Another purely visual observation is the tendency for increased scatter of loss rate as WP generation increases. The loss rate values are concentrated to a more defined range during the leftmost part of the graph when little WP is generating. Any more definitive conclusions regarding this large grid area are hard to draw. It consists of several smaller grid areas, that if defined, would have very different load situations and shares of consumption, export etc. Further dividing up the grid into smaller areas would make for a more nuanced analysis.

The observed values are several times more plentiful when WP is generating <50 % of its capacity, a distribution plot is presented in section 4.3.1.5 figure 42 to further back this up. That area in the plot (left side) is when loss rate decreases. If the decrease is caused by WP generation, the overall effect on losses by WP generation in SYD can be concluded as positive.

4.3.1.5 Comparison of the Grids

The different loss rate WP curves are plotted on the same axes in figure 40 below. The varying length of the curves depends on the maximum WP generation within the grid.

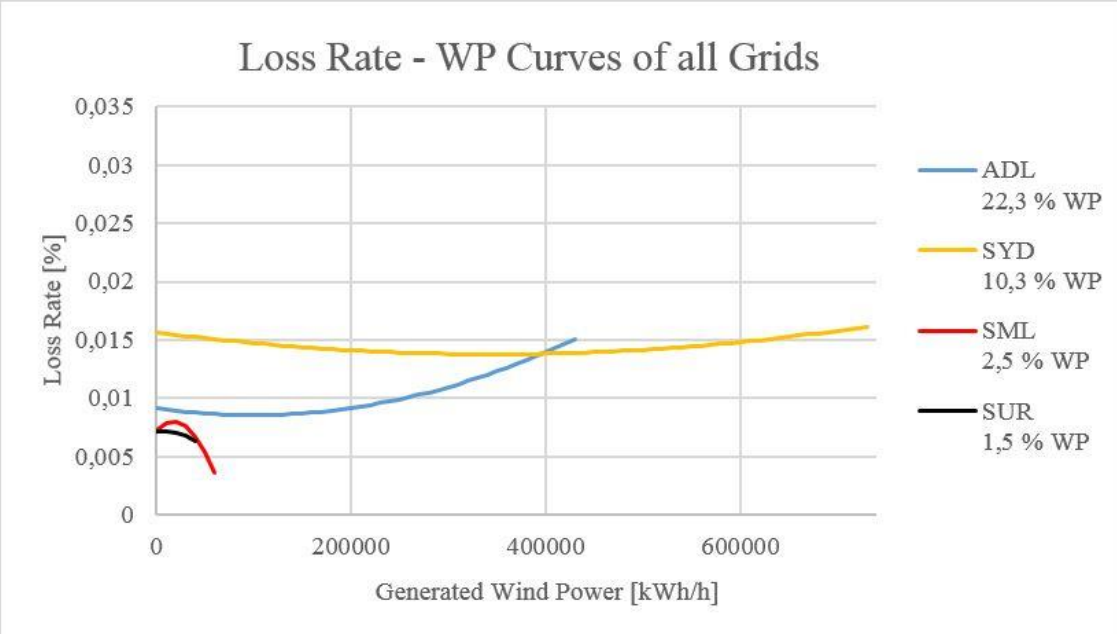

FIGURE 40. THE LOSS RATE CURVES AS A FUNCTION OF WP GENERATION WITHIN THE GRIDS.

In order to better be able to compare the curves, all the curves were normalized to display the x-axes as % of the total WP capacity within the specific grid. WP at 100 % implies that all WP connected to the grid is generating at maximum capacity. The result is presented in figure 41 below.

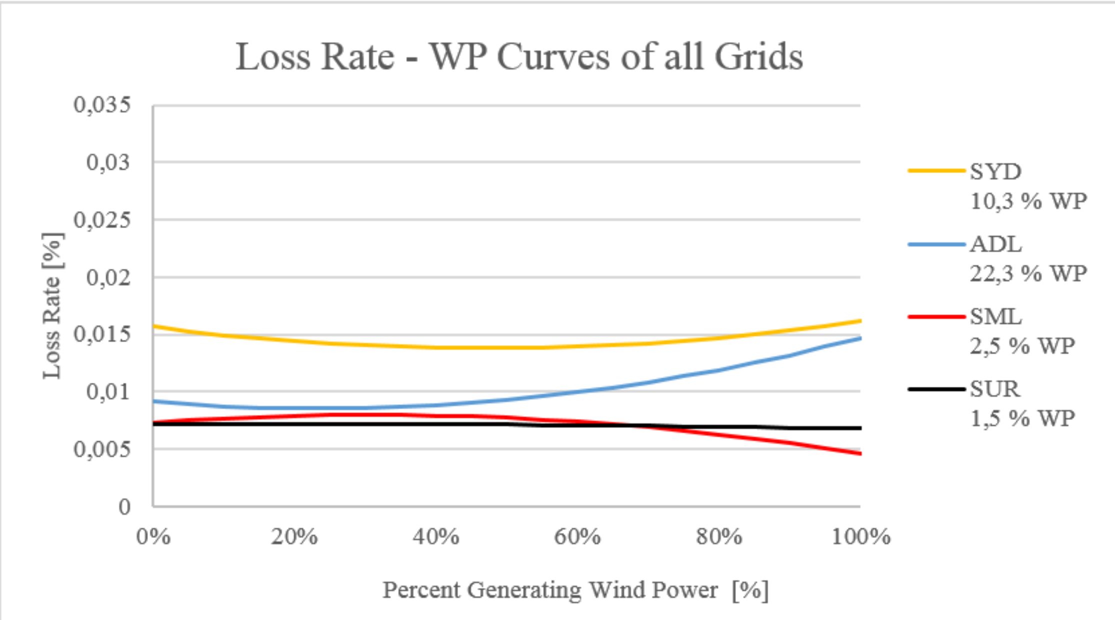

FIGURE 41. THE FITTED LOSS RATE - WP CURVES OF THE STUDIED GRIDS PLOTTED AGAINST PERCENT WP GENERATION OF TOTAL INSTALLED CAPACITY WP WITHIN THE GRID.

The curves of ADL and SYD show some resemblance, a decreasing loss rate for low levels of WP generation. After a certain point the trend is reversed and the loss rate increases. ADL has more than double the share of WP generation as SYD and a much steeper inclination towards the end. It is not clear whether WP causes a reduction of the losses to a certain point, or if the loss rate is higher in the beginning of the graph due to other reasons. As discussed in ADL section 4.3.1.1, there could be the effect of high pressure systems in winter which cause higher losses during hours of no WP generation. An eventual explanation for WP as the cause of reduced loss rate is that its distribution can help to cut the distance over which electricity is transported on the grid. If the electricity generated by WP can be supplied to customers close to where it is consumed, the distance from the point of import from an adjacent grid becomes less strained and contributes to creating less losses.

The steep slope exhibited by ADL is likely a result of the losses increasing with the current squared, as exhibited in Equation 7. The squared relationship can cause losses to vary by several hundred percent during the course of minutes. It is not known by the authors how well hydro power is able to be regulated in the short term. Drastically regulating hydro power generation helps compensate for short term variations from intermittent power sources such as WP. If hydro power regulation is not able to respond fast enough to an increase in WP, a generation spike will occur. The rapid variations and peak loads from WP are in that case likely to coincide with maximum hydro generation at some point. That would cause the strain on the grid to increase further towards its thermal limits and further increase losses.

In table 8 below the different correlations between loss rate and generation are shown. The observed correlations are used for determining how strongly the plotted values follow a linear trend. This can give an indication of how well a trend between loss rate and WP is accentuated.

TABLE 8. DIFFERENT CORRELATIONS REGARDING LOSS RATE

	ADL	SML	SUR	SYD
Loss Rate and WP generation	0,24	-0,028 ** 0,26	-0,098	-0,073
Loss rate and generation, Other	0,085	-0,72	0,20	0,18
Loss rate and All generation	0,26	-0,71	0,19	0,070

**When the Nuclear generation is under 100 000 kWh/h (meaning the Nuclear is off or under start up/shut down)

For SML there is a difference in correlation between loss rate and WP generation when the nuclear is generating and when it is not. The correlation is much stronger for when only WP generation is present, implying that a relationship is present between the two. When the nuclear generation is off the loss rate curve shows similar characteristics to the loss rate curve for ADL and SYD. Since the loss rate and WP correlation is positive, this shows that it might not be ideal to install additional WP in this grid.

The overall correlation in SYD is negative, although a very small value. This further corroborates the authors impression that WP is helping to reduce the overall losses in SYD.

Interestingly enough, the correlation between loss rate and WP is stronger than between loss rate and other generation in ADL. In the words, the values of WP are likely to have a closer relationship with loss rate than other generation.

In SUR the correlation between WP and loss rate is weakly negative. In contrast, the correlation between loss rate and other generation is positive. If anything can be concluded, although only having a weak trend of -0,098, it would be that WP is helping to reduce losses within SUR. The reason could be the consumption facilities directly connected to SUR. The industries in SUR consume a constantly high amount of energy (S. Svensson, personal communication, April 8, 2016). The export line following the line of "other generation" suggests that little or none of the hydropower generated connected to SUR is used to supply the consumption. That would imply that most of the power supplied to the industries stems from import. Having WP generating close to these facilities could reduce the load on the grid from the point of import. If that distance is long, the transport losses on that line would decrease if the WP generation is close to the consumption.

It is important to remember that even if more WP is implemented the overall loss rate might not be significantly higher. In ADL and SYD the loss rate curve first decreases as WP starts generating before the trend is reversed. Important to keep in mind is that maximum generation of WP is rarely achieved. The distribution of observations can be seen in figure 42 below. The most frequently observed percent generation of rated capacity of WP is around 5-10 %. Most observations of WP generation are concentrated to low percent of generation utilization, when loss rate is decreasing. This implies that the effect of WP mostly helps to decrease the losses. If WP is the cause of initially declining loss rate, as observed in ADL and SYD, the effect of installing more WP will most have an overall positive effect. The number of observations decreases for high levels of WP utilization. Only a hundred something observations out of the total 8736 for each grid area show WP generating at close to 100 % of its capacity. That in turn makes for few situations where loss rate is the highest for the ADL grid area.

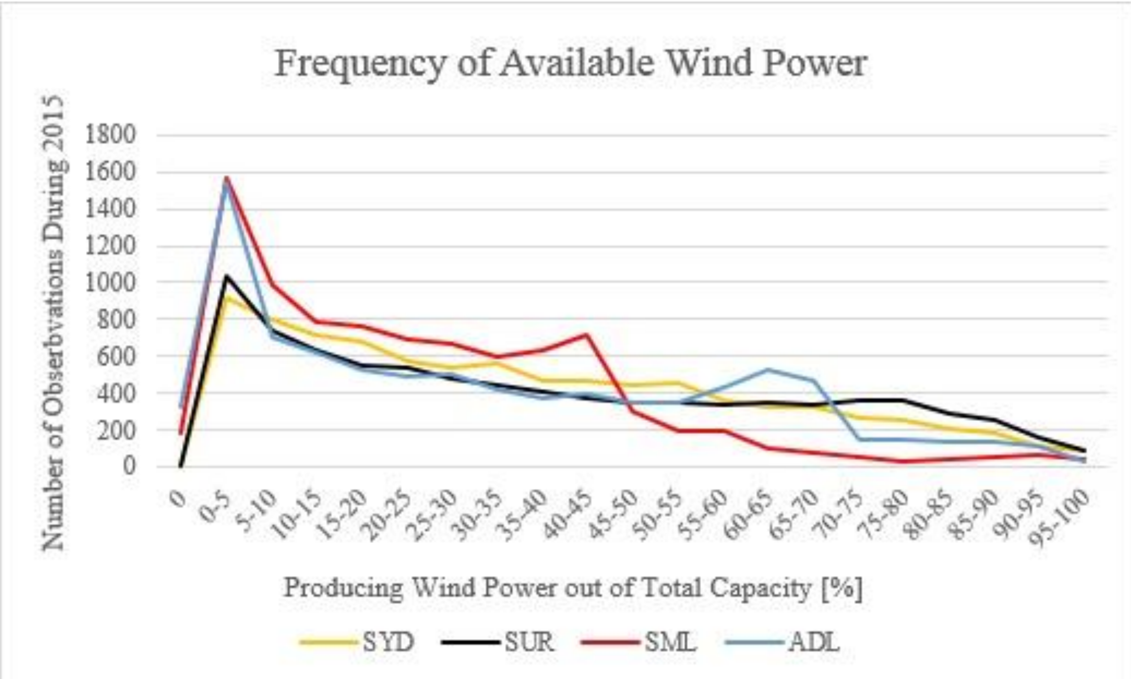

FIGURE 42. FREQUENCY DISTRIBUTION OF WP GENERATION IN THE STUDIED GRIDS. NUMBER OF OBSERVATIONS WITHIN 5 % INTERVALS OF TOTAL GENERATION CAPACITY DURING ONE HOUR

4.3.1.6 Measure for Reducing the Consequences of Increased Losses

Energimarknadsinspektionen (2015) rules that a change in losses over different reporting periods is to have a positive or negative impact on the economic result of the DSO. As the incentive is stated, it is applied to regulatory reporting units and not grid settlement areas as are studied in this Thesis. The grids of E.ON are bunched together into two regulatory reporting units, RN North and RN South. If the overall losses during 2013-2016 are larger than during 2010-2013, the incentive penalizes or rewards according to equation 12 below (REF).

Cost of increased losses for DSO=

$$(Losses_{norm,\,2010-2013} - Losses_{outcome,\,2013-2016}) * Price_{2016-2019} * 0{,}5 \quad \text{EQ. 12}$$

As the framework is stated, an overall increase of grid losses within a regulatory reporting is to cause a "penalty" corresponding to half of the costs for covering up the losses. However, if the increase can be proved to be caused by additions of "local generation" the penalty can be "reasonably" reduced (Energimarknadsinspektionen, 2015).

