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Threat scenarios to the Swedish power system

Assessment of security and extreme weather events

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Threat scenarios to the Swedish power system

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Abstract

Electricity is essential to the functioning of modern societies, and its importance is growing as electrification is the enabler leading the transition towards net zero emissions in most sectors. However, threats to the Swedish power system have increased in recent years, primarily as a result of the evolving security situation in Europe, but recurring extreme weather events also poses growing threats. Therefore, security of electricity supply has become increasingly important to address threat scenarios to the power system.

The Swedish power system has a high security of supply, with the main causes of disturbance being environmental and technical faults. Meanwhile, some of the main threats to the power system include damage towards physical and digital infrastructure, such as cyberattacks and sabotage of production, substations and lines. In particular, the control system represents one of the main vulnerabilities, together with major production units and nodes.

Power system simulations of threat scenarios demonstrate that events towards critical infrastructure could have a high impact on the power grid and its customers, with overloads, voltage violations and energy not supplied. Meanwhile, the power system seems capable of handling other serious threat scenarios towards less vulnerable nodes and branches without major impact. Measures to mitigate threat scenarios generally include different types of power system stabilizers, but long-term reinforcement of vulnerable nodes and a meshed grid design should be pursued. This also enables synergies with economy and sustainability.

Keywords

Power grid, HILP event, reliability, threat scenarios, security, extreme weather

Sammanfattning

Elektricitet är en förutsättning för att moderna samhällen ska fungera, och dess betydelse ökar i takt med att elektrifieringen leder omställningen mot nettonollutsläpp inom de flesta sektorer. Hoten mot det svenska kraftsystemet har dock ökat under de senaste åren, främst till följd av det förändrade säkerhetsläget i Europa, men även återkommande extrema väderhändelser utgör ett växande hot. För att hantera hotscenarier mot kraftsystemet har därför elleveranssäkerheten blivit allt viktigare.

Det svenska kraftsystemet har en hög leveranssäkerhet, där de främsta orsakerna till störningar är miljö och tekniska fel. Samtidigt är några av de främsta hoten mot kraftsystemet skador på fysisk och digital infrastruktur, till exempel cyberattacker och sabotage mot produktion, transformatorstationer och ledningar. I synnerhet utgör kontrollsystemet en av de mest sårbara punkterna, tillsammans med större produktionsenheter och noder.

Kraftsystemsimuleringar av hotscenarier visar att händelser mot kritisk infrastruktur kan få stora konsekvenser för elnätet och dess kunder, med överbelastningar, spänningsbortfall och icke levererad energi. Samtidigt verkar kraftsystemet kunna hantera andra allvarliga scenarier mot mindre sårbara noder utan större konsekvenser. Åtgärder för att mildra hotscenarierna omfattar i allmänhet olika typer av kraftsystemstabilisatorer, men långsiktig förstärkning av sårbara noder och en maskad nätdesign bör eftersträvas. Detta möjliggör också synergier med ekonomi och hållbarhet.

Nyckelord

Kraftnät, HILP, leveranssäkerhet, hotscenarier, säkerhet, extremväder

Acknowledgments

This master's thesis is the scientific report from a project performed in collaboration between KTH Royal Institute of Technology and the Swedish transmission system operator, Svenska kraftnät. The thesis is conducted by the student Arvid Johannisson and concludes five years of study within the engineering degree program Energy and Environment, with the master Sustainable Energy Engineering.

I would like to thank everyone that have contributed to the thesis project. A special thank you to my industrial advisor Ebrahim Shayesteh, for the support, guidance and contacts at Svenska kraftnät. I would also like to acknowledge the warm welcome and helpful contributions of the rest of my colleagues at the Department of Grid Development, especially Tobias Edfast and Jan Brangefält for reviewing the report. I would also like to thank my academic advisor Patrik Hilber, and examiner Anders Malmquist, for sharing your expertise and valuable advice during the meetings throughout the project. The master's thesis project has been educational, challenging and developing, but above all very fun.

Stockholm, June 2025

Arvid Johannisson

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List of Abbreviations

CHP	Combined Heat and Power
CPI	Consumer Price Index
DSO	Distribution System Operator
Ei	Swedish Energy Markets Inspectorate, *Energimarknadsinspektionen*
ENS	Energy Not Supplied
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FOI	Swedish defense research agency, *Totalförsvarets forskningsinstitut*
HILP	High Impact Low Probability
HVDC	High Voltage Direct Current
IEA	International Energy Agency
kV	kilo-Volt
MUST	Military Intelligence and Security Service, *Militära underrättelse- och säkerhetstjänsten*
MWh	Megawatt hours
NATO	North Atlantic Treaty Organization
O&M	Operations and Maintenance
PSS	Power System Stabilizer
PSS/E	Power System Simulator for Engineering
SDGs	Sustainable Development Goals
SEK	Swedish crowns
STATCOM	Static Compensator
SVC	Static Var Compensator
SVK	Swedish National Grid, *Svenska kraftnät*
SÄPO	Swedish Security Service, *Säkerhetspolisen*
TIC	Total Interruption Cost
TSO	Transmission System Operator
TWh	Terawatt hours
UN	United Nations
var	Volt Ampere Reactive
VoLL	Value of Lost Load

Chapter 1

Introduction

This chapter describes the research problem and introduces the background and purpose of the thesis project. In addition, it also outlines the research methodology and delimitations of the thesis.

1.1 Background

Electricity is central to the functioning of modern societies, and its importance is growing as more sectors are powered by electricity, such as heating and transports [1]. While power generation today accounts for the largest share of all greenhouse gas emissions, around 32% globally [2], it is also the enabler leading the transition towards net zero emissions through renewable electricity. Ensuring access to clean, affordable and secure electricity is therefore a core challenge for the energy transition. [1]

Globally, 2024 was the warmest year on record since industrialization, exceeding 1.5°C of warming, contributing to a record number of extreme events, including floods, heatwaves, and wildfires around the globe. Climate change is an increasing threat to society, imposing costs and displacing people through extreme weather events [3]. To address the major global challenges, the Sustainable Development Goals (SDGs) were formulated by the United Nations (UN) in 2015 [4]. In the associated Paris Agreement, the UN stated that global leaders should pursue efforts to limit the temperature increase to below 1.5°C in this century [5], a threshold that has already been exceeded. [3]

Alongside climate change, geopolitical tensions have increased in recent years, expressed through technological protectionism, trade barriers, and escalating armed conflicts, which have had a major impact on global markets. The geopolitical shift has also put the energy transition in a new context, where energy security is of great importance. Experiences from past years have also highlighted how dependencies can turn into vulnerabilities and energy infrastructure become legitimate targets in conflicts. [6]

Sweden is a small country in northern Europe that has been a leader in climate action for decades, and in recent years also adapted to the evolving geopolitical situation. The country is rich in natural resources, which through processing and exports have developed Sweden's prosperity. The use of domestic renewables has also been a prerequisite for the clean, affordable, and secure energy system [7], which however will be threatened by more frequent extreme weather in the future [3]. In past centuries, Sweden has stayed outside of armed conflicts. However, due to the security policy situation following Russia's war against Ukraine, Sweden chose to depart from its longstanding non-alignment by joining NATO. The heightened antagonistic threat against Sweden is among others reflected in intensified disinformation, cyberattacks, and sabotage against infrastructure, including the power system. [8]

The Swedish power system, which is primarily based on nuclear power and hydropower, has historically been very reliable. However, the electrification of society alongside with the increased risk of extreme weather and security threats is expected to reduce the power system's resilience and contribute to increased societal vulnerability. Energy Not Supplied (ENS) not only puts a strain on society, but also contributes to societal costs, which are usually measured as the Value of Lost Load (VoLL). [9]

1.2 Problem

Climate change and the deteriorating security situation in Sweden's neighborhood have increased threats to the power system in recent years. In particular, extreme weather events due to climate change are expected to be more frequent, which put electricity supplies at risk [3]. Experiences from Ukraine also highlights that power system infrastructure are legitimate targets in armed conflicts [10]. As part of the deteriorating security situation in Europe, threats and sabotage against the Swedish power system has also increased. Alongside with a societal electrification, this has contributed to higher threats to electricity supply in Sweden. [11]

This master thesis aims to answer the following research questions:

1. Which are the main security and extreme weather threats to the Swedish power system?
2. What are the impacts of threat events to the Swedish power system and how can these be mitigated?

1.3 Purpose

The overall aim of this thesis is to identify threats and vulnerabilities in the Swedish power system, related to security and extreme weather events. In particular, the thesis aims to investigate the technical and economic impacts as well as mitigation measures for a number of threat scenarios, based on the evolving global situation.

1.4 Goals

The goal of this project is to increase knowledge of how the Swedish power system could be affected in the event of a crisis. The project has been conducted together with the Transmission System Operator (TSO) in Sweden, Svenska kraftnät, hence the outcome aims to be relevant from a grid operators' perspective but could also benefit other national authorities or stakeholders interested in energy supply and civil preparedness. Potentially, the project could also contribute to the redundancy of the Swedish society at large. The goal has been divided into the following three sub-goals:

1. Identify threat events with major impact on the Swedish power system.
2. Investigate technical and economic impacts of threat scenarios related to security and extreme weather.
3. Identify mitigation measures to the threat events and discuss their contribution to security of supply.

1.5 Research methodology

This study is based on a quantitative methodology. The research approach is to identify vulnerabilities and threats to the power system through literature review, based on which threat scenarios are designed. These scenarios are then simulated and analyzed using the software tool PSS/E, which is a power grid simulation model used by Svenska kraftnät and other TSOs.