S. Nivhede (Personal communication, March 30, 2016) explains that the measurement data from the reference period of 2010-2013 is not of good enough quality to use for the types of analysis that have been conducted in Section 4.3.1. E.ON Elnät has been working hard to improve the collection and cataloging of data, improving both quality and structure of the data. This makes for a significantly improved accuracy in calculating losses and performing the analysis as in Results 4.3.1. S. Svensson (Personal communication, April 8, 2016) confirms this, explaining that the reduction is of administrative losses, the non-technical losses. The reduction of administrative losses has been accomplished foremost by improving the collection of metering data. This implies that the overall "losses" have decreased in most grids, corresponding better now to what is believed to be represented by mostly technical losses. An overall decrease of losses would make the reduction of a penalizing fallout of the incentive irrelevant.

The reported losses during 2010-2013 are final, despite any eventual uncertainties regarding their accuracy. In the way equation 12 is stated, only the overall losses are compared between the periods. In Section 4.3.1.1 of ADL it is clear that the addition of additional WP has a profound effect on the loss rate. The mean power losses per kWh during one hour has increased by 4 % after the additional WP is installed. The loss rate also increases significantly when WP is generating. Proving that WP is the cause of increased losses within a grid settlement area is one thing. Proving it as the cause of increased overall losses in an entire regulatory reporting unit is another. One way to prove the overall losses in one grid settlement area as the cause of overall losses in a reporting unit could be to sow other grid settlement areas as stable in terms of losses and added local generation during the same period.

SUR and SML do not have large enough installations of WP to draw any conclusions regarding the relationship between WP and losses. SYD and SML are both included in RN South. Since SYD experiences higher overall loss rate and is much bigger than SML, the losses fluctuate in absolute terms much more than in SML. If the conclusion that WP decreases losses in SYD is correct, additional installed WP in SYD will likely help to further decrease losses in SYD (to a certain point). As a consequence, the overall losses in RN South would likely decrease. That would result in a positive turnout of the EI losses incentive, making the clause on reduced deduction irrelevant for all of RN South, including SML.

Many other factors influence losses. A hotter climate, for example, would reduce the electricity demand for heating and as a result reduce the transport losses experienced primarily during winter. That could cause an overall decrease in losses, making the incentive turn out favoring not only the overall energy efficiency, but also for DSOs.

4.3.2 Voltage Deviations due to WP (Originally: Overvoltage due to PV)

As described in 1.5 Method, the effects of WP on the 10,3 kV low voltage grid of Påboda was chosen for the analysis. The layout of the transformer station is presented in a schematic overview in figure 43 below. Only the WP generation from the two WP bays represented in the figure were included in the analyzed data. The "Mixed wind power and consumption" was not included, as consumption within that subsection distorts the output from the slot. Detailed measurements of WP generation and consumption on that line are not available.

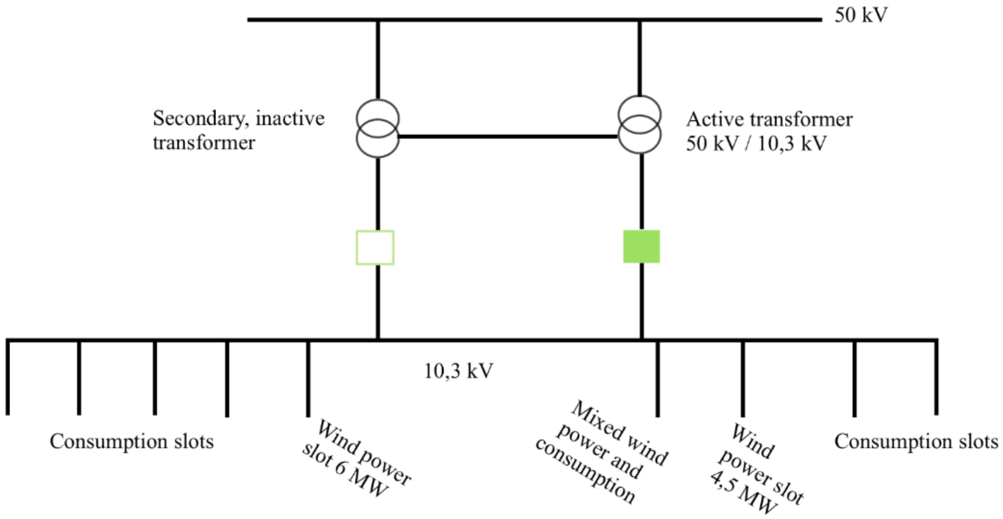

FIGURE 43. SCHEMATIC OVERVIEW OF PÅBODA TRANSFORMER STATION

Figure 44 below shows the maximum and minimum coutput of the two WP slots during 85 hours. The maximum and minimum values are the highest and lowest momentary values registered during one hour. This is the period with the most deviant levels of voltage at the transformer station during the year 2015. Maximum and minimum power through the transformer at the Påboda 50/10kV grid station is plotted in the same graph. Max WP generation and minimum load on the transformer show a mirroring relationship. The same can be said for Min WP generation and Maximum load on the transformer. When WP generation is high, the load through the transformer is negative, implying that power is being transferred to the overlying 50 kV grid. This is a result of the WP generation being larger than the average load for the station.

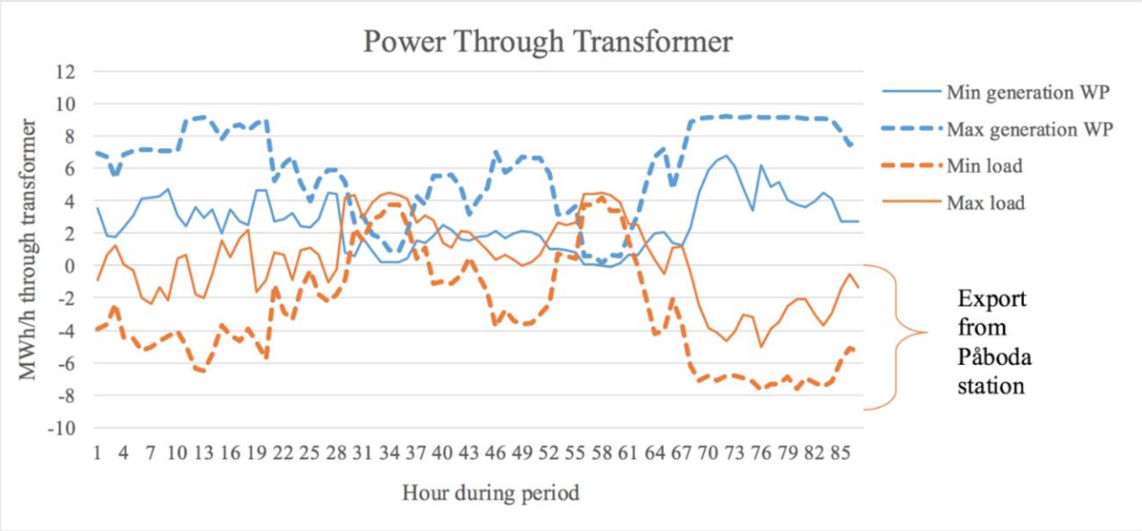

FIGURE 44. POWER FLOW THROUGH TRANSFORMER IN PÅBODA

The corresponding values of voltage at the transformer station were plotted in figure 45 below. The red lines represent the upper and lower acceptance levels for voltage, 11.3 and 10.1 kV respectively. The operators are automatically alerted of a deviation outside this interval. As seen in the figure, voltage does not go outside of the accepted limits during even this most turbulent part of the year. The station is able to control the voltage deviations that WP causes on the grid by altering the number of windings in its circuit using tap changers.

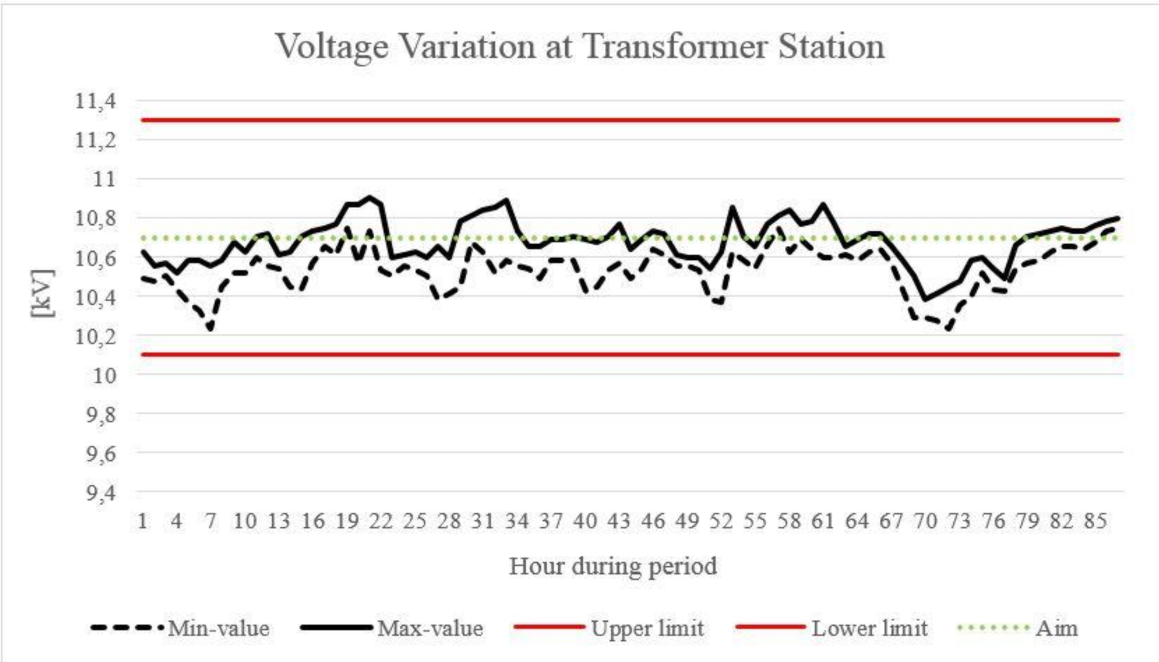

FIGURE 45. REGISTERED MAXIMUM AND MINIMUM VOLTAGE AT THE TRANSFORMER STATION IN PÅBODA.

Reactive power exported to the grid causes voltage to rise. The reactive power output from each WP slot during the studied time period is plotted in figures 46 and 47 below. The limits for variation do not come close to being transgressed during this period. The same overall appearance was observed throughout the rest of the year. The reactive power output from these two slots of

WP is kept close to the stipulated norm, which is little or no contribution (Larsson & Larsson, 2006).

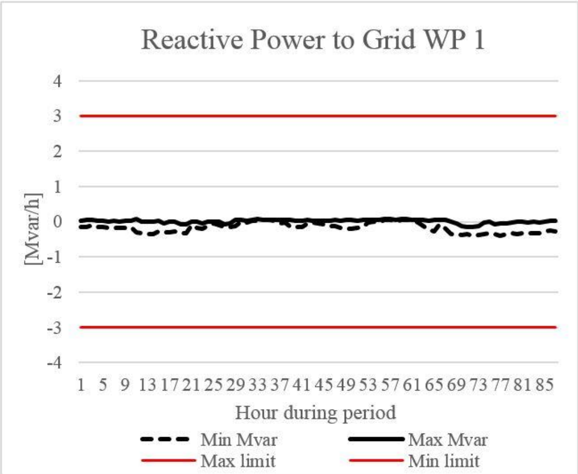

FIGURE 46. THE REACTIVE POWER OUTPUT FROM WP1

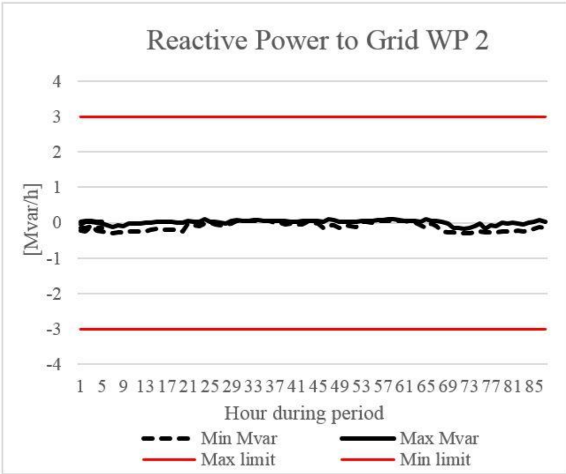

FIGURE 47. THE REACTIVE POWER OUTPUT FROM WP2

To summarize, no voltage stability problems due to WP could be found in the local or regional grids of E.ON. The analysis of the low voltage grid in Påboda showed no signs of voltage deviations outside acceptable ranges. It is therefore not considered necessary at the present to take measures for mitigating the consequences of this risk scenario. It can, nonetheless, be good to take measures in order to ensure future stability.

The occurrence of voltage deviations due to WP can be probably be avoided in the future by following the technical requirements when installing more capacity, as suggested in section 4.1.3.3. More suggestions for risk reduction measures in that section can be implemented to further ensure that voltage is kept stable. Reactive power control as suggested in section 4.1.3.4 can be implemented in individual generation units or connections, such as the two WP slots studied above. Regulating reactive power output from the WP slots in response to voltage deviations in the transformer station would result in a more stable voltage. As seen in figures 46 and 47, reactive power can be varied a great deal before grid code limits are exceeded.

CHAPTER 5

DISCUSSION

This chapter discusses the work performed in the thesis, its methods, results and other aspects. The terms reliability and validity is used to point out what might have affected the results and the outcome of the study. The outline has been divided into sections according to the research questions. Some reasoning regarding the results have been left in chapter 4, Results and Analysis, in order to maintain stringency of presentation.

5.1 OVERALL RELIABILITY AND VALIDITY FOR THIS MASTER THESIS

The authors believe that the reliability and the validity of the presented study is increased by the fact that the authors have different academic backgrounds. One author studies Risk Management and Safety Engineering whilst the other studies Environmental and Energy Systems Studies. This has given the authors different areas of expertise, different views and opinions which provides a broader perspective. The authors also have had three supervisors, one at the department of Risk Management and Safety Engineering, one at the department of Environmental and Energy Systems Studies and one at E.ON Energy Controlling. This is believed to have increased the validity, since feedback from different perspectives has helped scrutinize the work.