For this type of research, both qualitative and quantitative methodologies are possible. For example, several qualitative studies on electricity supply have been conducted by Swedish authorities, providing an overview of the threat situation. Meanwhile, many quantitative studies in risk- and vulnerability analysis have also been conducted using grid simulation models similar to PSS/E, such as [12] and [13]. Another framework commonly used in risk assessment is risk matrixes. These can be both qualitative and quantitative, suitable as a platform for communicating risks or when simulation tools are insufficient, also in this thesis project. However, since this thesis project is supervised by the department of grid development at Svenska kraftnät it was natural to conduct a quantitative research, using their software tool PSS/E. The chosen methodology is also considered the most appropriate to achieve the goals of this thesis project. In addition to existing studies, the results from this thesis will also bring new perspectives and insights on how the Swedish power system can be affected by extreme events, through simulations with threats targeting vulnerabilities. The method is further discussed in Chapter 4.

1.6 Delimitations

This thesis project is delimited to focus on the existing power system in Sweden, as well as the vulnerabilities and threats in the near future. The scope is also limited to threats related to security and extreme weather. Furthermore, the threat scenarios are focused on High Impact Low Probability (HILP) events towards physical infrastructure at the transmission grid level, causing issues with short-term security of supply. Consequently, the project does not directly cover the long-term impacts of climate change, ageing infrastructure or risks projected far into the future. The simulation is also delimited to not include the impact on regional- and local grids as well as digital threats, such as cybersecurity, IT and control systems. Finally, cost impacts will be evaluated at society level and not to specific actors.

1.7 Structure of the thesis

Chapter 2 and 3 presents relevant background information on the Swedish power system, security of supply, and the risk situation, including vulnerabilities and threats. Chapter 4 outlines the methodology used in the thesis project. Chapter 5 introduces the threat scenarios, followed by results and analysis in Chapter 6. Finally, the research findings are concluded in Chapter 7.

Chapter 2

Background

This chapter provides a basic background about the Swedish power system and concepts related to security of supply. Additionally, this chapter describes the general threat situation in a Swedish context.

2.1 Sweden’s power system

Historically, Sweden was an early adopter of the electricity system. Today, the country is a leader in clean energy systems and has major future plans for decarbonization. This brings challenges for the power system, which is key in the energy transition. [7]

2.1.1 Overview of the electricity balance

Currently, the annual electricity supply in Sweden is around 160 TWh, mainly from hydro- and nuclear power, but with a growing share of wind power, shown in Figure 2-1. Meanwhile, most of the electricity is used in buildings and services together with industries. However, the power system faces a major transition in the coming decades [14]. When electrifying the industry and transport sector the demand is expected to increase significantly, from around 140 TWh to somewhere between 200-340 TWh by 2050. Short-term, most of the increase is expected to be met by wind power but long-term, the government is also preparing for deployment of new nuclear reactors. [7]

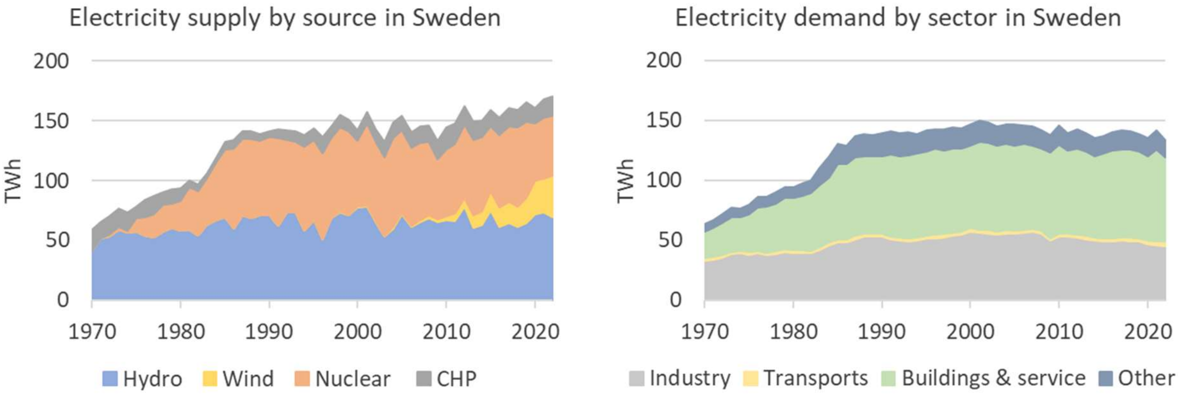

Figure 2-1: Electricity supply and demand in Sweden [14]

Most of the hydropower is located in northern Sweden, while the nuclear power is in south, as the majority of today's demand. Hence, nuclear power provides baseload power near the customers, while hydropower is important in balancing the daily and seasonal load fluctuations. Therefore, it is very common with power flows from northern to southern Sweden. [15]

2.1.2 Electricity market and grid development

The power grid can be described as a market that connects electricity supply and demand at different locations. However, there are physical limitations in the transmission grid that restrict electricity trading. To address this market imperfection, Sweden is divided into four electricity price areas, shown in Figure 2-2, where the grid limitations and imbalance between supply and demand are reflected in the electricity price. The generation surplus in northern Sweden generally means lower prices compared to south. Socioeconomically, this market design increases the societal benefits and should incentivize supply and demand to locate close together, which reduces the need for extensive transmission grids. [16]

In Sweden, the transmission grid is maintained and developed by the TSO, Svenska kraftnät, and consists around 17 500 km of power lines, 200 substations and multiple cross-border connections. To accommodate the electrification Svenska kraftnät will undertake major grid investments in the coming decade, increasing from around SEK 3 to 20 billion annually, building 1 500 km of new transmission lines, as well as renovating both 2 500 km of existing lines and nearly 100 substations. This will improve flexibility and increase capacity between Sweden's electricity price areas and the neighboring countries. The Swedish transmission grid is shown in Figure 2-2. [17]

Figure 2-2: Map of the Swedish transmission grid [18]

Reliability is important in power systems and the dominating reliability principle in grid development is called the N-1 criterion. This means that the power system should be able to manage a sudden outage (with a common trigger) of the largest single generator, line or load at any given time. Therefore, there are procured power reserves, alternative lines and load shedding procedures to ensure security of supply. Svenska kraftnät's strategy is to build a meshed grid, which is based on the same principle and strongly linked to the ongoing projects. The investment package NordSyd is a good example, which will address both vulnerabilities and bottlenecks in the transmission grid. More information on NordSyd is available in Appendix A. [17]

2.1.3 Roles and responsibilities

Sweden has a deregulated electricity market, like the rest of the European Union (EU), where electricity trade and transmission are separated. This means that electricity is traded under free competition between producers and consumers, while the power grids are operated as regulated monopolies. The purpose of this market design is to ensure that the combined resources of the EU's internal market are used as efficiently as possible. [19]

The Swedish power grid is interconnected with the Nordic synchronous area as well as the Baltic and continental regions through power lines and offshore High Voltage Direct Current (HVDC) cables [19]. Power grids are usually classified in three levels; transmission grid with voltages at 400 to 220 kV, regional grid between 130 kV and 40 kV and local grid down to 230 V, where the grids at lower voltage levels are maintained and developed by Distribution System Operators (DSOs) [20]. To promote the functioning of the market, Energimarknadsinspektionen (Ei) is responsible for analyzing and monitoring the development of these regulated grid monopolies. [21]

Energimyndigheten is the sector responsible authority, with the main responsibility to lead, coordinate and support the work in the electricity sector. In addition, Energimarknadsinspektionen, Svenska kraftnät and Strålsäkerhetsmyndigheten have different roles and responsibilities in the sector. These are all preparedness authorities, which means that in the event of crisis or war, they are responsible for maintaining their capabilities to ensure the most important functions of society. As a preparedness authority, Svenska kraftnät is tasked to ensure that the Swedish electricity supply is prepared for emergency events, such as war, extreme weather or other disturbances beyond the responsibilities of individual power utilities. In addition, Svenska kraftnät is also the supervisory guidance authority for dam safety and the regulatory authority for the security of electricity supply. [22]

The Swedish government has in its long-term energy policy directive decided on two goals, which Svenska kraftnät is responsible to monitor. First, the planning goal (“Planeringsmålet”) is to ensure that the power system can meet the growing demand of electricity and support the energy transition in the coming decades. Secondly, the reliability goal (“Leveranssäkerhetsmålet”) is about the ability to supply sufficient amount of electricity where and when it is needed, as long as it is socioeconomically effective. [23]

2.2 Security of electricity supply

Security of supply in power systems is of great importance, as constant electricity supply is a fundamental societal service. In addition to technical aspects, costs and disturbance events are also important for optimal risk- and asset management in power systems. [24]

2.2.1 Performance definitions

Security of electricity supply is about technical performance of power systems and has many dimensions with different relationships. A core dimension of power system performance is reliability, often recognized as the same concept as security of supply itself. It describes the probability that the system can perform the required function under a given condition and time interval. Related to reliability are also resilience, vulnerability, robustness, stability and power quality. The definition of these concepts is listed below and the relation between them is represented in Figure 2-3. [24]

• Reliability	Probability that the system can perform a required function under a given condition and time interval.
• Resilience	Ability to limit the extent, severity, and duration of system degradation following an extreme event.
• Vulnerability	Opposite to resilience.
• Robustness	The extent of the system function maintained during unexpected disturbance.
• Stability	Ability to restore the systems initial conditions after disturbance.
• Power quality	Ability to supply a clean and stable power supply.