If the study was to be performed again the authors would include more people from other DSO companies. Most of the interviewees were from E.ON Elnät, which might have affected the results. The results from study might be specific and fit the operations of E.ON Elnät and not DSOs in general. It could prove advantageous to have anonymous interviews, perhaps then the interviewees could express themselves more freely. Instead of a survey it could be preferable to have a workshop, since the response frequency of the survey was only aroung 50 %. A workshop makes it possible for the interviewees and the authors to interact. It could be a good way to investigate uncontrolled islanding and Unwanted events due to unmanageable system further, as they are the two biggest threats for a reliable distribution according to this study.

5.2 THE QUALITATIVE STUDY

Open interviews were used to identify future risk scenarios. The authors did not have an overview of the distribution system nor the technical background for identifying risks within the system. It was therefore considered necessary to assess the system through expert input. As presented in chapter 3, risk perception is influenced by past experiences and views on what is important. The students tried to take this into account when choosing the risk scenarios to investigate further. This is the reason why harmonics were not chosen, as the respondents were believed to have an outdated view. The authors also used literature sources for nuanced identification of risks. Hopefully, this has contributed to a good balance between a technical risk view and a socially constructed view resulting in a holistic and full covering view.

The first contact with the interviewees was in most cases through email. The potential interviewees were informed of the background of the Thesis and given the opportunity to decline if they felt unable answer the questions at hand. Hopefully this made the interviewees comfortable and open. Some of the interviews were held over the phone which means that body language could not be studied, hence some information might have been lost. Both authors have experience with contacting new people and communicating professionally, which has facilitated a smooth dialogue.

One disadvantage the authors experienced with the chosen interview technique, "in-depth", was discovered when sorting out the relevant information from the interviews. All the interviews were different which made the analysis afterwards harder, there was no clear structure. The advantage of using an open interview is that the interview is not forced in a certain direction by the interviewers. Rather the interviewees are in control, allowing for focus on what they feel is important. This means that the subjective view of risks is likely to affect the content of the interview. The authors experienced some trouble interviewing people from other countries. Communication both ways proved difficult due to language barriers and poor phone connections, often making it necessary to repeat and rephrase. How the authors perceived the interviews and the survey responses could be a source of misinterpretation. Many people were interviewed during a short time, some with the same background within the energy section. It is not all unlikely that certain claims have been misquoted or referred to the wrong interviewee. Summarizing the interviews using the recordings was done to minimize those risks. Interviewees were also asked to read and correct the summaries before publication. The supervisor at E.ON worked as a middleman for contacting the right people. His selection has surely affected the outcome of the findings. However, the people selected were chosen to have complementary knowledge.

The survey helped to assess the risks in a quantitative manner. Putting them in a scale of severity and believed increase or decrease in future likelihood helped get an overview of their weighted severity. The process of designing the survey and defining proper questions proved difficult. The respondents could not ask for clarification of the questions nor could the authors explain or ask for elaboration of the answers during the process of answering. It was hard to balance between keeping the questions focused and at the same time not directing the answers of the respondents. The authors needed help from both the supervisors at the Faculty of Engineering and the supervisor at E.ON. One of the respondents working at E.ON Elnät was asked to test the survey before it was sent out to the rest of the interviewees. This was in order to ensure clarity of the questions and understanding of the risk scenarios. Interpreting the written answers proved challenging. Many were brief and vaguely specified, resulting in the risk of misinterpretation by the authors.

All the interviewed agreed during the interview to take part in the survey. Unfortunately for the results only seven out of thirteen completed the survey. Some have not commented on the summaries which have been sent to them, but fortunately none have refused to have their answers cited in the Thesis. A draft of the final Thesis was also be sent out before publication, in order for the responders to be able to correct any misquotations.

Several measures for reducing the severity/likelihood of risks and/or their consequences have been presented. The identified measured were not evaluated to suggest when or if they should be taken. It might seem easy to mitigate risks when several alternatives are presented. Many problems are of a technical character and might therefore be of a more practically amendable nature. However, the results of the Thesis identify several impediments for doing so. Cost and benefit of interventions need to be weighted and responsibility assigned to a proper actor. This was made clear when managerial and economic issues were identified. All in all the authors believe the transition to a renewable energy system is more dependent on willingness and political steering than any eventual technical impediments.

For each future risk scenario its consequences and suggestions for mitigation are only briefly described. There is much potential in further assessing each of these individually. They are varyingly quantifiable, some better documented than others. Ideally, empirical studies like those performed in the quantitative study would be done for each risk scenario. Furthermore, modelling future scenarios in individual parts of distribution grids would give a better understanding for the consequences and likelihood thereof. The research questions in this Thesis only aims to identify future risk scenarios and identify which are the most severe, a goal that does not necessarily require further depth.

5.2 THE QUANTITATIVE STUDY

The validity of some conclusions in the quantitative study is questioned by the authors. The data used was quality assured, used as the final settlement report from the division of Energy Controlling at E.ON Elnät. However, it was extracted, sorted and analyzed by the authors, who had little prior knowledge of its structure. It is possible that relevant data was lost during the process or wrong time series were used. The process of sorting tested the patience of the authors, taking three whole days to complete. The sorting was further complicated when hidden WP data were identified, the values of which had to be subtracted from "import" and added to "WP generation". The risk of making mistakes became apparent when one grid area seemed to be exporting several times more than what was supplied to it. It was discovered to be a simple copy-paste error, which was easily corrected. All the one year series of the grids were controlled by subtracting export, losses and consumption from import and generation. Errors were found in one more grid and the data reentered correctly. It is not unlikely that similar mistakes have been made in any given part of the qualitative study. A way of minimizing such problems is to specify the sought time series when extracting data. The authors also noticed some poor quality in the data at the end of the year in one medium voltage grid. Therefore, the data from the last two weeks of 2015 within that grid was not included.

As both parts of the research questions proved extensive, it was deemed necessary to limit the extent of the statistical part of the quantitative analysis. The ambitions of the analysis were at the beginning of the work process much higher, but time and statistical knowhow was limited. Correlation between WP and loss rate was the calculated value, which only shows an indication of how well the observations followed a trend and if the trend was an increase or decrease. As a result, only limited conclusions can be drawn. The validity of the conclusions would be more certain if more parameters had been included in the analysis. There are many other parameters that affect losses e.g. reactive power, which, due to the size of the excel files, was removed. It would also have been interesting to analyze residuals and the contribution to variance that the different loss affecting parameters have. If the observed trends are caused by WP generation alone is not possible to prove in a system with power from several other sources and many other influences affecting losses. The output of WP generation varies in a stochastic manner, coinciding with vastly different load situations on the grid. It is therefore hard to isolate the effects of WP, especially when its generation capacity only corresponds to a few percent of the total power on the grid.

Regarding the conclusions drawn in the analysis of Increased Distribution losses due to WP, the authors would like to clarify that the causes for WP influencing losses are not analyzed or established. The proof of WPs effect on losses is a varyingly strong trend observed in each grid settlement area and in the case of ADL also a statistically proven increase of the overall losses from one period to the next. WP generation can be said to have an effect on losses, but the analysis does not explain why that is.

The results of four vastly different grids are hard to compare. No consideration was taken to the geographical layout or technical specifications of the grids. Information regarding cable length, position of power generation, number of connections to other grids etc. proved difficult to attain. Trying to include those types of parameters would in any case have overly complicated the study performed. Such an approach would however be an interesting way of further categorizing the grids and help nuance the findings. The observed trends can be useful when planning new connections of WP. If conclusions regarding e.g. placement in grids, incentives for connecting in the "right" areas could benefit both the DSO and the GSO.

Regrettably, quantitative studies could only be performed on WP. The overall research question aimed to investigate if PV or WP already has caused the risk scenarios to be realized. Not even smaller isolated parts of the low voltage grids were found to have large enough installations of PV. This suggests that PV is not currently significantly affecting the operation of the distribution grids. Studying the effects of PV would have given the Thesis a better contribution to the knowledge of future development. WP is already implemented widely and its effects therefore better documented. PV is the fastest growing energy source in Sweden in terms of installed capacity and distributed much less centralized on the grids than WP. Its effects on grid operations are likely different than those of WP.

The process of identifying voltage deviations due to WP was done as good as time and availability of help from initiated people would allow. It proved difficult to assess the research question properly, since no instances of poor voltage stability could be identified. Several low voltage stations were looked at in detail for identifying large deviations, but none could be found. The authors are confident that the right people have been consulted, but to some extent regret that the research question was altered from the identified future risk scenario. It was PV's influence on voltage stability on local grids that was the original finding of the quantitative analysis. The conclusion that PV has not had any detrimental effect on voltage stability within the grids of E.ON is an important conclusion nonetheless. Both time and money can be saved in focusing on more pressing issues.

The conclusions regarding the measure for reducing consequences of losses are as comprehensive as the explanation of the incentive by EI will allow. It is in several aspects vaguely stated and provides no definition of how added local generation is to be proved as the cause of increased losses. How well the intervention will compensate is left up to the regulation authority of EI. It is also up to them to decide if a similar analysis as performed in the Thesis can function as a basis for appeal of the incentive outcome.

Different statistical software was tested for analyzing the attained data. Excel 2013 was found to be both simple to use and efficient for the performed tasks. No time consuming learning of new programs was needed. Foremost, it is a frequently used software at both E.ON and available at LTH. This makes the analysis easy to repeat if for example more grid areas need to be analyzed. Some problems did arise in the beginning. The Excel-files were initially too big to handle. The problem was solved by removing all measurements of reactive power, which reduced the size of the files by roughly half. One year data with approximately 8700 values in every row proved to be the difficult for Excel to handle. If the study is repeated, the authors recommend either shortening the time series length or using a more powerful computer than the ones used for the study.

CHAPTER 6

CONCLUSIONS

This chapter aims to summarize the findings of the Results and Analysis section and present key findings. The students also give recommendations for future work and similar studies.

6.1 RISKS AFFECTING THE RELIABILITY OF DISTRIBUTION

Six technical future risk scenarios were identified. The survey ranked them from most to least problematic: Uncontrolled Islanding, Undesired Events due to Unmanageable System, Harmonics on the Grid, Overvoltage on the Grid, Unacceptable Levels of Reactive Power and Increased Distribution Losses.

Uncontrolled Islanding was ranked as the biggest threat in regards to increase in likelihood and high consequences. As far as the authors know, uncontrolled islanding caused by PV or WP has not occurred in Sweden. The typical severity of its consequences vary from negligible to high, depending on who is asked. The Authors recommend that uncontrolled islanding is prioritized as a substantial risk. Making sure the proper detection functions and cut out of generation is installed within generation systems is likely that the most effective way of avoiding Uncontrolled Islanding. That can be enforced by the DSO.

In second place came Undesired Events due to Unmanageable System. It is a complex risk scenario which addresses the whole of the distribution system. The events that can occur are unknown and there might be unknown consequences, which makes this risk hard to manage. How does one reduce a risk or a consequence if one does not know what to address? Most of the other risk scenarios identified have been realized before and are recognized. Data of both voltage and losses are measured parameters which DSOs are used to measuring. The surveillance of the power system might not measure the right parameters for identifying the potential risks that have not yet been observed. The authors recommend that DSOs also have unexpected risks in mind when continuing to facilitate new installations of PV and WP generation and to observe other DSOs who in some cases might be ahead in the development.

Harmonics has been ranked as one of the most serious future risk scenarios, but dismissed by the authors as an exaggerated risk. The input provided by experts on the subject were considered more reliable than those of the other respondents of the survey. Harmonics caused by WP and PV is becoming less of a problem as the technology is improving. Harmonic overtone filters can also be used to reduce the prevalence of harmonics.

Overvoltage is likely to become a problem in the future if installations in Sweden are performed in the same way as in Germany. The survey identified it as one of the most problematic future risk scenarios considering both increase in likelihood and severity. This risk scenario is possible to mitigate using DG itself. Active voltage regulation using reactive power compensation is used in large scale WP and is becoming economically feasible for small generation units as well. Installing such functions to DG can help mitigate the problems it causes and maybe even contribute to a better voltage stability on the grid. A potential impediment to those types of solutions is identified in section 4.1.3.5, Managerial and Economic Issues. There are no clear rules for responsibility or economic compensation for the functions from EI.

The identified consequences of the six future risk scenarios were Electrocution of People and Animals, Fire Hazard, Damage to Utility Equipment, Damage to Customer Equipment/Property, Decreased Efficiency, Lower Competitiveness, and Blackouts/Disturbances. All the scenarios can cause negative impact on DSOs economy. However, Overvoltage on the Grid and Undesired Events due to Unmanageable System can in excess of this also have a negative impact on society. Uncontrolled Islanding can have negative impacts on all three, society, environment and economy. Conclusive for most of the identified future risk scenarios is that their likelihood is reduced by following restrictions and requirements according to the relevant grid codes.

Several risk reducing measures were suggested in the result. Most of the technical risks are practically amendable. There are many technical solutions that can be implemented. Problems regarding cost and responsibility allocation remain. To get a broader perspective of the risks DSOs face, manageable and economic issues were identified. They are more of a strategic character. The identified issues were Undefined Responsibility for Financing of New Regulatory Functions, New Solutions Making Old Investments Redundant, Unclear Apportion of Balance and Regulatory Responsibility, Customer Independence, Threshold Situations and Unfair Apportion of Costs, and New Regulatory Directives. These might lead to Economic Losses, Bound Capital, Larger Investments and Hampered Development. Possible solutions are Planning, Development and Testing of new solutions, and Stricter Grid Codes.

6.2 Effects on the Operation of the Distribution Grids Today

Distribution Losses and Overvoltage were investigated further to see if they already today affect the operation of the distribution grids operated by E.ON. Problems regarding voltage deviation caused by WP could not be found. The study was continued by looking into a low voltage grid with several times more capacity of WP generation than internal demand of electricity. No unmanageable voltage deviations could be found at the transformer station through which the surplus generation was transported. No immediate impact from the underlying WP could be detected on voltage stability nor was the reactive power at unacceptable limits. The conclusion from the study is that WP at current levels has not affected voltage stability to a degree that is unmanageable.