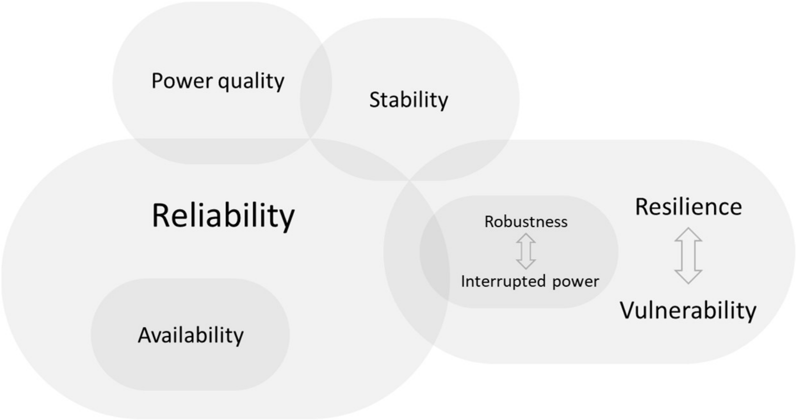

Figure 2-3: Relationship between dimensions of security of supply [24]

2.2.2 Characterization of events

Disturbance events include all events that lead to disturbances on the power system. These can be divided into ordinary events which are minor disturbance encountered in daily system operation and, extraordinary events causing outages and major societal impacts but with a low probability of occurring, often referred to as High Impact Low Probability (HILP) events. Furthermore, HILP events can be characterized based on the magnitude of the interrupted power and the duration, where duration is defined as the time required to return to full system operations and productivity. An example of how HILP events can be represented is shown in the scatterplot in Figure 2-4. Together, interrupted power (MW) and duration (h) give the ENS (MWh), which represents the amount of energy that could not be delivered to customers because of the HILP event, indicated by the colored area in Figure 2-4. [25]

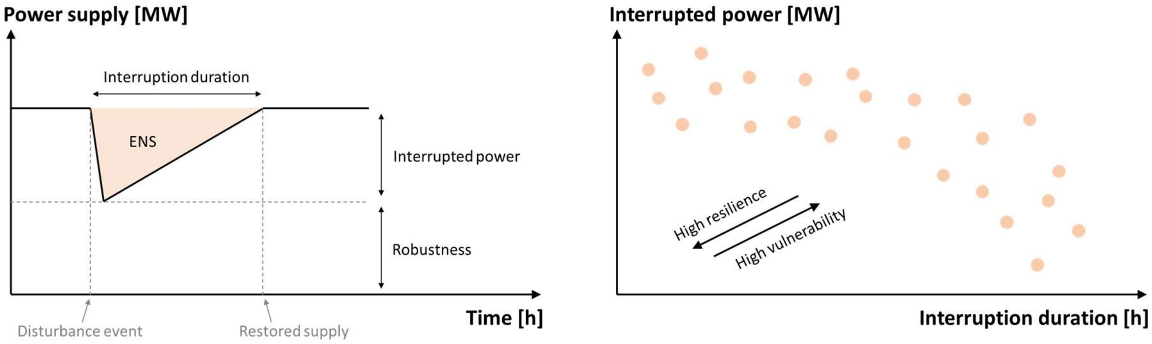

Figure 2-4: Resilience and vulnerability analysis of HILP events [25]

Focusing on security of supply rather than individual events, it is typically divided into long-term and short-term. Short-term issues arise when the supply capacity is sufficient to meet demand, but the system has a low ability to maintain continuous electricity supply during disturbances. In contrast, if interruptions occur because the supply capacity can't meet electricity demand during normal conditions, either due to power- or energy shortage, it's a long-term adequacy issue. Mitigating long-term issues require strategic investments in the supply capacity, including generation and grids, to prevent bottlenecks during normal demand, while short-term security focus on system control and Power System Stabilizers (PSS) rather than major investments [24]. Further, supply interruptions can be divided into three characteristic situations; power shortage, energy shortage and power outage, where the shortages relate to the system adequacy and long-term security of supply, while power outage relates to short-term security of supply, shown in Figure 2-5. [22]

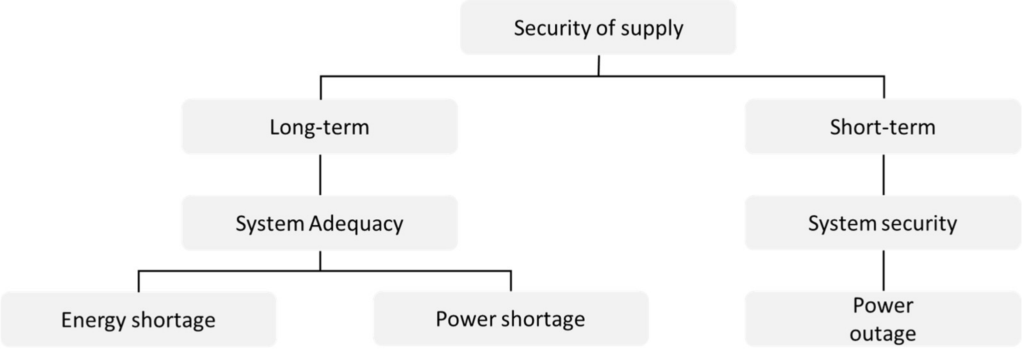

Figure 2-5: Difference between long-term and short-term security of supply in power systems

2.2.3 Power system costs

To ensure security of supply in power systems, it is continuously maintained and developed, which is associated with several types of costs. Some of the key costs are investment costs, operation & maintenance costs and damage costs. Investment costs are linked to the installation of infrastructure in the power system but can also include reconstructions of lines and substations [24]. When undertaking investments, socioeconomic analyses are always conducted to ensure an optimal design of the power system [17]. Operation & maintenance costs are the expenses associated with ensuring the functioning of the power system assets. Together, these are important to avoid damage costs, which is the lost economic value from power system incidents, failures and outages [24]. Damage costs can be estimated by VoLL (in SEK/kWh), which is based on the economic loss to customers as a result of ENS, shown in Table 2.1. The damage cost (in SEK) is usually called Total Interruption Cost (TIC), obtained by multiplying the ENS with the VoLL. [26]

Table 2.1: Value of Lost Load (VoLL) for different sectors, durations and weighted total, 2024 [26]

	0-1 HOUR	**1-2 HOURS**	**2-3 HOURS**	**WEIGHT OF TOTAL**
AGRICULTURAL	79	57	52	4%
INDUSTRY	319	297	255	12%
SERVICES	259	249	212	19%
PUBLIC	147	135	121	6%
HOUSEHOLD	10	10	11	59%
WEIGHTED AVERAGE	**104**	**98**	**86**	SEK/kWh

From a security of supply perspective, it is important with high investments and maintenance to address ageing infrastructure and reduce the risk of disturbances to cause ENS. However, in practice it is key to optimize the costs, as over-investment can lead to excessive expenditures that cannot be justified socioeconomically, while under-investment over time leads to unacceptably low security of supply, with recurring ENS. The optimal level of security of supply can be achieved by minimizing the total cost, which is a balance between the cost for ensuring uninterrupted electricity supply and the damage cost due to the supply interruption, as shown in Figure 2-6. [24]

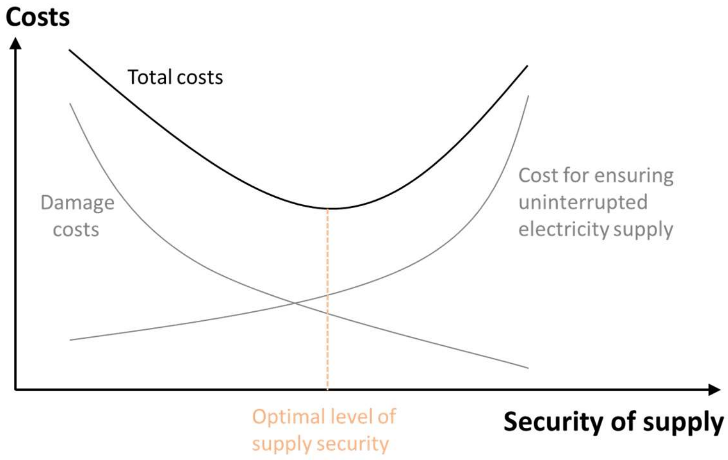

Figure 2-6: Optimal level of supply security

It can also be noted that the different types of costs affect different types of actors with different responsibilities. Damage costs largely affect customers, while the cost of ensuring uninterrupted electricity supply is the responsibility of producers and grid operators. Consequently, it is also their responsibility to ensure that the power system has an optimal level of security of supply. [24]

2.2.4 Reliability and events in Sweden

In a global context, Sweden has a very reliable power system that has continued to improve in recent years. Over the past decade, the number of disturbance events in the transmission grid has amounted to 420 annually, of which about 160 caused ENS, corresponding 1.3 GWh/year [27]. Meanwhile, for the entire power grid the annual ENS have varied between 10 and 20 GWh, which is less than 0.02% of the annual electricity demand in Sweden. Meanwhile, the direct costs of ENS to customers are estimated at around SEK 1.5 billion annually. [28]

The most significant causes of ENS in the transmission grid are environmental, together with technical faults and unknown causes, shown in Figure 2-7. In particular, lightnings are the most common, while strong winds cause the most extensive disturbance, together accounting for the majority of ENS with environmental cause. Most of these disturbance events occur against either overhead lines or substations. [27]

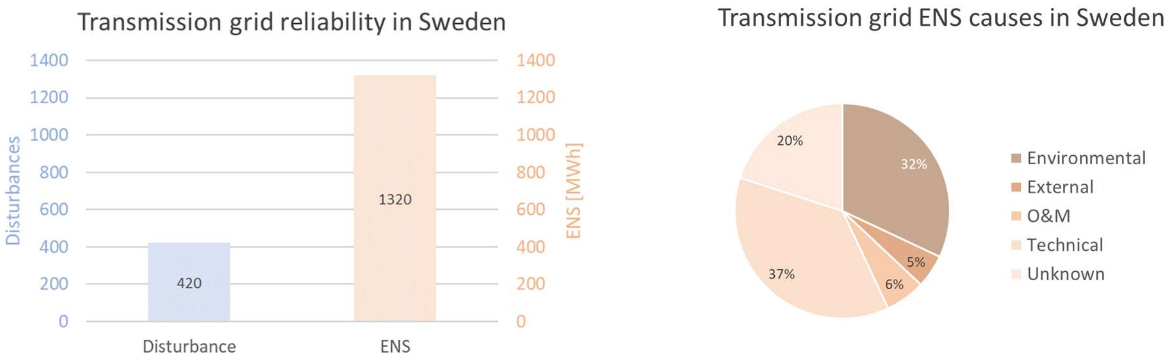

Figure 2-7: Average disturbance and Energy Not Supplied (ENS) in the transmission grid [27]

Historically, some of the most extensive disturbances of electricity supply in Sweden have been caused by storms. The most significant HILP event is the storm Gudrun in 2005, which caused outages for around half a million people and lasted for weeks in some places. The ENS was estimated at around 111 GWh, corresponding socioeconomic cost between SEK 4-5 billion, with VoLL around 36 SEK/kWh. Furthermore, Gudrun was followed by the storms Per in 2007 and Dagmar in 2011. In particular, the storms hit the local grids in rural areas hard, since lines had higher exposure to falling trees and lower redundancy than other areas. This has been addressed through underground cables in the local grid, reducing the risk of ENS significantly. [9]

2.3 General threat situation in a Swedish context

The turbulent global situation is affecting Sweden and will likely continue for a long time [29]. While the dynamic geopolitical situation has deteriorated in recent years, climate change is another upcoming threat with increased risks of extreme weather, also expected to have a major impact on society. [22]

2.3.1 Categorization of threats

Threats are generally divided into antagonistic and non-antagonistic threats, based on their origin. The antagonistic threats include actor threats such as terrorism, organized crime and states, while non-antagonistic refers to threats that may be posed by extreme weather or accidents. However, sometimes it can be difficult to determine the type of threat, as they may be interlinked. The basic categorization of threats is shown in Figure 2-8. [29]

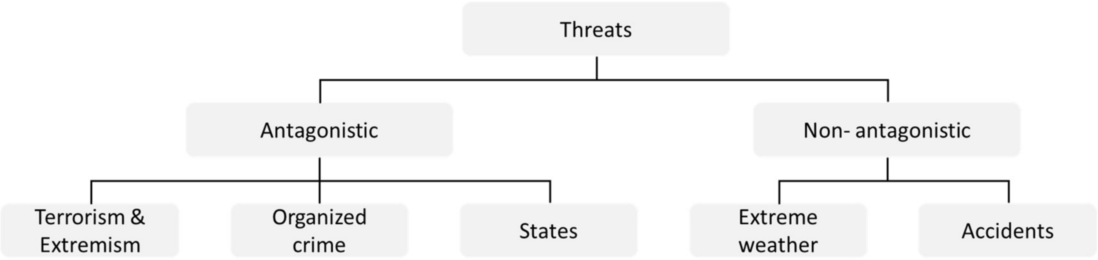

Figure 2-8: Categorization of threats

2.3.2 Security threats

In recent years, the threat landscape has become more complex, with interconnections between different actors and simultaneous tactical threats. For example, different types of disinformation, cyber intrusions and sabotage can be conducted by organized criminals but coordinated by a state actor. This ambiguous approach is known as a hybrid threat and has become more common since they are highly deniable and have lower risks of escalation. [30]

In a Swedish context, security threats from antagonistic states comes mainly from Russia, but also China and Iran. Through intelligence operations, these actors gain knowledge of critical infrastructure and develop capabilities to influence and pressure society [30]. For power systems, this involves intrusions to the digital control system and identifying vulnerable lines, nodes and substations that cause major disruptions in the event of an outage. [31]

Experiences from Ukraine highlight that the preparatory step of intelligence operations can materialize through sabotage and attacks on critical infrastructure. It is also reasonable to assume that this escalation is transferable to a Swedish context [10]. In fact, there has been an increase in potential sabotage against infrastructure in Sweden and its neighboring countries. Cable breaks in the Baltic Sea and explosions at the Nord Stream gas pipeline are some of the most recognized events. Physical sabotage and provocations have also occurred against communication, water, and power supplies [30]. For example, there are reports of drones that have flown near the Swedish nuclear power plants [32], and cyberattacks against Swedish authorities occurring daily. [29]

2.3.3 Extreme weather threats

Unlike security threats, extreme weather is non-antagonistic and not enforced by any specific actor [29]. Still, the impacts of extreme weather events can be significant for both the environment and society. As a result of global warming, extreme weather events are also expected to become both more frequent and increasingly severe in the future. [3]

In general, Sweden is expected to be less exposed to extreme weathers, such as heat waves and storms, than other parts of the world [33]. However, there will be weather changes with a significant impact on the Swedish society. Some of the most prominent weather changes expected in Sweden are drought during summer, increased precipitation during the cold months, and generally higher temperature levels, which is already observed. In turn, this will increase the risks of extreme weather events like floods and wildfires. These events also have different impacts locally depending on topology and vegetation, with highest risks for floods in western Sweden and wildfires in southern and central Sweden. [34]

Withstanding and managing weather exposure is a challenge for most infrastructure regardless of if it is buildings, roads, water or energy supply. As the power lines in Sweden are almost 650 000 km in total, weather exposure has a major impact and requires climate adaptions and mitigation measures. For example, extensive adoptions to the local grid were made in response to the storm Gudrun, where more than 75% of all local grid consists of underground cables nowadays. Preventive measures are also taken to mitigate the impacts of other types of extreme events and natural accidents in the power grid. [17]

Chapter 3

Risk situation

This chapter provides definitions in risk assessment and a detailed background on vulnerabilities and threats to the power system.

3.1 Definitions in risk assessment

Formally, a threat can be defined as a broad scenario based on some event that could be harmful. Meanwhile, vulnerability is usually defined as something that is sensitive to disturbance or attacks. It could be a weakness in IT systems, physical protection, regulations, supply chains or system design. Usually, threats come from external sources and are thus difficult to influence, while vulnerabilities to a high extent can be controlled and mitigated internally. Threats are often targeted towards vulnerabilities and together these create risks. Consequently, risks are usually defined as probability times impact of an event. To mitigate risks, measures can be taken towards the vulnerabilities or threats, to reduce the probability or impact of a particular event. A chart describing the relationship between threats, vulnerabilities, risks and measures is shown in Figure 3-1. [11]

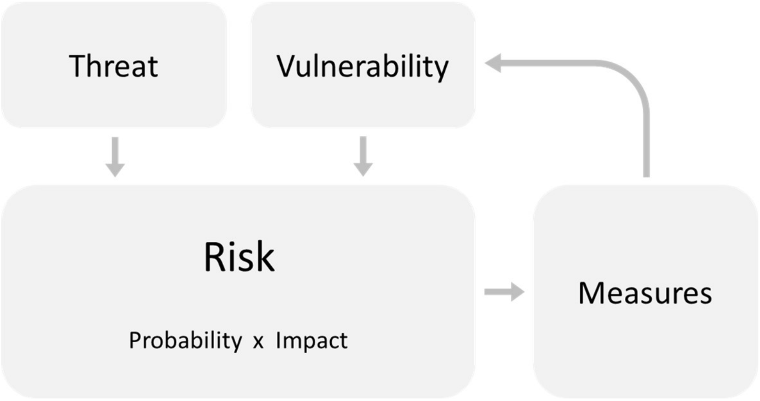

Figure 3-1: Relationships in risk assessment

3.2 Vulnerabilities in the power system

Vulnerabilities exist around key functions or units, which are difficult to replace or do without. Some general types of vulnerabilities present in most systems and organizations are information security, employees, physical protection, regulations, value chains and system design. [11]

In the power system, these vulnerabilities exist in all types of infrastructure, from supply, transmission and demand. One of the main vulnerabilities in the power system is the control system, since it has a core function in the operations. To secure the system functionality major efforts are also made to protect the digitalized control system from intrusions and cyberattacks. [31]

Another similar type of vulnerability is centralized production units. As an example, each of the nuclear reactors has a considerable contribution to the electricity supply in Sweden. Conversely, extensive decentralization is another type of vulnerability, causing increased operational complexity and exposure to weather intermittency with less dispatchable production. [11]

In addition, there are also vulnerabilities in the transmission grid. According to [12] the structural bottlenecks at the electricity price area interfaces could be such examples, where a line or substation failure near interface 2 or 4 could have larger impacts than in other parts of the grid. Another example is lines without redundancy, which are common in local grids and cause ENS in case of failure. A more comprehensive explanation of these and other power system vulnerabilities is provided in Appendix B. The vulnerabilities and how they have changed recently are also summarized in Figure 3-2. [33]