WP has affected losses differently in the studied medium voltage grids. WP has a reducing effect on losses in SYD. The loss rate in that grid decreases when WP generation is active. The relationship is reversed when more than half of all available WP is generating, then the loss rate starts increasing. The majority of observations are concentrated to lower percentage of WP generation, when loss rate is observed as lower. Less frequent are the observations with high WP generation, which exhibit an overall higher loss rate. This implies WP's aggregated effect on losses is a decrease in SYD. The presence of WP generation also seems to increase the spread of losses within this grid. SUR, which has a high consistent consumption, seems not to be affected at all. The loss rate in general is very stable. This grid is likely to handle more WP well. In SML, WP generation has a negative effect on loss rate. Removing the observations with nuclear power generation reveals one of the stronger trends of increased loss rate as WP generation increases. Although not much WP is installed to this grid, the addition of further WP could increase the share of losses. In ADL the extra WP generation has profoundly affected the loss rate. After a WP plant started to generate on the 27th of July, a rather high increase of loss rate is observed. Furthermore, the observations show a more scattered distribution. What the actual causes of the change might be is unknown, but adding more WP to the grid would likely further affect losses negatively. There seems to be a threshold when high enough WP generation causes the loss rate of a grid to increase.

A large enough addition of local generation during the following years could cause the losses to increase enough for the EI incentive to fall out negative. The detrimental effect of WP in some of the studied grids could make the reduction of the incentive relevant for the settlement period of 2016-2019. Recent years show decreased overall losses in most grids, possibly ruling out the use of the clause in the formulation of the losses incentive. One crucial element remains before this measure can be concluded as a relevant for reducing the economic consequences of increased losses. Only EI can decide if proving WP as the cause of increased losses in one grid settlement area can work as evidence to prove WP as the cause of increased losses in an entire regulatory reporting unit. “Reasonably” is the formulation used for how large the reduction of the incentive should be. This formulation leaves room for speculation regarding the value of an appeal.

Although PV has not here been assessed in the same way as WP, important conclusions can be drawn. None of the consulted experts could identify areas with enough PV for studying the two risk scenarios in a quantitative manner. The overall absence of PV leads to the conclusion that PV has not currently detrimentally affected the grids operated by E.ON, at least not measurably. This might seem obvious, but it does answer part of research question number two. It also means that focus can be shifted to addressing more urgent risks. Until PV reaches a large enough total capacity to study on a bigger scale, it is important that the proper functions and quality requirements are met by new connections. The problems experienced in other countries with more PV can hopefully be avoided by taking the proper precautions and demanding that PSOs follow rules and regulations.

6.3 To the Future and Recommendations

The Thesis has covered many aspects of reliability of distribution and technical risks. Any of these could be elaborated further and some would on their own qualify for analysis on a master thesis level. Since Uncontrolled Islanding and Undesired Events due to Unmanageable System were ranked as the biggest future threats it is recommended that the DSOs acknowledge these. Risk reducing measures might be necessary for maintaining a high reliability of distribution of electricity in Sweden.

The change in likelihood of each risk scenario was estimated. For future work it is recommended by the authors that a more thorough evaluation of the likelihood is performed. How often consequences arise and how severe each type is could help to identify the "correct" risks.

As of today, PV generation installations are small and scarce. There is no noticeable impact on any aspect of operational security because of PV. A significant increase of installed capacity would make a repetition of the qualitative study analyzing the effects of PV relevant. Avoiding future problems can be done by following the rules and regulations for installing new generation units.

It is recommended that the increased losses in ADL are investigated further in order to determine the total economic impact of the increased loss rate and spread thereof. The authors recommend asking EI to further specify the premises and methodology for appealing an eventual negative outcome of the incentive.

A thorough investigation of the characteristics that make losses in grids respond differently to WP generation is recommended. Consideration for how individual grid areas respond to WP in terms of losses could be beneficial for creating a more efficient distribution and perhaps even reduce the losses in some grids.

Many of the suggestions for risk reduction in chapter 4.1.3 can be used proactively for mitigating eventual effects of PV and WP. That would ensure a continued high reliability of distribution of electricity in regards to the studied risk scenarios. One particularly interesting suggestion is the use of DG as means of regulating voltage and reactive power. Making such functions available should be considered as a complement to upgrading voltage only in transformer stations. That would provide voltage regulation at more peripheral points in the grid, providing better control. If PV becomes more plentiful, such control could hopefully prevent problems similar to those in Germany.

CHAPTER 7

REFERENCES

4C Strategies (2013) Risker och sårbarheter i smarta elsystem - En förstudie. Stockholm: 4C Strategies AB

Abo-Khalil, A. G. (2013). *Impacts of wind farms on power system stability*. INTECH Open Access Publisher.

Alaküla, M., Gertmar, L. & Samuelsson, O. (2011) *Elenergiteknik*. Lund: Industriell Elektroteknik och Autmation, Lunds Tekniska Högskola

Barbu, C. M., & Capuşneanu, S. (2011). Remarks regarding the notions of risk and uncertainty. *International Journal Of Academic Research*, *3*(4), 444-450.

Berglund, S. & Åkerlund, J. (2004). *EMC, elkvalitet och elmiljö - guide för elanvändare och allmänt sakkunniga inom elområdet*. Stockholm: Elforsk

Bollen, M. (2009). *Mikrogenerering och Elnätet - Bedömning av påverkan vid stora mängder mikrogenerering på lågspänningsnätet* (Elforsk rapport, 09:49). Elforsk

Bryman, A., & Nilsson, B. (2002). *Samhällsvetenskapliga metoder*. Malmö: Liber ekonomi, 2002 (Trelleborg: Berling Skog)

Davidsson, G., Postgård, U., & Hardestam, P. (2003). *Handbok för riskanalys*. Karlstad: Statens räddningsverk, 2003 (Östervåla: Elander Tofter)

Ding, X. & Crossley, P. (2005). Islanding detection for distributed generation. *2005 IEEE Russia Power Tech*, 1. doi:10.1109/PTC.2005.4524688

Energiläget 2015. [Elektronisk resurs]. (2011). Eskilstuna: Energimyndigheten, 2015.

Energimarknadsinspektionen. (2015). Föreskrifter om vad som avses med ett effektivt utnyttjande av elnätet vid fastställande av intäktsram (EIFS 2015:6). Energimarknadsinspektionen

European Commission. (2016). EU climate action. Collected 2016-04-08, from http://ec.europa.eu/clima/citizens/eu/index_en.htm

Heylighen, F., Cilliers, P., & Gershenson, C. (2007). Complexity and philosophy. In J. Bogg & R. Geyer (Eds.), Complexity, science and society (pp. 117-134). Oxford: Radcliffe Publishing

IEC (2009). IEC 31010:2009: Risk management - Risk assessment techniques. Geneva: IEC.

Jiménez, R., Serebrisky, T., & Mercado, J. (2014). *Power Lost: sizing electricity losses in transmission and distribution systems in Latin America and the Caribbean.* Inter-American Development Bank. Available http://www10.iadb.org/intal/intalcdi/PE/2014/14933.pdf

Johansson, H. & Jönsson, H. (2007). Metoder för risk- och sårbarhetsanalys ur ett systemperspektiv. Report 1002. Lund University Centre for Risk Analysis and Management, Lund.

Kaplan, S. (1997). The Words of Risk Analysis. *Risk Analysis: An International Journal*, *17*(4), 407-417

Kaplan, S., & Garrick, B. J. (1981). On The Quantitative Definition of Risk. *Risk Analysis: An International Journal*, *1*(1), 11-27

Kaplan, S., Haimes, Y., & Garrick, B. (2001). Fitting Hierarchical Holographic Modeling into the Theory of Scenario Structuring and a Resulting Refinement to the Quantitative Definition of Risk. *Risk Analysis: An International Journal*, *21*(5), 807.

Kraftringen. (2016). Från Stamnät till Lokalnät. Collected 2016-05-01, from http://www.kraftringen.se/Privat/El/Elnat/vart-elnat/

Kvale, S., & Torhell, S. (1997). *Den kvalitativa forskningsintervjun*. Lund: Studentlitteratur, 1997 ; (Lund : Studentlitteratur).

Larsson, Å., & Larsson, R. (2006). ASP: anslutning av större produktionsanläggningar till elnätet. Stockholm: Elforsk, 2006.

Lindahl, J. (2014) National Survey Report of PV Power Applications in Sweden 2014. Energimyndigheten.

Luu, N. A. (2014). Control and management strategies for a microgrid.

Magnusson S. E., Nilsson, J., Hallin P-O. & Lenntorp, B (2000). Integrerad regional riskbedömning och riskhantering. Report 1002, Lund University Centre for Risk Analysis and Management, Lund.

Manwell, J. F., McGovan, J. G., & Rogers, A. L. (2009). Wind energy explained: theory, design and application. Chichester : Wiley, 2009.

Microsoft. (2016). CORREL function. Collected 2016-04-07, from https://support.office.com/en-US/article/CORREL-function-995DCEF7-0C0A-4BED-A3FB-239D7B68CA92

MSB (2011). MSB24: Vägledning för risk- och sårbarhetsanalyser. Myndigheten för samhällsskydd och beredskap (MSB)

Mörée, G. (2015). Elnätsföretagens redovisning av risk- och sårbarhetsanalyser och åtgärdsplaner 2014 -Ei PM2015:01. Energimarknadsinspektionen

Nilsson, J. (2003). Introduktion till riskanalysmetoder. Report 3124, Department of Fire Safety Engineering Lund University, Lund.

(REN21) Renewable Energy Policy Network for the 21st Century (REN21). (2014). *Renewables 2014 Global Status Report*

Renn, O. (1998). The role of risk perception for risk management. *Reliability Engineering and System Safety*, *59*(1), 49-62.

Ritchie, J., & Lewis, J. (2003). *Qualitative research practice: a guide for social science students and researchers*. London: SAGE, 2003.

SFS 1997:857. Ellag. Stockholm. Miljö- och energidepartementet

Short, T. A. (2004). *Electric power distribution handbook*. Boca Raton, FL: CRC Press, 2004.

Svensk Energi. (2015). Elnätet. Collected 2015-11-16, from http://www.svenskenergi.se/Elfakta/Elnatet/

Svenska Kraftnät. (2015a). *Nätutvecklingsplan 2016 - 2025 : en tioårsplan för det svenska stamnätet.* Sundbyberg [2015].

Svenska Kraftnät. (2015b). *Investerings- och finansieringsplan för åren 2016 – 2018.* Sundbyberg

Svenska Kraftnät. (2013). *Perspektivplan 2025: en utvecklingsplan för det svenska stamnätet.* Sundbyberg

Sgarbossa, R., Lissandron, S., Mattavelli, P., Turri, R., & Cerretti, A. (2014). Analysis of ΔP-ΔQ area of uncontrolled islanding in low voltage grids with PV generators. doi:10.1109/ECCE.2014.6954178

Söder, L., Dahlbäck N., Sture Larsson, S. & Linnarsson, J. (2014). *Reglering av ett framtida svenskt kraftsystem.* NEPP (North European Power Perspectives)

Vikesjö, J. & Karlsson, D. (2013). *Affärsmöjligheter med frekvens- och spänningsreglering med nya produktionskällor* (Elforsk rapport 13:45). Elforsk

APPENDIX A

SUBJECTS OF INTERVIEWS

The interviews were conducted as "in-depth interviews". As explained in section 1.5.1.2 method the issues and questions that needed to be answered were written down and worked as a template of what topics the interviews needed to cover. Below are the subjects and questions that the authors wanted to cover and hence were discussed during the interviews. The subjects varied some from interview to interview depending on the expertise the interviewee had. Some of the interviewees, R. Nilsson, A. Larsen and G. Bolin were strictly asked about managerial and economic issues.

Technician interviews

- Identify the technical risks that arise with the increase of renewable electricity generation
- What problems exist today and which problems will occur in the future?
- How is the operation of the grid affected by the risks?
- How have the conditions changed negatively for the electricity system in connection with the expansion of renewable energy production?
- Has anything been done and, if so, what has been done to cope with the impact from the renewable energy production?
- What can be done to increase the reliability of distribution?

Managerial and economic issues

- What managerial and economic issues might occur when implementing more WP and PV?
- What managerial and economic issues might be a problem when striving towards a green future?
- How can one handle the issues that arise?

Appendix B

Summary of Interviews

Appendix B is the summarized transliteration of the interviews. The interviews are sorted in alphabetically order according to interviewees' last name. The order can be seen below.

1. Ann-Christine Andersson, E.ON
2. Michell Andersson, E.ON
3. Sonny Bodell, E.ON
4. Göran Bolin, E.ON
5. Niclas Broman, Vattenfall
6. Torben Eybye Fonnesbæk and Torben Skødt, Energinet.dk
7. Björn Karlsson, Mälardalen Högskola
8. Alf Larsen, E.ON
9. Rune Nilsson, E.ON
10. Fredrik Roos, E.ON
11. Sebastian Schmidt, Bayernwerk
12. Poul Ejnar Sørensen, DTU
13. Patrik Thuring E.ON

Interviewee: Ann-Christine Andersson, E.ON
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 11/1, 2016

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Ann-Christine Andersson works as Key Account Manager at E.ON Elnät. She has worked in various fields of electricity distribution with the implementation of PV and WP, especially with small scale distributed generation.

Summary of Interview

The market is changing. Before there was little distributed energy generation, but now we have wind farms and solar panels. Today we are talking about microgrids. It is hard to predict the generation of PV and WP. The grid needs reinforcements to handle full generation from the new generation. Maximal theoretical generation from renewable generation is assumed when calculating the capacity of the grid.

It is difficult to withhold the balance, which needs to be maintained continuously. One problem identified is the risk of uncontrolled islanding. If an unacceptable error occurs at a substation or other component, a grid portion will be cut off from the rest of the grid. This is when islanding might occur, which means that the local generation continues feeding the error. Voltage sensing protection (NUS-skydd) is needed (current sensing is not enough), hence demands are put on the customers who are interested in producing electricity.

The problem with renewable energy sources is that they are intermittent. The different sites and stations generate stochastically and gives variations in the grid. This is the reason that the capacity is calculated using the maximal generation from all the sites. The grid has to be able to handle peak loads.

Any advantages regarding the reliability of the distribution of electricity when the amount of PV and WP increases are not mentioned. Today nuclear and hydro power are the main power sources. A phase out of these sources will be a problem for securing energy supply a windless winter day. Then we have to compensate with electricity from other sources of generation.

Storage is mentioned as the main solution to what has to be done in order to obtain a secure power supply with a high amount of renewable energy sources. Trying to control the consumption is not believed to be solution since it is too time consuming and people are too lazy.