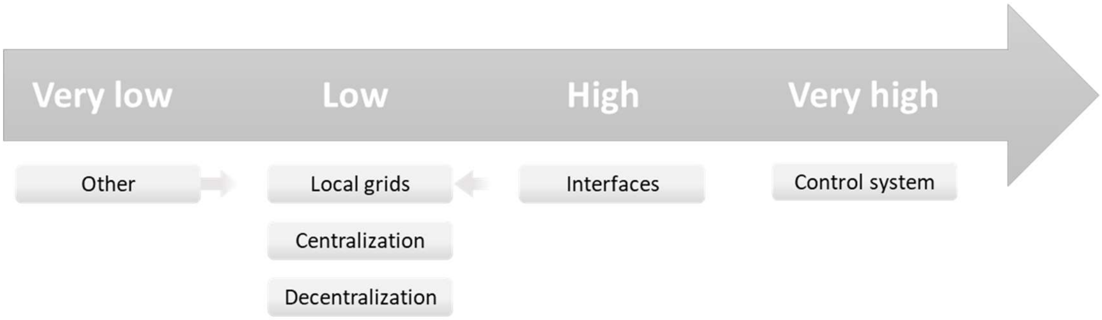

Figure 3-2: *Summary of vulnerabilities in the power system*

Sweden is generally more dependent on electricity than other countries, as the country is highly electrified, with higher demands, more sectors and developed systems powered by electricity. Consequently, this also makes Sweden more vulnerable to security of supply in the power system than other countries. Addressing vulnerabilities is therefore of great importance to ensure the functioning of essential activities of society. [31]

3.3 Threats to the power system

Power system threats have become more relevant in recent years. The annual risk analysis by Svenska kraftnät highlights that threats to electricity supply in Sweden come mainly from China, Russia and Iran, where the most likely character of these threats is "physical or digital damage caused by attacks from criminals or terrorists", with the main targets being infrastructure, information and employees. In addition, extreme weather events are a growing threat that require adoption of the power system. The measures to mitigate these events can sometimes be the same, but the character determines which measure is most effective. [31]

One of the main threats to security of supply in power systems is cyberattacks, since activities and operations are highly digitalized. Cyber threats targeting vulnerabilities such as the control system or centralized production units pose particularly high risks [31]. Another major security threat is sabotage against physical infrastructure, such as power plants, substations, lines and HVDC cables, where the probability have increased recently. For example, there have been several events of potential sabotage on infrastructure in the Baltic Sea [22]. The war in Ukraine have also actualized the physical protection of infrastructure, as they become legitimate targets for antagonistic actors. [10]

Focusing on extreme weather rather than security, there are firstly threats related to a warmer climate, such as drought, heat waves and wildfire. These could for example, affect inflows of hydropower, cooling possibilities of thermal power plants and grid transmission capacity, which are mostly related to long-term security of supply [22]. Secondly, precipitation patterns are expected to change, with heavier rainfall and snowfall, causing high flows, floods, landslides and avalanches. In combination with temperature changes it can also cause icing of lines and ice storms, which risks damaging the power system infrastructure. However, although precipitation could bring serious weather events it is not considered as a major threat to the security of supply, especially not short-term [33]. Lastly, there is also powerful weather events, such as storms and lightning, which are the most common cause of disturbance [27], and unusual events, such as earthquakes, volcanic eruptions and space weather. A comprehensive list explaining the different threats is presented in Appendix C. The threats and how they have changed recently are summarized in Figure 3-3. [33]

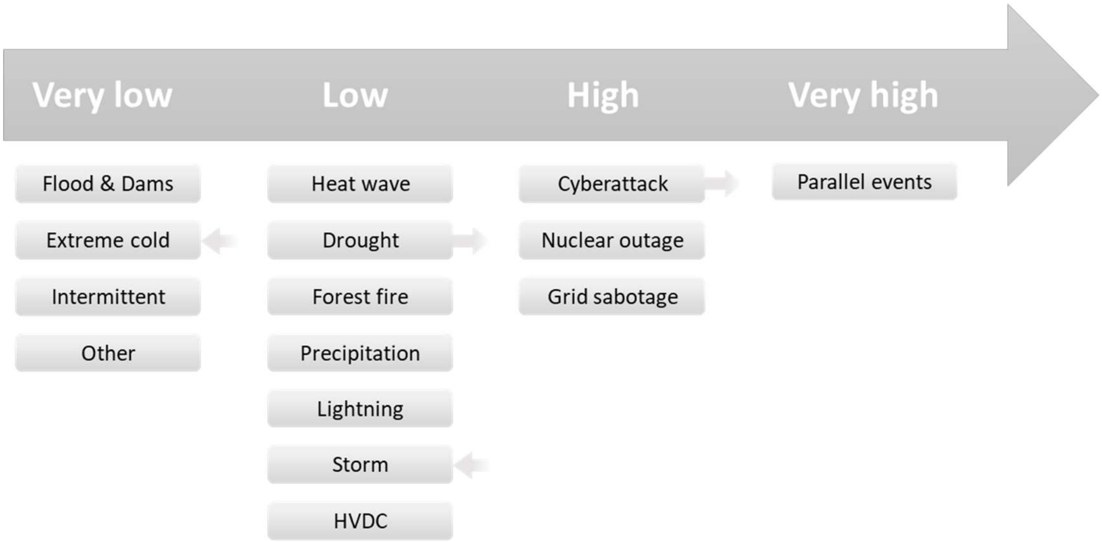

Figure 3-3: Summary of threats to the power system

3.4 Research gap

Research on how the power system is affected by security and extreme weather events has become more relevant because of the global situation. Many studies have been conducted to describe threats to electricity supply and vulnerabilities in power grid infrastructure. Some of the most important literature and what is not included in these references will be presented below.

3.4.1 Related work

As security and power systems to a high extent are national concerns, governmental reports have generally been the main literature for the background of this thesis. In particular, reports from Svenska kraftnät have been important, with the main sources being [31] together with [17] on power system risks and development. In addition, the EU report [22] and [33] by Energiforsk have also been important to describe how the power system is affected by security threats and extreme weather respectively.

Scientific papers have also been key to form the basis of this report. Primarily, concepts from [24] by Duvnjak Žarković and [25] by Bakken Sperstad et al. have been useful for the background. Further, the PhD thesis [35] and associated papers by Forsberg on power grid resilience and HILP events have also been important for the background and method of this thesis.

3.4.2 Identified gap

Grid simulation models are widely applied to identify vulnerabilities in the power grid, for example in [12] by Forsberg et al., and similar methodologies are also common in risk analysis. There are also many publications on threats to the power system, such as [31], [22], and [11], from different authorities. However, there are few published studies with simulated threat scenarios to the power system, partly because they are subject to confidentiality which also constrains this thesis. Another explanation to the research gap could possibly be diverging interests between these actors, with businesses mainly concerned about internal aspects of threat events and authorities about the extent and overall impact on society. Therefore, this thesis project aims to address this research gap, through simulation of threat scenarios with major impact on the power system, focusing on technical and economic impact. In this way, the thesis will bring new perspectives and insights on how power systems can be affected by HILP events, but without confirming others conclusions.

Chapter 4

Materials and Methods

This chapter presents the methodology of the thesis and how the modeling was conducted. In particular, the materials and methods used for data collection and the design of scenarios, simulations and assessments are described.

4.1 Methodology

To identify and analyze vulnerabilities and threats to the power system there are several possible methodologies. In general, qualitative studies are useful to provide an overview of the threat situation, and sometimes necessary when it is difficult to quantify the research problem. Some of the related works that form the basis of this thesis are qualitative studies. A quantitative research methodology has other qualities that differ from qualitative studies. Generally, methods driven by data and simulations can provide complex analysis and specific results, however with uncertainty. There are also a variety of possible tools to use when analyzing the impact of threat scenarios on the power system, such as grid models or electricity market models.

The choice of methodology and tools depends largely on the purpose of the study, as well as the type of results desired. For this thesis, the identified threats are summarized with a qualitative risk matrix, while the impact on the power system is analyzed quantitatively using the software tool PSS/E.

4.2 Research approach

The research approach started by defining the aim of the thesis project, as well as the scope and delimitations. With this as a basis, the literature review was undertaken and necessary data collected. Then the background and risk situation were described by identifying vulnerabilities and threats. Based on the identified risks, the threat scenarios were designed by selecting relevant HILP events to the power system. Further, the scenario narratives were transformed into simulations and then the results were analyzed with focus on impacts, measures and uncertainties. Finally, the findings and future work were concluded. An overview of the research approach is shown in Figure 4-1, followed by detailed description in following sections.

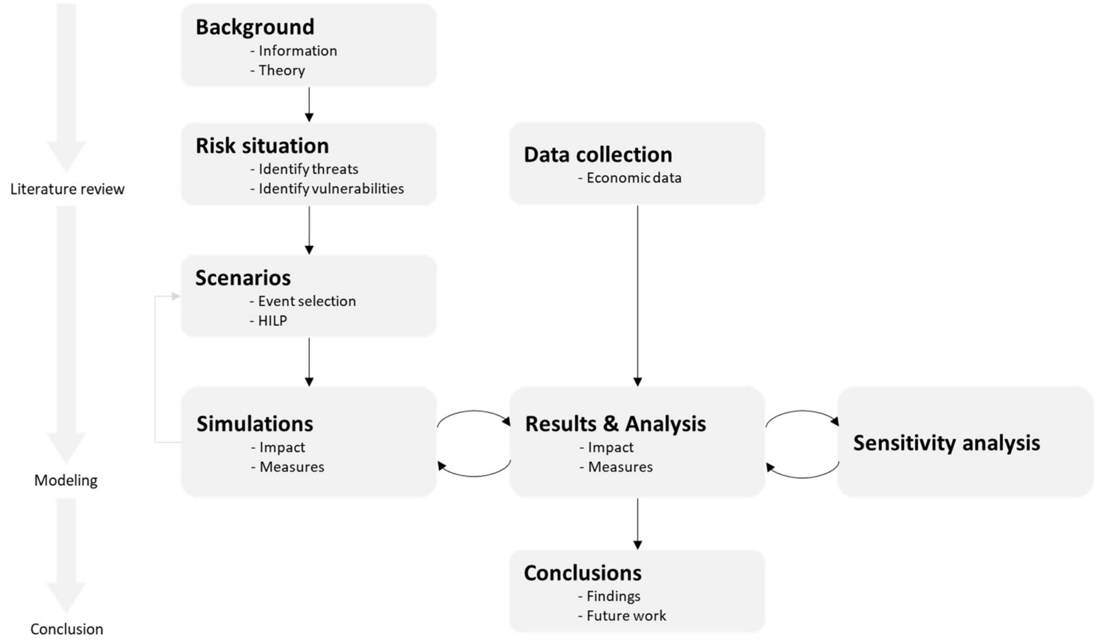

Figure 4-1: *Research approach*

4.3 Literature review

Data collection has mainly consisted of compiling literature, since all of the technical data on the Swedish power system was provided internally by Svenska kraftnät and the grid simulation model PSS/E. In addition, economic data was sourced from Energimarknadsinspektionen. In general, reports from authorities have been important in the literature review, but also scientific publications. An overview of the sources used for each part of the report is shown in Figure 4-2.

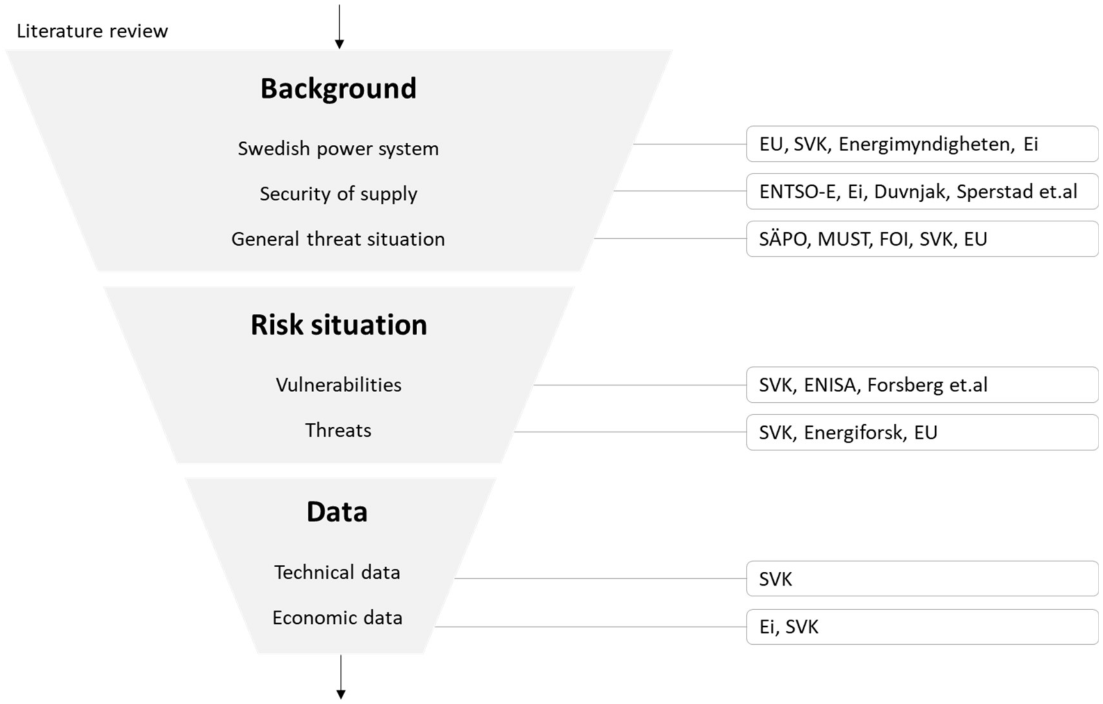

Figure 4-2: Literature review and data collection process

To ensure the scientific quality of the literature and data used in this thesis, sources have been carefully selected. Overall, government reports in Sweden and EU can be considered credible and scientific articles have only been used from publishers and journals of high reputation. To a high extent, literature and data have also been validated against each other, particularly regarding the threats and vulnerabilities. More on how the scientific quality of the results of this thesis has been ensured is described in the following section.

4.4 Modeling

The results in this thesis have primarily been developed through modeling, including scenarios, simulations and analysis. Below is the method for how the modeling was conducted.

4.4.1 Scenario design

The scenarios have been designed to ensure that each scenario is relevant, while providing a balanced portfolio of different types of events. The design process started by identifying the main threats, followed by the vulnerabilities they could target. Overall, the scenarios are characterized by HILP events with a major impact and simultaneously being hard to mitigate or prevent through conventional measures in the power system. A fundamental criterion for the selection of events was also that they should be possible to simulate properly in PSS/E. As a result, cyberattacks on for example, IT- and control systems were excluded from the scenarios although they could have a devastating impact if they were under foreign control. Likewise, some of the most common and well-studied weather events, such as storms and lightning, were also excluded, to highlight less researched but relevant events. Finally, the severity of the scenarios was defined at a purposeful level beyond traditional contingency analysis (N-1), without being too unrealistic while having a significant impact, such as N-2 events or well-targeted attacks. The narratives of the scenarios studied are presented in chapter 5.

4.4.2 Simulation design

Simulations have been developed to be consistent with the narrative of each scenario and should reflect the actions taken in the grid if a real event occurs. Each scenario was simulated separately but the process was similar for all scenarios.

First, one of Svenska kraftnät's predefined base operation cases for the current transmission grid was selected, with flows, system load and production mix consistent with the scenario narrative. Then, at least three candidate cases were investigated with the same event happening at different locations, and based on a pre-assessment the candidate with the highest overall impact was selected. For example, it could be three vulnerable substations, where one is selected for further investigation. A chart of the simulation process is shown in Figure 4-3. To customize the simulation based on how the scenario would be managed in reality, operational procedures from Svenska kraftnät for handling such events was collected and the simulation settings were made accordingly.

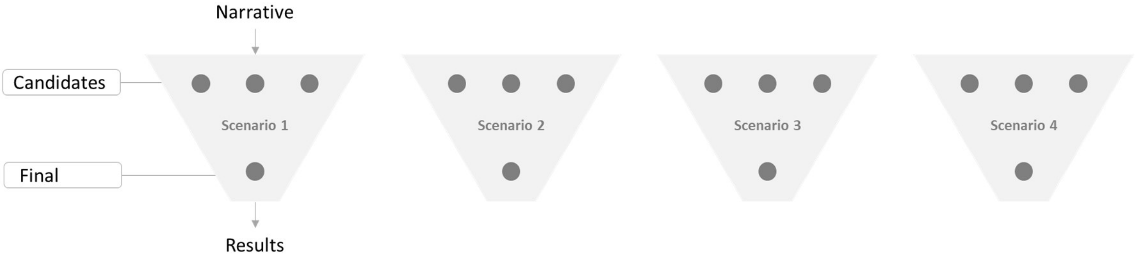

Figure 4-3: Simulation process from scenario narrative to results

To facilitate the implementation in PSS/E and make the simulation method reproducible the load flow was simulated by developing a phyton script for each scenario. The solution settings applied automatic tap adjustment and switched shunts to mimic the real automatic grid actions taken during disturbance. Further, the manual generator- and load adjustments for each scenario was made according to the operational procedures, which differs between the scenarios. Specifically, whether the event causing interrupted power supply is due to outage of generation or transmission capacity. The method for determining ENS in each of the two cases is described below.

Generation outage: For scenarios when power generation is lost the supply is compensated by other dispatchable generators in the Nordic synchronous area. If the supply increase is not enough to replace the generator and additional grid losses in the slack bus, load is disconnected until the generator power is reduced to zero.

Transmission outage: For scenarios where transmission capacity is lost, the line is replaced by a fictive load at the buses on each side, with the same powers as the line had. Then, these fictive loads are reduced gradually while supply from dispatchable generators in the Nordic synchronous area is increased to compensate grid losses in the slack bus. At the point when the load shedding is required, loads are disconnected until the fictive loads are reduced to zero, meaning that the line is out of service.

In both cases, the sum of the total disconnected load equals the magnitude of interrupted power, which is used to determine the ENS. Consequently, if no load needs to be disconnected there is no ENS.

It is important to emphasize that only actions to limit the propagation of the disturbance are taken in the simulations. Thus, there will be lines, transformers and buses in the grid that are still overloaded and violated, requiring further actions from the operators in the control room. This is because the operating procedures can be considered sensitive. More about ENS and how its uncertainties are assessed is described in the following section. Details about PSS/E as a simulation tool are also found in Appendix D.

4.4.3 Assessment

The simulation results are assessed in three ways, primarily by analyzing the power quality and security of supply, but also a qualitative assessment to cover most of the relevant aspects of the scenarios. The power quality criteria intend to cover the main technical impacts on the power grid, while security of supply focuses on both technical and economic impacts to customers and society. Other overarching aspects are addressed in the qualitative analysis. The entire Swedish transmission grid is considered in all scenarios.