The energy quality is strictly regulated but there might be a problems since the sum of the future effects is quite big. Ann-Christine believes that the quantity of the renewable is today too small to see the problem it will cause in the future.

If the price of electricity is increased and installing your own generation becomes more accessible, Ann-Christine believes that owning your own generation will be more common. Today it is complicated to install your own PV system. In England it is possible to buy PV systems from IKEA, which they install.

Even if PV would increase drastically it probably would not be a big problem. The flow through the transformers would decrease if a lot of households install their own energy generators but this is not a problem. It would only mean that the energy companies have to be more flexible. It does not really matter which way the electricity flows.

A note is that the energy companies are slow to keep up with the change that is happening. There are technologies and ways to handle reactive power mm. It would be good to have a map online to see where there is capacity to install renewable energy generation. Then you might not need to expand the grid, which costs a lot of money.

Interviewee: Michell Andersson, E.ON
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 11/12, 2015

Transcribed by Ludvig Carlman Bydén
Revised by Sara Persson

Michell Andersson was a high voltage installation technician at E.ON Malmö. During the time of the qualitative study he has moved on to work at Kraftringen with the same type of assignments.

Summary of interview

Sweden and the industry is still waiting for the "boom" in PV capacity. On average E.ON handles around 1000 new connections every year. WP installations are today almost exclusively on the 130kV (medium voltage) grid. These installations are "higher up" in the grid, and therefore affect lower voltage grids less in terms of voltage fluctuations and other parameters of electricity quality.

Regarding PV and other micro generation. Documentation is vital, it can literally save lives. Non registered generaters can be charged for the electricity they generate. A faulty line or component after the protective relay in connection to a small subset of the low voltage grid can inhibit the monitoring and regulation of the isolated subsystem. If the subsection contains micro generation that is not switched off, the whole system can experience a rise in voltage. This phenomenon is known as Islanding, where a distributed generator (micro generater) keeps on generating effect which is fed to the disconnected grid subsystem. The rise can in turn cause electrical discharges and subsequently fire, damages to property and electrical devices as well as harm people and animals. It is standard for new systems to sense the rise or drop in voltage that comes with the disconnection.

WP installed with modern technology has reached a much better level of maturity than PV. Already today, with the low total installed effect, PV is increasingly problematic on a low and medium voltage grid level. A doubling or tripling of the speed of implementation, new scenarios arise which need to be properly assessed.

- What happens during uncontrolled islanding?
- Which protective measures are in place?

"The risks of consequences due to DG distribution is high, and the implications of those quite severe, which will make additional measures necessary"

Overgeneration from DG, when the direction of load flow is reversed, is when the real problems for the grid operation begins. Additional relay protection is not invested in if the DSO does not suspect the direction of net effect to have changed. That is why documentation of DG is extremely important. Having to implement additional protective relays on all affected potential islanding subsystems would be an unbearable expense for DSOs if all roofs are fitted with micro generation.

The recent talk of nuclear power is only made possible by the today almost equivalent amount of WP that has been installed.

The total time from the initial order of a medium voltage grid connection of a new generation plant to the completion of construction spans over a total of 4-5 years.

In extreme situations of massive electrical infrastructure interference, such as a weather event, information etc. risks are much higher for further failures and damages.

"Proper maintenance of the transmission highways would make it unnecessary to replace suspended lines with buried cable". There are long delivery times for grid components. They are custom constructed to fit the conditions at the site and are not easily replaced. There is one or two portable backup substations ready to be deployed.

Interviewee: Sonny Bodell, E.ON
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 12/1, 2016

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Sonny Bodell works with meter technique at the division of Meter System. He has good knowledge of what the meters can handle within the grid, their ability, limits and weaknesses.

Summary of interview

Sonny explained that the meters work almost 100% of the time. The reason for missing values is 99.99% of the times due to failure in communication with the measuring equipment. It is extremely rare that a meter is broken or influenced by poor electricity quality. He is certain that increasing renewable energy generation will not affect the meters or the amounts of values received. However, Sonny sees the need for analytical tools for analyzing the data in order to see if transformers need to be replaced.

Most, or all, new meters can measure electricity both ways. Older models measured the absolute value of the electricity. The direction of effect was not taken into account, as it was safe to assume the one way flow path from generation to customer. If the consumer, for example a house with PV panels, generates more electricity than is consumed, the measured value when the electricity is exported to the grid registers as negative. When the household is a net positive consumer, the result is a positive value. generation from any generator is always hourly measured, but the household as a whole is only checked monthly for the sum of consumption. The “prosumer” pays for the volumes they consume and get paid 0,2 kr/kWh (exclusively price of electricity) for the electricity surplus they export to the grid. That price is only guaranteed as long as the household exports less electricity than it consumes.

Interviewee: Göran Bolin, E.ON
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 17/2, 2016

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Göran works at E.ON Sweden Malmö. At the division of Stakeholder management, Regulatory Affairs.

Summary of interview

Göran explains that more renewable energy sources are used and that the energy generation is getting more decentralized. The future is green. Göran believes that in the future around 2045, 2050 the nuclear power era will be history. E.ON has to accept this and embrace the change and development.

The future is green, the question is rather how far we have come in 2045. One thing that might stand in the way is the fact that EU has a hard time uniting over an energy policy. Everything that happens in the world affects the development. Like the price of oil, the war in Syria, the conflict between USA and Russia. Geopolitics and power play affects the development. "Money makes the world go round."

The whole Swedish electricity grid costs about 45 billion Swedish crowns yearly to maintain. Göran does not know if it might be a problem if too many store electricity in the future. He thinks that the project in northern Sweden is where they are going to disconnect a part of the grid from the rest will give an indication. Some parts of the grid infrastructure might prove superfluous in the future. Either way, the industry needs to accept the change and get on the train of development.

Interviewee: Niclas Broman, Vattenfall
Interviewer: Ludvig Carlman Bydén and Sara Persson
Date: 18/1, 2016
Telephone meeting

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Niclas is the Head of Development and Tendering at the division of Operational Readiness, Generation, BA Wind, Vattenfall Vindkraft AB.

Summary of interview

The DSOs are not very keen on implementing more WP since the investment costs are high. More WP challenges the structure of the distribution system, as generation is changing from centralized to more local and decentralized generation. DSOs face both technical and economic challenges as the trend continues.

WP plants can be fitted with features which are beneficial for the grid. Furthermore, he explains that they sometime get paid for reducing the power generation from the WP plants, mainly in Denmark, as a service.

In one way the reliability of distribution is higher with more WP and PV. Distributed generation instead of large centralized generation reduces the impact of when a power plant malfunctions. However, with more intermittent power you lose the ability to plan the generation.
When building a WP plant the main factor investors take into account is the wind conditions at the site. Second is the possibility and cost of land acquisition, coming to an agreement with the landowner and authorities.

In Sweden a drastic increase of the offshore WP is not likely since it cannot economically compete with the onshore. Although wind conditions are better, the costs are too big.

When asked about multi-lateral collaborations in utilizing the favorable natural conditions for offshore wind farms off the coast of Sweden he responds with two contrary arguments. From an engineering perspective it is sound and possible to reduce neighboring countries dependence on fossil fuel for electricity generation with WP generated in Sweden. It is however politically difficult to come to agreements for such projects.

The work that is being done today regarding the function of WP plants focuses on making unforeseen and unplanned events predictable. Manufacturers try to get indications that a component is about to break at an early stage. This provides better continuity in maintenance and possibility to repair the systems before they become out of operation.

A perspective provided is the technology developing rapidly. During planning and construction, as soon as one system is decided upon and installed it is outperformed by a better version. One new technology that has proven useful is the fault ride through function. Back in the day if there was a drop in voltage the WP generation was cut off, today the generators can support the grid and ease the transition back to normal conditions (fault ride through).

Interviewees: Torben Eybye Fonnesbæk and Torben Skødt, Energinet.dk
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 19/1 2016
Telephone meeting

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Torben and Torben work at the Danish equivalent to Svenska Kraftnät and have witnessed the transition to large shares of WP in Denmark and the challenges it presents.

Summary of Interview

Denmark has a problem with transportation of electricity when they have overgeneration. There is also a lot of WP in northern Germany which means that their coinciding generation cannot be exported to Germany. Instead, they are asked to buy electricity from Germany. High generation during times of low consumptions have in some instances created negative prices for electricity. The prices shift with the access to energy, if there is a lot of WP generation the prices are low. Through this market incentive they hope to control the consumption to some extent.

WP is seen as a good source of energy. Denmark is dependent on Sweden and Norway for import or export of electricity, to which the connections are good. The market is well functioning and there are solid agreements between the countries. The National ambition is to keep on expanding the use of WP.

Voltage stability and quality - The power plants are equipped with synchro compensators which deliver reactive power. It is possible to use WP to actively regulate reactive power.

They explain that back in the day there were problems with voltage deviations caused by the asynchronous WP generators. However, these WP stations are between 20-25 years old and are being replaced. Hence, this problem is disappearing. Today it is mainly negative prices and overgeneration that cause problems. WP plants can be used to regulate the voltage. This is not generally used today but in the future it will probably be more common.

When Germany has overgeneration they should ask Denmark to buy their electricity before they reduce the generation from the WP.

In Denmark the grid owners do not receive any additional compensation for the losses due to renewable energy generation.

Today Denmark has 3 500 MW (or more) WP installed which they are able to manage, which was not thought possible five years ago. If however, the connections between Denmark, Sweden and Norway would break down it would be a big problem. Overgeneration is possible to control since it is possible to decrease the generation. There is now a project aiming to connect England and Denmark using a cable between the countries.

Energinet.dk is obliged to use the electricity generated from renewable sources, if they disconnect the renewable energy sources they have to pay compensation.

Denmark and Germany are planning a joint WP plant. Sweden's Svenska Kraftnät was supposed take a part in it as well, but declined. The project has started, the WP plant is not yet in use.

It is believed by the interviewed that Denmark's main risk with implementing more renewables is insufficient energy generation from WP to supply Denmark's need in combination with limited access from neighboring countries. This is why they are installing connections to other countries, in order to always have backup power.

A Nordic balance collaboration with Denmark, Sweden, Norway and Finland will soon be a reality where the volumes between the countries will be coordinated. This is due to an initiative from EU. Renewable energy requires solving problems in a bigger perspective, increasing the need for cooperation.

Interviewee: Björn Karlsson, Mälardalen Högskola
Interviewers: Ludvig Carlman Bydén, Sara Persson
Date: 18/1, 2016
Telephone meeting

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Björn is a professor in energy technology at Mälardalen Högskola (MDH). He works at the Division of Energy, Building and Environment. Björn has plenty of knowledge regarding PV.

Summary of interview

The conversation is initiated with the (not perfectly paraphrased) opinion that there is no need for Sweden to install PV cells since we do not use any, or at least very little, fossil fuels for electricity generation. He explains that the contribution to the electricity system in Sweden as a whole is the ability to reduce private consumption of the households on which they are mounted. There is better use for PV in other parts of the EU and the rest of the world. However, PV is attractive and people want to install PV. There will (might) be a boom. For homeowners the main advantage of installing PV is not to overproduce, but rather to reduce costs by not having to buy electricity. This is because one 1 kWh saves roughly 1 SEK crown, but if 1 kW is sold to the grid instead of consumed the selling price is only 0.20 SEK.

Today there is a tax reduction for installing PV. Side note "There is no practical need for PV and hence the technology should not be subsidized or subject to tax reductions."

Batteries and other forms of storage will help save the energy from hours of generation to hours of consumption. However, this is not realistic as of today, since batteries are of poor performance and economic viability.

When looking at the grid, there is no problem with implementing a lot of PV in a city, because there is a consumption to satisfy. Elisabeth Kjellsson has done studies on this. The potential for PV is enormous, the problem is to make them technologically and economically viable. A problem would be having large generation on the countryside where the grid is weaker.

Björn stresses the importance of being able to automatically turn off PV generation. This protection is built in to the inverter, which senses the loss of voltage on the grid side. Both islanding and the risk of fire are possible, the latter not extensively documented.

Side note: Björn informs us that he is active within Socialdemokraterna and this might affect his opinions and point of view during this interview.

Interviewee: Alf Larsen, E.ON
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 11/2, 2016

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Alf Larsen works with grid business development at the division of Grid Business Intelligence at E.ON Elnät.

Summary of interview

Alf is looking at how the energy market will change, what problems it will face and what decisions that need to be made regarding the operation of the energy system. Alf says that if we imagine a future where every roof has PV or other generation, the grid would not really be necessary. Hypothetically it would be possible for the consumers to disconnect themselves from the grid. This scenario is not realistic today, but feasible in a future where the technology is more efficient and affordable. In this scenario, when consumers only are connected to the grid as a backup, how much will they be willing to pay for that backup? The problem is that they would probably want to pay less, but the cable still costs as much as before. That is a challenge that E.ON and other DSO's face.

When a consumer installs PV it might be necessary to enhance the grid to keep the voltage at a good and stable level. The grid is made for transporting electricity from higher levels of voltage, down to the finer low voltage grids and not the other way around. A challenge is to enhance the functions of the grid within the economic bounds of the regulations that govern their revenue limit. They consider the available techniques and what requirements they need to enforce on "prosumers". Being able to store energy would help evening out the variations in availability. Can that be asked of prosumers, or can it be implemented by the DSO itself? Perhaps storage on a large scale should be taken into account when planning the grids of tomorrow? The overall costs increase when enhancing the grid, but there is no guarantee that the investments will be useful in the future.

With the possibility to store electricity at different sites of the grids it might be possible to reduce the flux of power from the WP and PV. That would decrease the need for much of the extra transmission capacity that needs to be able to handle the increasing spikes in generation. What requirements E.ON can enforce on the prosumers are determined by the regulation from EI. The political hindrance is sometimes a problem for E.ON. Today there is no comprehensive legislation regarding storage. As the current laws are stated, the interpretation can be read as DSOs not being allowed to implement their own electricity storage. The rules on how electric regulatory technologies can be used in combination with micro generation are unclear.