The power quality criteria consider overloading of lines and transformers, as well as bus voltage violation in the transmission grid. For lines and transformers, it is measured by the number of overloads and the average of these overloads. Similarly, the number of violated buses and the average deviation outside the upper and lower normal operating voltage limits of these are measured, which is further explained in Appendix E. The table template for power quality results is shown in Appendix F.1.

Security of supply is measured with ENS at transmission grid level, where the ENS is calculated in the same way as Svenska kraftnät does to ENTSO-E, by multiplying the average interrupted power with the duration, shown in Equation 1. In this thesis the interrupted power is multiplied with 1, 2, and 3 hours respectively as the exact duration of the scenario impacts is uncertain. The ENS can be seen as a lower limit for the required load shedding, as overloads remain to be addressed in this case. Economically, the impact is estimated with TIC (in SEK), obtained by multiplying the ENS with the total aggregated VoLL for each hour. The calculation is shown in Equation 2 and the result template for ENS and TIC is presented in Appendix F.2.

$$ENS_{(i)} = Interrupted\ power \times Duration_{(i)} \tag{1}$$

$$TIC_{(i)} = VoLL_{(i)} \times ENS_{(i)} \tag{2}$$

The qualitative assessment considers important aspects that are not covered by the previous assessments. As uncertainties are hardly quantified in this case the sensitivity analysis will be a core part of the qualitative assessment, where assumptions and observations during simulation as well as the risk for cascading effects will be discussed. In addition, mitigation measures are another important part of the qualitative assessment. As internal mitigation measures, such as tap- and switched shunt adjustments are taken already in the simulations, the implementation of PSS and power reserves are mainly discussed. The impact of different measures as well as potential multiple values of these will also be addressed to broaden the perspective of this study. Some reference values to anchor the results and enable comparisons are presented in Appendix G.

Chapter 5

Scenarios

This chapter presents the scenarios of the thesis project. In particular, the scenario narratives are described together with some background information.

5.1 Nuclear outage

The narrative behind the nuclear scenario is that an antagonistic actor uses physical threats to force one of Sweden's nuclear power plants to shut down all its reactors within 15 minutes. As nuclear power plants have comprehensive safety regulations to avoid nuclear accidents and dispersion of radioactivity, the nature of the incoming threat implies that the risks and damages to society are less if the reactors are stopped than if the threat is realized into physical actions. The scenario takes place on a cold winter day when the system load is high.

In Sweden something like this has never happened. However, as nuclear power plants are centralized production units, where each reactor has a significant contribution to the electricity supply, it is a plausible threat scenario that antagonistic actors could target this vulnerability in some way. This scenario does not mean that Sweden’s nuclear power plants are part of an armed conflict as in Ukraine [10], but rather a deniable hybrid threat that may be part of an escalating security situation aimed at testing the capability of the power system and the redundancy of Swedish society in a broader perspective.

In an emergency, a nuclear power plant can be stopped within seconds. Internally, each reactor has multiple backup components and independent safety systems to maintain operational reliability and avoid outage of several reactors at the same time due to internal faults or incidents [36]. However, external threats are different, and in the worst case they could force several reactors to be shut down at the same time. This means that the power grid is designed to be able to handle the loss of one reactor but not several. [37]

5.2 Wildfire

In the wildfire scenario, the narrative is that a heat wave contributes to dry vegetation in southern Sweden, leading to the spread of a large wildfire that damages a vulnerable power line. Due to the heat wave the transmission capacity in the grid is assumed to be reduced by 10% while the damaged line needs to be taken out of service in a controlled manner, making it a strained N-1 case. As the scenario takes place during summer the system load is low.

Large wildfires covering around 10 000 hectares have occurred in the Västmanland region in 2014 and Ljusdal in 2018 [33]. However, no wildfires of the same magnitude have recently occurred near the transmission grid [27]. Apart from the fact that wildfires can destroy lines, poles, insulators and other components, lines may need to be taken out of service for safety reasons. For example, soot can cause flashovers and energized ground, while higher ambient temperatures can cause low-hanging lines, posing major safety risks. High temperature also reduces thermal transmission capacity, increasing the risk of overloading during heat waves and wildfires. How transmission capacity changes with temperature, wind, solar radiation and other weather parameters are shown in Appendix H. [38]

5.3 HVDC sabotage

The narrative of the HVDC scenario is that an antagonistic actor breaks two of Sweden's offshore HVDC cables simultaneously at different locations through a coordinated attack. Given the security situation and recent events in the Baltic Sea, the probability of sabotage has increased significantly from low levels. To ensure the relevance of the scenario, while providing a strained and complementary perspective to previous analyses by Svenska kraftnät, this N-2 case is investigated. The scenario takes place when the load in Sweden is high, with HVDC flows from the continent.

Sweden has several offshore HVDC cables to countries such as Finland, Lithuania, Poland, Germany and Denmark. In some places there are larger single cables, while in others there are several parallel cables. In addition to HVDC cables, the power grid is also interconnected with a large number of AC lines to the Nordic countries. In the Baltic Sea, several types of cable breaks have occurred since the outbreak of the war in Ukraine, including the Estlink 2 HVDC cable and several internet cables. These are suspected to be sabotaged by dragging anchors of ships belonging to the Russian oil fleet. [30]

5.4 Substation sabotage

The narrative behind the substation scenario is that an unknown actor undertakes a discrete precision attack towards a critical 400 kV substation, leading to an outage of the entire substation. As the location of the substation is normally a congested part of the transmission grid, the node could be more vulnerable to outages. To avoid overlapping scenarios, the selected substation is not directly connected to any nuclear power plant, HVDC cable or the area where the wildfire occurs. The scenario takes place during winter when the system load and transmission is high.

The context of this scenario may be that the sabotage is preceded by intelligence operations mapping grid vulnerabilities, and at a given time the resilience of the system is tested through physical actions. Substation sabotage of a similar nature has occurred, for example, during December 2022 in North Carolina, USA, where an unknown actor through gunfire damaged two substations causing power outages for over 40 000 people with a duration longer than three days. [39]

Chapter 6

Results and Analysis

This chapter presents the results and analysis of the thesis. In particular, the identified threats and scenario results will be analyzed. The most sensitive scenario results are anonymized in section 6.2 while 6.1, 6.3 and 6.4 are public.

6.1 Threat analysis

This section will introduce the threat analysis to the Swedish power system, related to security and extreme weather. These results are primarily based on literature compiled in section 3.

Security and extreme weather are two of the main types of threats to the Swedish power system, and their relevance have increased in recent years. In common, they put power system infrastructure at risk, which needs to be managed through various measures. However, there are differences in how the infrastructure and security of supply is threatened by security and extreme weather respectively. In general, extreme weather can occur over wide areas, which means that measures involve large parts of the existing power grid. For example, in terms of material selection, pole qualifications, line type, and maintenance of line corridors. In contrast, security threats are largely about identifying specific weaknesses, components or nodes that are particularly vulnerable, requiring more specific measures. For security of supply, this means that security threats usually cause short-term security of supply issues, while extreme weather to a higher extent also has an impact on system adequacy and thus both long- and short-term security of supply.

The most common extreme weather events causing disturbances and ENS are storms and lightnings. Meanwhile, events related to drought and precipitation are expected to increase in the future. Droughts can impact both long-term and short-term security of supply, through reduced hydropower supply or wildfires. Meanwhile, precipitation can bring a variety of events, such as high flows, floods, landslides, ice storms and icing of powerlines. Related to the vulnerability of ageing infrastructure and dam safety, these pose risks, but from a security of supply perspective these threats can be assessed as low, given the redundancy of failures in individual lines and hydropower stations.

For security threats, the most likely events are related to "physical or digital damage caused by attacks from criminals or terrorists", according to Svenska kraftnät. Given its core function of the power system, the digital control system is among the most valuable to protect from antagonistic actors. Consequently, cyberattacks are also among the highest threats to the power system. In addition, the relevance of physical sabotage against critical infrastructure has increased in recent years. Therefore, attacks on major production units and nodes in the grid represent some of the main risks. This includes nuclear power plants, substations and HVDC cables. Finally, the most severe scenario would be parallel events, where several of these events occur simultaneously. In Figure 6-1, a risk matrix on security of supply is shown, with the extreme weather events and how they have changed recently.

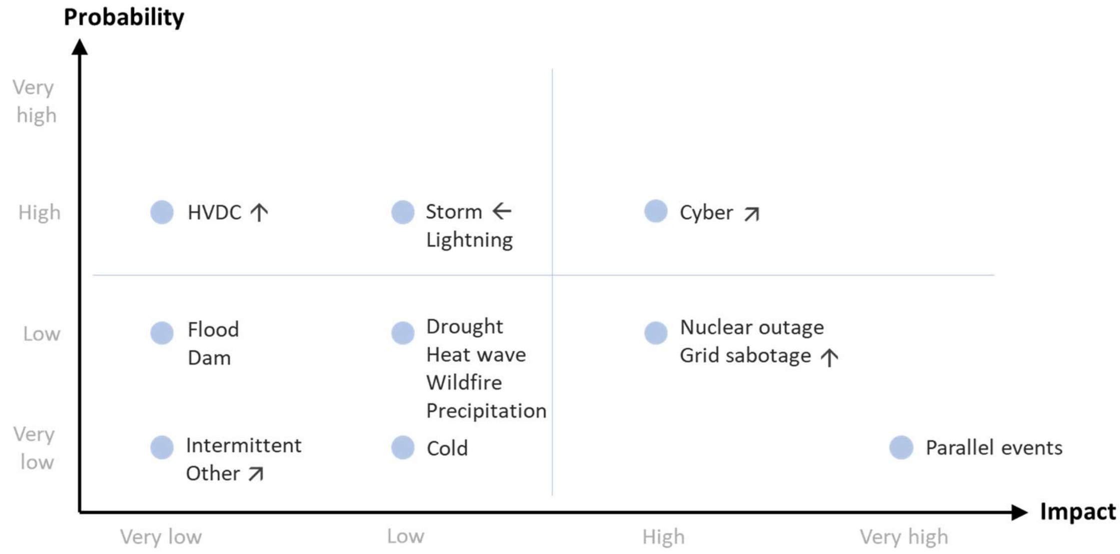

Figure 6-1: Risk matrix with major threat events to short-term security of supply

6.2 Scenario results

The following section will present the results of the scenario simulations, including the quality criteria and security of supply. Due to confidentiality the most sensitive scenario impacts in this section are anonymized.