The possibility of small independent grids ("controlled islanding" or microgrids) is discussed. For some communities it might be beneficial for both their economy and energy security to be part of an "island". Industries however, need the reliability and quality of electricity that is provided by the current infrastructure, with large scale planned generation.

Centralized generation is being replaced by local generation (phase out of nuclear energy). The trend does not eliminate the need for the grid but rather changes the structure of it. Alf believes that the local generation will work as a complement to the centralized generation, that the two “worlds” will intertwine and the challenges will be solved gradually.

Generation of electricity performed by a DSO can be used for compensating for the losses within their grid, but not for sale on the electricity market. It is possible to get compensation for the losses even if E.ON generate electricity to cover their own losses. The losses are considered as one parameter, one of many, when the intermittent generation is planned. Today E.ON has no plans for installing wind or PV generation where it would be beneficial to the operation of the grid. The electricity price is too low for such an investment to be profitable.

Interviewee: Rune Nilsson, E.ON
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 2/2, 2016

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Rune works with grid business development at E.ON, division of Grid Business Intelligence.

Summary of interview

Regulation by EI determines how much DSOs are allowed to charge their customers. However, new technology that is needed to solve technical problems caused by renewables are not on the list over what DSOs are to receive compensation for. Hence, E.ON might not get the proper compensation.

DSOs are not allowed to generate their own energy. There is one exception, they are allowed to generate energy to compensate for losses within their grids, so they do not need to buy the losses on the open market. They are not allowed to generate more.

E.ON is currently performing a pilot project researching the practical feasibility of controlled islanding in a community of 100 people. In northern Sweden a grid subsection will be disconnected, operating on purely on renewable energy, independent of the rest of the grid. The project covers many of the problems treated in this thesis. They deal with obstacles in regards to politics, economics, technology and other risks. The legal framework is not adapted to this type of solution. One impediment is the DSOs prohibition on producing their own electricity within the disconnected grid. Working around the problem, they can claim that they use it to partly cover their overall losses (E.ON in total experiences losses far greater than the generation in that micro grid). Still, disconnecting a grid has other legal issues. For this particular project they have been exempted from these predicaments, as the Minister of Energy sees the value in continuing with the project.

When someone wants to connect their own generation to the grid, calculations are made to determine what that customer should pay in connection fee. The payment should correspond to the investment the grid owner has to make when connecting them to the grid. If an installation requires a large additional investment, due to new load flow situations, it might cost more than an ordinary customer or generation investor can pay. Allocating the payment fairly is not so simple. Is it to be charged to the customer collective or to the GSO? What about the fact that others might have installed the same generation when capacity was vacant without paying extra? To DSOs with limited resources, a government loan can be granted to cover the costs of additional capacity in the short term.

If a DSO experiences annual losses smaller than the norm stipulated by EI, they are allowed to charge their customers according to the norm and keep the money that is not spent on losses. If a DSO has higher losses than the norm, they are not allowed to charge their customers with additional fees for covering their expenses when the losses increase. However, if they can prove that their losses have increased due to more installed renewable energy sources they can get their revenue cap set higher. The logic is that they can refer to their compulsion to install the generation that is applied for by investors. The same logic can be applied to DSOs with low losses, allowing them to increase their revenues. According to the interpretation of Rune, It can only be applied when the overall losses increase from one year to the next.

Hypothetically, in the future it might be possible that the consumers will be rather independent. If the batteries are good enough so that it is possible to store electricity there will not be the same need of the electricity companies as today. If this is the future then the biggest risk for independent users would be during the winter, during Christmas when we cook and watch TV etc. Then the energy generation and the stored energy might not be enough to supply the consumers. Having an idle connection to the rest of the grid might be a service people are willing to pay for when backup power is needed, but how much are they willing to pay? The costs for maintaining a functioning grid are not reduced just because electricity is not needed.

The technical possibility to solve and reduce most of the risks in connection to renewable energy was discussed. One question regards who is supposed to pay for the techniques that makes it possible to control the voltage, frequency etc. Rune says that Swedish Svenska Kraftnät has the ultimate responsibility. He informs that the oil power plants in Karlshamn have been used for backup power during this winter when it was extremely cold.

Rune explains that E.ON can buy the overgeneration from the houses to cover up for the losses within their grid. The consumer/generator does not care since they get paid the same price, their costs might even be reduced if the grid owner can use the overgeneration.

There is a backup plan if the power generation is much lower than the consumption, or in case of a major blackout event. There is a schedule over which areas that will be cut off in what order, switching them on and off so that no household is without electricity during a longer time. This plan has not yet been used.

Interviewee: Fredrik Roos, E.ON
Interviewer: Ludvig Carlman Bydén
Date: 15/1, 2016

Transcribed by Ludvig Carlman Bydén
Revised by Sara Persson

Fredrik Roos work with voltage quality (EMC) and magnetic fields (EMF) at E.ON Malmö. He has knowledge about quality of electricity supply, what affects it and what measures that can be taken to improve it.

Summary of interview

With the rapid implementation of renewable energy (RE), Fredrik emphasizes that problems regarding voltage quality are easily avoided if the disturbances caused by the electricity network users are well in the bounds of what is considered acceptable. He explains that as long as DSOs stipulate requirements which are obeyed by the network users, further implementation of RE will likely not pose any significant problems in regards to the voltage quality. He expresses some doubts regarding how well the rules are followed and enforced, or if the guidelines are strict enough on the generaters. To his knowledge no urgent problems have been identified as a result of the high amount of WP in the grid of E.ON. Total installed PV power is not yet of such a magnitude to cause any significant problems.

Rules are set and evaluated as time passes and problems arise. As more disturbing elements are introduced to the system, the effects are studied and measures taken in response.

Responding to the question as to how neighboring DSOs installed generation effects the own grid, he comments on the responsibility of the TSO (Svenska kraftnät) for keeping balance and quality throughout the whole electrical system. Guidelines have traditionally been set by the TSO, but new European EU grid codes are soon to be implemented (https://www.entsoe.eu/major-projects/network-code-development/Pages/default.aspx), which basically cover everything, i.e. things: electrical quality parameters for generators, network balancing, HVDC requirements, generation/consumption forecasting, connection practices....

On a subtransmission level the grid is modelled before large installations, simulating the new load flows. Assuming normal conditions, new generation is added to the model in order to predict the new flow patterns and decide on the necessary reinforcements needed on the grid. The load flow is regularly monitored on a large scale and the system model is stress tested. If reinforcements become necessary, the cost is usually included in the connection fee of the future GSO. There is some controversy regarding the allocation of costs due to these reinforcements. DSOs are obligated to connect generation systems to their grid, but they also have the right to charge accordingly. Eg. when a number of GSOs have had their systems connected to a line without extra connection costs, an additional generation unit connected to that line would require a higher transmission capacity. The reinforcement will require a large investment. Is the cost to be paid for by the operator of the last GSO connected, by all GSOs on the line or by the customer collective of the entire grid? These problems are called threshold effects and are now dealt with by the TSO.

Other questions raised by Fredrik concerned the possibility to use WP to regulate voltage and frequency. DSOs are responsible for setting requirements on GSOs. What should the generation plants be able to do? They can be used, but are they? Should they? Who operates them? Who pays for the additional features?

Fredrik recommends looking at the flow of reactive power in the grid as a part of the qualitative study. Are the losses thereof expected to be significant? Note: many overhead power lines are being replaced with cables, which are generating reactive power and thereby raising the voltage in the subtransmission system.

Voltage harmonics stress electrical equipment, such as generators, motors and transformers shortening their technical lifespan Filters can be put in place to reduce the content of voltage harmonics. Many industries apply such filters, as their machinery generate harmonics. Harmonics are not yet a big problem in the public electricity network, but they are expected to be in the future.

Interviewee: Sebastian Schmidt, Bayernwerk
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 13/1, 2016
Telephone meeting

Transcribed by Ludvig Carlman Bydén
Revised by Sara Persson

Sebastian Works at Bayernwerk, which is a recent addition to the E.ON concern. It is a subsidiary operating ⅔ of the distribution systems on the local and regional level in the Bavarian part of Germany.

Summary of Interview

There are more than 250000 PV installations in the grid operated by Bayernwerk in Bavaria, out of which 85% are installed to the low voltage grid. Generous pricing tariffs for renewable electricity generation has created incentives for installing many and large PV systems. Their influence on medium and high voltage grids is evident. The main concern is maintaining voltage levels. The challenge is reinforcing the grid to cope with the new flows. It is difficult to communicate with and control the individual PV-plants. There is a need for simple and effective ways of regulating the systems. Research, studies and measurements have been done in project areas, looking at the influence on the grid. This in order to form grid standards and guidelines for installations.

Notably the studies have shown that the maximum effect generated by the PV-systems does not correspond to their total installed capacity. This has allowed for rationalization of the grid reinforcements, which according to a new standard are dimensioned to 85% of the installed effect of the PV systems. Causes for this (speculative in regards to individual contribution): clouds, weather conditions, orientation towards the sun, heating of the panels, degradation of materials and consumption in connection to where the systems are installed.

Most of the installed PV is located in rural areas, whereas most of the consumption occurs in the more densely populated areas. This makes for longer distribution paths through primarily low and medium voltage grids, where losses are higher.

Voltage problems have become more frequent, overcurrent not so much. "How do we deal with voltage problems?" They designed control solutions; a dynamic voltage regulation in a primary substation. High PV infeed - "Try to lower voltage on 20 kV transformer to get more PV infeed in the grid and get more voltage rise on the lines without reaching the top of the voltage band". This refers to the fact that voltage drops from where effect is supplied and down the lines. Increasing voltage in the periphery of the grid causes the voltage on the substations further "upstream" to rise over normal conditions. Another option was an on line voltage regulation on the low or medium voltage grids or secondary substations. Pilot projects have been done.

Peak consumption occurs in December/January and peak infeed in April. At some instances there is 30 times more infeed than maximum load. There are more voltage problems on the low voltage grid than on the medium voltage grid. The many secondary substations with high infeed of PV-generation feed forth to primary substations, which in turn need to be reinforced and sometimes complemented by new ones altogether.

It is the overgeneration that raises the voltage to unacceptably high levels. It has some to do with the timing of the generation, which peaks at around midday - 13:00, whereas the consumption is at its highest earlier in the day and later in the evening. As voltage regulation has been in focus for some time, the overcurrent problems have in relation become more troublesome.

The installation of PV is not necessarily followed by higher losses in the grid. The grid reinforcements done in connection to the installations generally help decrease the losses, due to better capacity in the new lines and transformers (lower impedance). The grid does, however, experience higher reactive power flow, and thus higher losses due to the increased total power flow (the complex power). The rural placement of the systems are also contributing to losses through longer distribution paths. Studies are being done on how losses are influenced by grid reinforcements, voltage controls and substation improvements together with the increasing PV. The studies are as of now not completed.

Positive aspects of distributed generation includes lowered losses when the local generation and consumption is matched. DG can ease the problem of having halts in large centralized generation units by providing effect when they are offline. It can also make the operation more difficult when large stabilizing power plants are offline. PV in place today does not support reactive power, voltage or contribute with rotating mass to stabilize the frequency. Small PV power plants can be used for regulating reactive power and voltage. Communication with the new systems need to be developed to a better standard. Using the systems for regulation is a challenge. It is not easy to say what the positive effects could be from implementing such functions. It is as important or more to define rules and boundaries for the generation. The DSOs are currently helping to stabilize the system.

A serious problem is the island effect. It is possible to create grid areas with self-regulating mechanisms, so that a disconnection from the rest of the grid switches on the sub systems regulatory functions in order to run independently. As it is does not communicate with the rest of the grid, the frequency as well as other parameters might be mismatched. Reconnecting the subsystem will therefore be a very difficult task. An area of the grid being switched off could cause serious problems when trying to reconnect. This phenomenon is not only impractical, but dangerous when working on the grid. Maintenance is typically done at hours of low generation, so that the net flow to the area is positive and therefore controllable.

PV systems installed in the future could feature:

· Reactive power stabilization capabilities including voltage control. A reactive power management system would reduce voltage rise and reactive power losses.
· Active power control enabling active regulation of output. Allowing for a more dynamic use of the system and possibility to shut down generation.

Interviewee: Poul Ejnar Sørensen, DTU
Interviewers: Ludvig Carlman Bydén and Sara Persson
Date: 15/1, 2016
Telephone meeting

Transcribed by Sara Persson
Revised by Ludvig Carlman Bydén

Poul is a professor at the Technical University of Denmark. His research areas include: "Integration of wind power into power systems, interaction between wind power and power systems, wind power variability, dynamic simulation, power quality" http://www.dtu.dk/english/Service/Phonebook/Person?id=38456&tab=1 . For more information go to www.dtu.dk

Summary of Interview

WP affects voltage quality, mainly on the low voltage grid. However, today this is not in focus anymore since the WP plants are equipped with well-functioning voltage regulation. Today flicker is not as common as a problem. Generally, WP stations are not installed on the low voltage grid as much anymore, but rather on medium voltage grids.

The low voltage grid is influenced by the deviations on the medium voltage grid, which means that it is the low voltage grid that determines the requirements for energy quality.

It is easier to regulate the voltage today. Both the ability to regulate voltage and reactive powers are improved. At the WP stations of today, it is standard that you can regulate the reactive power.

Sometimes generation is disengaged, in order to match the generation with the consumption. If you install WP stations on the low voltage grid you have to consider the ability to cut off generation.

There is a correlation between increasing amount of WP and bigger losses. If the nearby consumption is equal to the generation, the losses are significantly reduced. Decentralized energy generation can reduce the reactive losses.

In 2015, 42% of Denmark's electricity was generated from WP (2014, 39%). It is possible for Denmark to increase their WP further since Denmark has a good connections to Sweden and Norway. This interconnectivity is the reason Denmark is able to manage the large amounts of WP.

One way to manage the surplus electricity is to store the electricity in sand, since sand has good heat capacity. Then it is possible to convert some of the heat back to electricity. A flexible consumption might help to some extent to match the generation with consumption. But it is not enough to solve the problem with overgeneration.

Interviewee: Patrik Thuring E.ON
Interviewer: Ludvig Carlman Bydén and Sara Persson
Date: 17/12, 2015

Transcribed by Ludvig Carlman Bydén
Revised by Sara Persson

Patrik Thuring works with at E.ON Energy Controlling at the division of volumes & gross margin. Patrik has experience of the WP industry and now also a DSO perspective.

Summary of interview

Most WP is installed to the 130kV grid, some to the 400kV grid. Some GSOs choose to own their own transformer station, some even apply for grid concession when they cannot come to an agreement with the grid operator involved with securing their connection. Grid fees are a large part of the yearly variable cost. Having their own transformer station means a lower tariff.

"Nätnytta" - sometimes the grid tariffs are negative, which means the GSO is compensated by the DSO for supporting the grid where effect or regulatory services are needed, instead of being charged for feeding power to the grid. This can be seen as the GSO providing a service to the DSO, for example minimizing the influence on the grid by placing the generation close to where it can be used.

SvKFS2005:2 states rules for electricity quality from a generation unit. It defines in what interval are the following parameters allowed to vary: reactive power, voltage, overtones, frequency etc. Other DSOs can stipulate their own norms for the quality of electricity that connects to their grids.

Two main categories of WP generators:

1. Doubly-fed induction generator
   Some of the energy generated is run through a power inverter, the rest directly to the transformer substation. This gives some regulatory ability regarding voltage, frequency and reactive power. Somewhat cheaper than 2.
1. Full-fed to power electronics
   This type allows for a greater amount regulatory capacity and ability to handle disturbances, as the full effect of the generator is run through inverters. Thereby, the effect generated is "isolated" from the grid. Better control than 1. It is a bit more expensive. Does imply more losses due to the extensive regulatory capacity, however better quality electricity.

The effect of WP can be regulated within seconds. A standard adopted by some DSOs, although no in Sweden, is to allow only around 90% of the maximum available power to be generated, allowing for some regulatory capacity if the output quickly needs to be increased. This means that WP can, to some extent, be used as regulatory power when wind conditions allow it.

Reactive power regulation of less sophisticated wind turbines is done through large coils (reactors) at the transformer substation, which consume reactive power. The reactive power itself raises voltage when put out on the grids and when present in generators it heats them, creating losses.

It also occupies some of the available transmission capacity in the distribution system (sum of the reactive and active effect vectors). Most turbines of today are only able to compensate for reactive power when effect is generated, in other words when it's windy. Some newer models of for example Siemens do have reactive power support even at standstill.

When building a large power producing facility, the net reactive power to the grid must be adjustable to near zero, according to SVK's standards. In the past grid operators have not been particularly strict in applying that standard. Today it is important, due to the size of the wind parks. Also voltage is thoroughly regulated, both in long and short term deviations.

Other quality parameters
Flicker - very fast voltage deviations. Not a significant problem in newer models.
Frequency - overgeneration leads to higher frequency, a loss of generation during high demand lowers the frequency.

High performance park pilot - HPPP, control system is installed at the point of connection to the Grid. It allows for regulation of the wind park as a whole in regards to output and other quality parameters. This is controlled by the grid operator when needed. When energy security is threatened - grid operators are allowed to steer the park to a lower generation level. GSOs get no compensation when that is the case.

In the case of a voltage drop on the grid and all the way into the park's internal cable system, "fault ride through" is today a requirement for large generation units. This ensures that the park does not shut down immediately, but carries on supporting the grid during a few seconds. That is until the voltage is restored or the park is cut off from the grid. This buys time and eases the transition back to normal operating conditions. Losing voltage means compensating with reactive power, which increases voltage on the grid.

ENTSO-E - European Network of Transmission System Operators for Electricity. They are implementing unison standards of electricity quality throughout Europe, as the grids are increasingly interconnected. Supposed to also help with planning, forecasts, supporting with regulatory power and harmonization of electricity prices.

Decreasing rotating mass a problem with larger shares of renewables. In new WP, the generator itself can soon be used as a rotating mass, but only in the very short term. Decreasing the rotational speed can be done, compensating during a short period. This however, puts the turbine outside of its optimal rpm.

Reactive power losses, with the new regulatory capacity reactive power, will no longer be a problem if all new WP installed is of that dignity.

"Locally" generated energy is usually consumed close to the point of generation, decreasing the flows through different parts of the network and thus decreasing losses. It if foremost the spikes in generation associated with the intermittency that causes longer distance of distribution and high currents, which create heat losses. The distribution system is during these periods of peak power strained to its limits and emit losses in heat form.

APPENDIX C

SURVEY

Risks regarding increasing share of solar and wind power in a distribution system

1. Please fill in the information below

Name

Workplace and Position

Years of experience within the energy sector

Country

Do we have your permission to use your name and answers in our report?

Nästa

2. How do you think the likelihood of the identified risk scenarios will change with an increasing share of wind and solar power in the local and/or regional grids?

	Class 1 Substantial decrease in likelihood	Class 2 Decrease in likelihood	Class 3 No change in likelihood	Class 4 Increase in likelihood	Class 5 Substantial increase in likelihood	Don't know/no comment
Uncontrolled islanding	○	○	○	○	○	○
Unacceptable levels of reactive power	○	○	○	○	○	○
Overvoltage on the grid	○	○	○	○	○	○
Increased transport losses	○	○	○	○	○	○
Undesired events due to unmanageable system	○	○	○	○	○	○
Overtones on the grid	○	○	○	○	○	○

Would you like to add something or comment on your answers?

Back   Nästa

3. Below you can see the identified consequences for each risk scenario. Please categorize the severity of the typical (most likely) impact. If you know of any other consequences, please specify in the comment section.

	Class 1 Negligible	Class 2 Low	Class 3 Moderate	Class 4 High	Class 5 Extreme	Don't know/don't want to answer
Uncontrolled islanding *(Damage to utility equipment, damage to customer equipment/property, fire hazard, electrocution of people and animals)*	○	○	○	○	○	○
Other consequences and/or comments						
Unacceptable levels of reactive power *(Damage to utility equipment, decreased efficiency)*	○	○	○	○	○	○
Other consequences and/or comments						
Overvoltage on the grid *(Damage to customer equipment/property, lower competitiveness, damage to utility equipment, blackouts)*	○	○	○	○	○	○
Other consequences and/or comments						

Increased transport losses
(Decreased efficiency)

Other consequences and/or comments

Undesired events due to unmanageable system
(Decreased efficiency, damage to utility equipment, blackouts/disturbances)

Other consequences and/or comments

Overtones on the grid
(Decreased efficiency, damage to utility equipment, lower competitiveness)

Other consequences and/or comments

Back Nästa

4. Again you can see the identified consequences for each risk scenario. Please categorize the severity of the worst case impact.

	Class 1 Negligible	Class 2 Low	Class 3 Moderate	Class 4 High	Class 5 Extreme	Don't know/don't want to answer
Uncontrolled islanding *(Damage to utility equipment, damage to customer equipment/property, fire hazard, electrocution of people and animals)*	○	○	○	○	○	○
Unacceptable levels of reactive power *(Damage to utility equipment, decreased efficiency)*	○	○	○	○	○	○
Overvoltage on the grid *(Damage to customer equipment/property, lower competitiveness, damage to utility equipment, blackouts)*	○	○	○	○	○	○
Increased transport losses *(Decreased efficiency)*	○	○	○	○	○	○
Undesired events due to unmanageable system *(Decreased efficiency, damage to utility equipment, blackouts/disturbances)*	○	○	○	○	○	○
Overtones on the grid *(Decreased efficiency, damage to utility equipment, lower competitiveness)*	○	○	○	○	○	○

Would you like to add something or comment on your answers?

Back Nästa

5. With both likelihood and severity in mind, please rank the risk scenarios from most troubling (1) to least troubling (6) for the operation of a distribution system given a substantial increase of solar and wind power. (Drag and drop the alternatives to rank them)

- Uncontrolled Islanding
- Unacceptable levels of reactive power
- Overvoltage on the grid
- Increased transport losses
- Undesired events due to unmanageable system
- Overtones on the grid

Back Nästa

6. What measure(s) would you suggest to minimize the likelihood of the risk scenario and/or its consequences?

Uncontrolled islanding	
Unacceptable levels of reactive power	
Overvoltage on the grid	
Increased transport losses	
Undesired events due to unmanageable system	
Overtones on the grid	

Back Nästa

7. What managerial or economic issue do you consider the biggest problem for the DSOs when more wind and solar power is implemented?

Back Nästa

8. What are the consequences of the issue you specified in the previous question?

Back Nästa

9. How can one manage or reduce either the occurrence of the issue or its consequences?

Back Klar

APPENDIX D

SURVEY ANSWERS

1. PLEASE FILL IN THE INFORMATION BELOW

Name: Alf Larsen
Workplace and Position: Grid Business Development
Years of experience within the energy sector: 30 years
Country: Sweden

Name: Ann-Christine Andersson
Workplace and Position: E.ON Elnät Sverige AB, Key Account Manager
Years of experience within the energy sector: 16
Country: Sweden

Name: Patrik Thuring
Workplace and Position: E.ON Elnät & Subscription manager
Years of experience within the energy sector: 8 years
Country: Sweden

Name: Björn Karlsson
Workplace and Position: Professor vid MDH i Västerås
Years of experience within the energy sector: 25 år vid Vattenfall 15 år vid Universitet
Country: Sverige

Name: Rune Nilsson
Workplace and Position: Reglering
Years of experience within the energy sector: 36
Country: Sverige

Name: Michell Andersson
Workplace and Position: Kraftringen Nät AB, Grid Connection Engineer
Years of experience within the energy sector: 8
Country: Sweden

Name: Fredrik Roos
Workplace and Position: E.ON Elnät Sverige AB, Nobelvägen 66, Malmö, Power Quality Specialist
Years of experience within the energy sector: 10 years
Country: Sweden

1. How do you think the likelihood of the identified risk scenarios will change with an increasing share of wind and solar power in the local and/or regional grids?

	Class 1Substantial decrease in likelihood	Class 2Decrease in likelihood	Class 3No change in likelihood	Class 4Increase in likelihood	Class 5Substantial increase in likelihood	Don't know/no comment	Totalt
Uncontrolled islanding	0,00% 0	0,00% 0	28,57% 2	71,43% 5	0,00% 0	0,00% 0	7
Unacceptable levels of reactive power	0,00% 0	0,00% 0	57,14% 4	42,86% 3	0,00% 0	0,00% 0	7
Overvoltage on the grid	0,00% 0	0,00% 0	42,86% 3	57,14% 4	0,00% 0	0,00% 0	7
Increased transport losses	0,00% 0	14,29% 1	42,86% 3	28,57% 2	14,29% 1	0,00% 0	7
Undesired events due to unmanageable system	0,00% 0	0,00% 0	42,86% 3	57,14% 4	0,00% 0	0,00% 0	7
Overtones on the grid	0,00% 0	0,00% 0	42,86% 3	42,86% 3	14,29% 1	0,00% 0	7

Comments:

- Myby some of the aspects above increase in likelihood, but this doesn't necessarily means increased consequences for the system as a total. (A. Larsen)
- Uncontrolled islanding occurs if you don´t install right protection in the grid. (A. Andersson)
- Mass energy inertia (rotating mass) will be reduced with a larger portion of wind/solar. This could cause problems with stabilizing the grid (P. Thuring)
- PV gives less distribution losses Wind gives more (B. Karlsson)

2. Below you can see the identified consequences for each risk scenario. Please categorize the severity of the typical (most likely) impact. If you know of any other consequences, please specify in the comment section.

	Class 1Negligible	Class 2Low	Class 3Moderate	Class 4High	Class 5Extreme	Don't know/don't want to answer	Totalt
Uncontrolled islanding(Damage to utility equipment, damage to customer equipment/property, fire hazard, electrocution of people and animals) Kommentarer (3)	14,29% 1	0,00% 0	42,86% 3	42,86% 3	0,00% 0	0,00% 0	7
Unacceptable levels of reactive power (Damage to utility equipment, decreased efficiency) Kommentarer (2)	14,29% 1	14,29% 1	57,14% 4	0,00% 0	0,00% 0	14,29% 1	7
Overvoltage on the grid (Damage to customer equipment/property, lower competitiveness, damage to utility equipment, blackouts) Kommentarer (2)	0,00% 0	28,57% 2	28,57% 2	42,86% 3	0,00% 0	0,00% 0	7
Increased transport losses(Decreased efficiency) Kommentarer (1)	14,29% 1	28,57% 2	28,57% 2	28,57% 2	0,00% 0	0,00% 0	7
Undesired events due to unmanageable system(Decreased efficiency, damage to utility equipment, blackouts/disturbances) Kommentarer (1)	14,29% 1	14,29% 1	28,57% 2	28,57% 2	14,29% 1	0,00% 0	7
Overtones on the grid (Decreased efficiency, damage to utility equipment, lower competitiveness) Kommentarer (0)	0,00% 0	14,29% 1	28,57% 2	42,86% 3	0,00% 0	14,29% 1	7

Comments:

Uncontrolled Islanding	• It increase the importance of a well functioning control system. (A. Larsen) • The risk is high if you don´t take care of it and demand the customer to install protection to prevent this. (A. Andersson) • Modern wind turbines are equipped with frequency derivative protection system which helps identify islanding (P. Thuring)
Undesired Events due to Unmanageable System	• Could cause blackouts, etc (P. Thuring)
Harmonics	
Overvoltage on the Grid	• Could Over/under voltage is a standard protection system in wind/solar plants (P. Thuring) • Will not occur within many years (B. Karlsson)
Increased Distribution Losses	• Mostly financial consequences and when dimensioning the grid (P. Thuring)
Unacceptable Levels of Reactive Power	• Again it highly depends on how the control system is designed and which resources we have for voltage control. (A. Larsen) • Mostly affects electrical losses and voltage variations (P. Thuring)

3. AGAIN YOU CAN SEE THE IDENTIFIED CONSEQUENCES FOR EACH RISK SCENARIO. PLEASE CATEGORIZE THE SEVERITY OF THE WORST CASE IMPACT.

	Class 1Negligible	Class 2Low	Class 3Moderate	Class 4High	Class 5Extreme	Don't know/don't want to answer	Totalt
Uncontrolled islanding(Damage to utility equipment, damage to customer equipment/property, fire hazard, electrocution of people and animals)	0,00% 0	14,29% 1	28,57% 2	42,86% 3	14,29% 1	0,00% 0	7
Unacceptable levels of reactive power (Damage to utility equipment, decreased efficiency)	0,00% 0	14,29% 1	85,71% 6	0,00% 0	0,00% 0	0,00% 0	7
Overvoltage on the grid (Damage to customer equipment/property, lower competitiveness, damage to utility equipment, blackouts)	0,00% 0	14,29% 1	42,86% 3	42,86% 3	0,00% 0	0,00% 0	7
Increased transport losses(Decreased efficiency)	14,29% 1	28,57% 2	42,86% 3	14,29% 1	0,00% 0	0,00% 0	7
Undesired events due to unmanageable system(Decreased efficiency, damage to utility equipment, blackouts/disturbances)	0,00% 0	0,00% 0	57,14% 4	14,29% 1	28,57% 2	0,00% 0	7
Overtones on the grid (Decreased efficiency, damage to utility equipment, lower competitiveness)	0,00% 0	14,29% 1	28,57% 2	42,86% 3	0,00% 0	14,29% 1	7

4. With both likelihood and severity in mind, please rank the risk scenarios from most troubling (1) to least troubling (6) for the operation of a distribution system given a substantial increase of solar and wind power. (Drag and drop the alternatives to rank them)

	1	2	3	4	5	6	Totalt
Uncontrolled Islanding	57,14% 4	14,29% 1	14,29% 1	14,29% 1	0,00% 0	0,00% 0	7
Unacceptable levels of reactive power	0,00% 0	14,29% 1	0,00% 0	42,86% 3	14,29% 1	28,57% 2	7
Overvoltage on the grid	0,00% 0	14,29% 1	42,86% 3	0,00% 0	28,57% 2	14,29% 1	7
Increased transport losses	0,00% 0	0,00% 0	14,29% 1	28,57% 2	28,57% 2	28,57% 2	7
Undesired events due to unmanageable system	28,57% 2	14,29% 1	28,57% 2	0,00% 0	14,29% 1	14,29% 1	7
Overtones on the grid	14,29% 1	42,86% 3	0,00% 0	14,29% 1	14,29% 1	14,29% 1	7

5. What measure(s) would you suggest to minimize the likelihood of the risk scenario and/or its consequences?

Uncontrolled Islanding	• Design of controlsystem (A. Larsen) • Installing NUS protection (voltage) (A. Andersson) • Include frequency derivation protection system (P. Thuring) • Investigate the probability for it to happen and develop intelligent protective apparatuses that will automaticly prevent islanding situations. (M. Andersson)
Undesired Events due to Unmanageable System	• Design of controlsystem (A. Larsen) • Grid code on robust system and Site Acceptance Tests (P. Thuring) • This is in my oppinion a low level risk that would not increase with a higher level of autonomos power generation (M. Andersson) • Only use robust and well tried and tested solutions and technology (F. Roos)
Harmonics on the Grid	• Technical requirements on connected equipment (A. Larsen) • Requirements in the grid code and thouroughly tests on this. Install harmonic filters if unacceptable (P. Thuring) • Equipments installed today is higly regulated in this aspect today why I see no direct risk associated with overtones since I do not expect these to increase. (M. Andersson) • Put requirements on the harmonic generation of production. (F. Roos)

Overvoltage on the Grid	• Appropriate resources for voltage control, relay system for protection (A. Larsen) • HPPP control functionality and voltage protection system (P. Thuring) • I find that the risk is already at an acceptable level. Protective measures taken today are effective (M. Andersson) • Focus on impedance and short circuit capacity when dimensioning the grid (F. Roos)
Increased Distribution Losses	• Appropriate resources for voltage control (A. Larsen) • Locally installed wind/solar where the load is thourgh incentives for example in the tariff (P. Thuring) • Autonomos powergeneration is in my oppinion more likely to decrease the risk of power loss due to distribution of energy through powerlines. Although, if measures would be taken I would suggest that serial reactive compensation would be one way to go forth. (M. Andersson) • Focus on impedance and short circuit capacity when dimensioning the grid (F. Roos)
Unacceptable Levels of Reactive Power	• Appropriate resources for voltage control (A. Larsen) • Certain equipment in the windfarms can be installed to minimize the levels of reactive power even if the equipment is expensive (A. Andersson) • Modern WTG has good Q capability otherwise compensation equipment needs to be installed (P. Thuring) • Increase the level of gridcontrol from Svenska Kraftnät, maybe (M. Andersson)

6. WHAT MANAGERIAL OR ECONOMIC ISSUE DO YOU CONSIDER THE BIGGEST PROBLEM FOR THE DSOS WHEN MORE WIND AND SOLAR POWER IS IMPLEMENTED?

- System design and network planning policys. New design of tariffs. (A. Larsen)
- I Think that batteries need to be installed to save the energy and distribute it when needed, those costs can be high. (A. Andersson)
- Tougher requirements on grids in regards to a more interconnected grid (both domestic and to other countries) in order to balacing the import/export in each Connection Point. Power quality issues with a larger amount of installed AC/DC/AC or DC/AC converters like harmonics, voltage variations and mass inertia problems. (P. Thuring)
- Base power during cold periods (B. Karlsson)
- I do not have the knowledge to give a satisfying answer to this question. Plus, what does DOSs mean? (M. Andersson)
- Resource allocation and resource utilisation. Wind and solar production are at maximum only few hours per year, while the transmission capacity has to be available constantly. (F. Roos)

7. WHAT ARE THE CONSEQUENCES OF THE ISSUE YOU SPECIFIED IN THE PREVIOUS QUESTION?

- Investment cost in the network and level of Revenues to finance the investments. (A. Larsen)

- How to store the energy is the critical Point here and the technology need to go forward in this area to ensure that we can store the energy without hugh battery package for example. Maybe some other ways to store the energy needs to be invented. (A. Andersson)

- Unstable grids (unacceptable frequency variations)
  Higher electrical losses
  Demands larger grid investments for the DSOs (P. Thuring)

- Import of fossil based power (B. Karlsson)

- It is purely an economic issue related to poorly utilised resources. (F. Roos)

8. HOW CAN ONE MANAGE OR REDUCE EITHER THE OCCURRENCE OF THE ISSUE OR ITS CONSEQUENCES?

- Planning, development and trying new solutions (A. Larsen)

- Install what you need by yourself not more. Saving energy should be a goal for every one of us. (A. Andersson)

- Stricter grid codes on Power quality
  Incentives in tariff or other subsidy to encourage local production close to load (P. Thuring)

- Keep the nuclear power stations as long as possible (B. Karlsson)

- By the use of energy storage, which will enable optimal utilisation of transmission capacity. However, energy storage is still too expensive for large-scale implementation.(F. Roos)

Appendix E

Summary and Weighted Results from the Survey

In Table 9 below the weighted Results from the change in likelihood of the risk scenarios are shown. This is a product from the survey where the respondents estimated the change in likelihood.

TABLE 9. WEIGHTED RESULTS FROM THE CHANGE IN LIKELIHOOD OF THE RISK SCENARIOS

Likelihood / **Risk scenario**	Class 1 *Substantial decrease in likelihood*	Class 2 *Decrease in likelihood*	Class 3 *No change in likelihood*	Class 4 *Increase in likelihood*	Class 5 *Substantial increase in likelihood*	**Weighted Average**
Uncontrolled Islanding	0 %	0 %	29 %	71 %	0 %	3.71
Unacceptable Levels of Reactive Power	0 %	0 %	57 %	43 %	0 %	3.43
Overvoltage on the Grid	0 %	0 %	43 %	57 %	0 %	3.57
Increased Distribution Losses	0 %	14 %	43 %	29 %	14 %	3.43
Undesired Events due to Unmanageable System	0 %	0 %	43 %	57 %	0 %	3.57
Harmonics	0 %	0 %	43 %	43 %	14 %	3.71

In Table 10 below the weighted severity of the most likely consequence of the risk scenarios are shown. This is a product from the survey where the respondents estimated the severity of the most likely consequence of each risk scenario.

TABELL 10. WEIGHTED RESULTS FROM THE SEVERITY OF THE MOST LIKELY CONSEQUENCE OF THE RISK SCENARIOS

Consequence / Risk scenario	Class 1 *Negligible*	Class 2 *Low*	Class 3 *Moderate*	Class 4 *High*	Class 5 *Extreme*	Weighted Average	Don't know/ Don't want to answer
Uncontrolled Islanding	14 %	0 %	43 %	43 %	0 %	3.14	0 %
Unacceptable Levels of Reactive Power	14 %	14 %	57 %	0 %	0 %	2.5	14 %
Overvoltage on the Grid	0 %	29 %	29 %	43 %	0 %	3.14	0 %
Increased Distribution Losses	14 %	29 %	29 %	29 %	0 %	2.71	0 %
Undesired Events due to Unmanageable System	14 %	14 %	29 %	29 %	14 %	3.14	0 %
Harmonics	0 %	14 %	29 %	43 %	0 %	3.33	14 %

In Table 11 below the weighted results from the severity of the worst case consequence of the risk scenarios are shown. This is a product of the survey where the respondents estimated the severity.

TABLE 11. WEIGHTED RESULTS FROM THE SEVERITY OF THE WORST CASE CONSEQUENCE OF THE RISK SCENARIOS

Consequence / Risk scenario	Class 1 *Negligible*	Class 2 *Low*	Class 3 *Moderate*	Class 4 *High*	Class 5 *Extreme*	Weighted Average	Don't know/ Don't want to answer
Uncontrolled Islanding	0 %	14 %	29 %	43 %	0 %	3.57	0 %
Unacceptable Levels of Reactive Power	0 %	14 %	86 %	0 %	0 %	2.86	14 %
Overvoltage on the Grid	0 %	14 %	43 %	43 %	0 %	3.29	0 %
Increased Distribution Losses	14 %	29 %	43 %	14 %	0 %	2.57	0 %
Undesired Events due to Unmanageable System	0 %	0 %	57 %	14 %	39 %	3.71	0 %
Harmonics	0 %	14 %	29 %	43 %	0 %	3.33	14 %

In Table 12 below the weighted results from the ranking of the risk scenarios are shown. This is a product of the survey where the respondents ranked the risk scenarios.

TABLE 12. WEIGHTED RANK OF THE RISK SCENARIOS

Risk scenario \ Ranking	Nr 1 *6*	Nr 2 *5*	Nr 3 *4*	Nr 4 *3*	Nr 5 *2*	Nr 6 *1*	Score	Weighted Rank
Uncontrolled Islanding	57 %	14 %	14 %	0 %	0 %	0 %	5.14	1
Unacceptable Levels of Reactive Power	0 %	14 %	0 %	43 %	14 %	29 %	2.57	5
Overvoltage on the Grid	0 %	14 %	43 %	0 %	29 %	14 %	3.14	4
Increased Distribution Losses	0 %	0 %	14 %	29 %	29 %	29 %	2.29	6
Undesired Events due to Unmanageable System	29 %	14 %	29 %	0 %	14 %	14 %	4.00	2
Harmonics	14 %	43 %	0 %	14 %	14 %	14 %	3.86	3

In table 13 below the weighted ranking is shown

TABLE 13. THE WEIGHTED RANKING OF THE RISK SCENARIOS

Rank	Risk Scenario
1	Uncontrolled Islanding
2	Undesired Events due to Unmanageable System
3	Harmonics
4	Overvoltage on the Grid
5	Unacceptable Levels of Reactive Power
6	Increased Distribution Losses

Below in figure 48 the weighted average likelihood and the severity of the most likely consequence of the risk scenarios are plotted in a risk matrix.

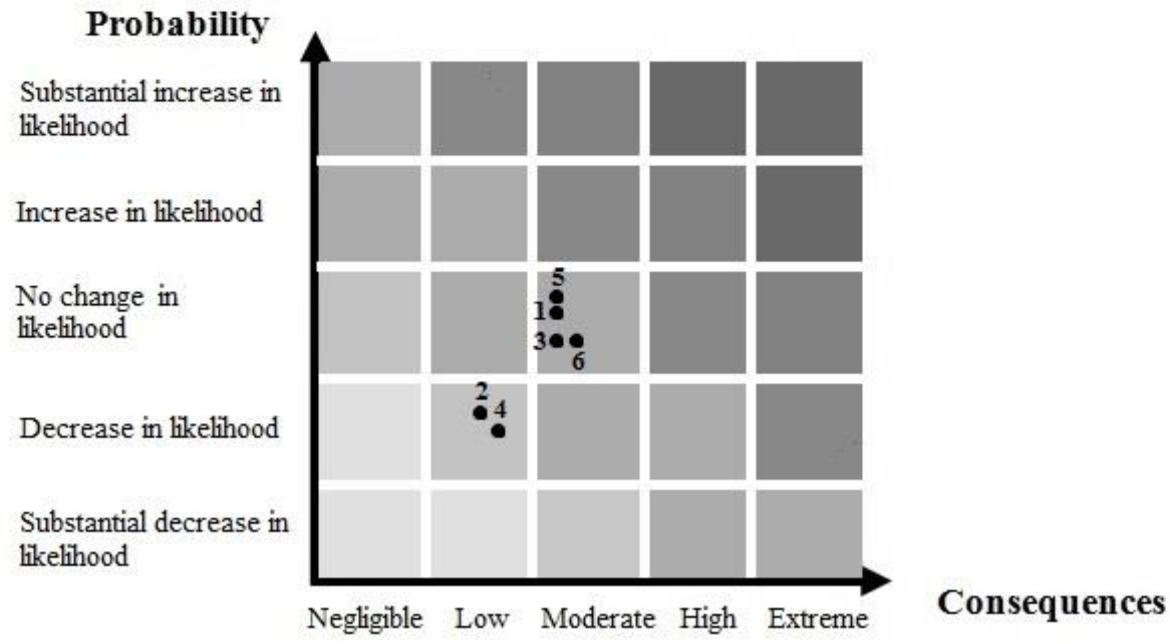

FIGURE 48. RISK MATRIX OF THE LIKELIHOOD AND THE SEVERITY OFF THE MOST LIKELY RISK SCENARIO

1. Uncontrolled Islanding
2. Unacceptable Levels of Reactive Power
3. Overvoltage on the Grid
4. Increased Distribution Losses
5. Undesired Events due to Unmanageable System
6. Harmonics