6.2.1 Scenario A

For the power grid the impacts are extensive in Scenario A, causing substantial overloading in several lines and transformers as well as significant voltage violations in more than a quarter of the Swedish transmission grid, shown in Table 6.1. In addition to the high number of violated buses, the average voltage deviation at 3.5% outside the normal operating limits is significant, indicating a lack of reactive resources. Most of the low voltages are also concentrated to a specific part of the grid, which brings both operational and design challenges.

Table 6.1: Overloads and voltage violations in the transmission grid for Scenario A

	LINES	TRAFOS	BUS VOLTAGE
NUMBER	15 (2.8%)	2 (0.7%)	125 (27%)
AVERAGE	117%	130%	±3.5%

To customers the impact is also significant, with an interrupted power at around 1 500 MW. Given that many lines are still overloaded, even higher ENS than presented in Table 6.2 could be expected to comply with the operating limits. The costs are also considerable, around MSEK 150 per hour.

Table 6.2: Energy Not Supplied (ENS) and Total Interruption Cost (TIC) in the transmission grid for Scenario A

	1 HOUR	2 HOURS	3 HOURS	
ENS	1 490	2 980	4 470	MWh
TIC	155	293	385	MSEK

In this case the uncertainties are mainly linked to the rapidity of the scenario, as ancillary services and procured power reserves have setting times, which in turn affect the ability to prevent major impacts on the grid. However, almost regardless of the rapidity, load shedding will be required, and if it is very fast it could result in significantly more load shedding and a considerable risk of cascading effects that could trigger a system blackout.

6.2.2 Scenario B

For the power grid, the impacts of Scenario B are significant, with high overloads in several lines and violations in more than a sixth of the transmission grid, shown in Table 6.3. In fact, an average overload of almost 140% in 14 lines means that the transmission grid has major remaining challenges to address. The fact that some of the affected lines are hard to mitigate further contributes to the serious situation. Apart from the high number of violated buses, the average deviation outside the normal operating limits is not very large, which could be explained by sufficient amount of reactive resources.

Table 6.3: Overloads and voltage violations in the transmission grid for Scenario B

	LINES	TRAFOS	BUS VOLTAGE
NUMBER	14 (2.5%)	1 (0.3%)	78 (17%)
AVERAGE	137%	134%	±1.8%

To customers, the impact is substantial with more than 1 000 MW interrupted power and a TIC around MSEK 100 per hour, shown in Table 6.4. However, in case the system capabilities are not sufficient to handle the overloaded lines these numbers will increase significantly, to return within normal operating limits. Depending on how much load shedding that can be applied at which location, the interrupted power could be up to twice as high.

Table 6.4: Energy Not Supplied (ENS) and Total Interruption Cost (TIC) in the transmission grid for Scenario B

	1 HOUR	2 HOURS	3 HOURS	
ENS	1 050	2 100	3 150	MWh
TIC	109	206	271	MSEK

The uncertainties of this scenario are mainly linked to the realization and the immediate grid response, where the time aspect is essential but hard to capture in the PSS/E simulations. Further, the operator's actions also have a strong impact on the outcome in reality. Given the flows and the location of the scenario, an event of this magnitude could have significant cascading effects that risks leading to a major system blackout. Mitigation measures include for example, further expansion of the fast ancillary service market, such as

Frequency Restoration Reserve (FRR) and Frequency Containment Reserves (FCR), and voltage stabilization resources.

6.2.3 Scenario C

Despite that Scenario C occurs during a strained period, the impact of the event is low both in terms of overloads and violations, shown in Table 6.5. The results indicate that only one line is overloaded, while three transformers are slightly overloaded. The voltage violations in the transmission grid are limited.

Table 6.5: Overloads and voltage violations in the transmission grid for Scenario C

	LINES	TRAFOS	BUS VOLTAGE
NUMBER	1 (0.2%)	3 (1.0%)	43 (9.1%)
AVERAGE	143%	114%	±1.4%

The immediate impact on customers is low, as the grid can handle the scenario without ENS. In simple terms, this could be explained by the fact that the existing ancillary services can handle this event, although this scenario is an unidentified contingency. Overall, this means that the transmission grid has sufficient capabilities to handle such scenario.

6.2.4 Scenario D

The results in Table 6.6 indicate that the impact on the power grid is limited. The low number of overloads could be explained by the fact that the grid has sufficient possibility to receive and redirect flows. Meanwhile, a sixth of the Swedish transmission grid is violated, partly due to reduced amount of reactive resources, resulting in more unstable voltages during disturbance. However, the average voltage deviation from the normal operating limits is not very high.

Table 6.6: Overloads and voltage violations in the transmission grid for Scenario D

	LINES	TRAFOS	BUS VOLTAGE
NUMBER	3 (0.6%)	0 (0%)	83 (17%)
AVERAGE	116%	0%	±1.4%

To customers the impact of this scenario is very low, without any ENS. Thus, a larger disturbance would be required to have a significant impact. However, the probability that additional or more critical units would be affected is low, given the extent and specific location required.

6.3 Scenario analysis

This section presents a general analysis of the scenarios. Measures, uncertainties and societal impacts related to each scenario will be addressed. The analysis in this section is based on public information.

6.3.1 Measures

To mitigate scenarios with generation outage, a larger power reserve and reactive resources are required. For example, more locally installed batteries and gas turbines at the nuclear power plants and HVDC link, as well as reactive power compensation from static var compensators (SVC), static compensators (STATCOM) and other PSS. However, this would mean a very high level of security of supply, which is probably not justified socioeconomically.

Mitigating transmission outage scenarios largely involve redundancy of lines and substations, primarily to manage N-1 cases, as this level is usually considered socioeconomically viable to avoid impacts. For N-2 cases, measures are established in Svenska kraftnät's system protection plan to mitigate (but not avoid) the impact of serious power system disturbance. This involves risk assessments of particularly vulnerable types of lines and nodes. Specific measures to mitigate line disturbance from wildfires but also storms and accidents are mainly to regularly clear line corridors from trees and bushes around poles and braces, particularly relevant at lower voltage levels with narrower line corridors, lower poles and less redundancy.

In general, avoiding security scenarios are largely beyond power system competence, but rather policy and defense competence. However, as a system responsible authority, Svenska kraftnät has an important role in mitigating the impacts when the disturbance occurs, through preventive measures. To avoid sabotage technical solutions could provide physical protection and monitoring of critical infrastructure, such as HVDC cables and power plants.

In the long term, most scenarios would benefit from a reinforced system design with a more meshed grid and higher capacity across bottlenecks. In fact, the investment package NordSyd will address parts of this vulnerability by reinforcing the transmission capacity between northern and southern Sweden. From an electricity market perspective, higher interconnection within and across the Swedish borders is favorable. However, foreign connections may be difficult to implement politically and need to be motivated socioeconomically.

6.3.2 Uncertainties

For scenarios with N-2 events the major uncertainty is the time separation between the events, since it could have a major impact on the grid stability with a risk of oscillations and cascading effects. Unfortunately, these effects are difficult to capture in the PSS/E simulations even if the events occur at the same moment. In the worst case, such an event could trigger a widespread blackout, as happened in the Iberian Peninsula in the spring 2025 [40]. It can also be stated that natural causes of parallel events occurring during a strained period have a very low probability. Therefore, such event could indicate that there is an antagonistic actor involved, who is also willing to take high risks and hold capabilities of planning and executing an advanced attack. [10]

Another uncertainty is related to the boundary conditions of the simulations. This is particularly relevant for the wildfire scenario and the level of reduced thermal capacity. As presented in Appendix H, there are many parameters that affect the capacity of a power line. Thus, assuming a general reduction based on measured relationships is a rough simplification of reality, where weather conditions change from hour to hour. However, given that the thermal capacity had a limited impact on the simulations, the simplification of this insensitive parameter can be considered valid.

Lastly, the duration of the events is also uncertain, which depends largely on the scenario narratives and whether components are broken and need to be repaired before it can return into operation. If operational measures can be implemented in a controlled manner, it is also beneficial from a security of supply perspective. For the nuclear scenario, it should be possible to restart the power plant as soon as the direct threats are eliminated, given that no major component is broken during the rapid shut down. For the scenarios with damaged infrastructure the impacts could be long-term with electricity market impacts, although the ENS should be possible to address within hours or days in the worst case. As a reference, the substation outage in North Carolina, USA in 2022 lasted over three days, the major forest fires in Västmanland and Ljusdal lasted several weeks [33], and the HVDC cable Estlink 2 is expected to return into operation after six months. [30]

6.3.3 Society

From a broader perspective, threat scenarios with high impact to the power system is also expected to have a major impact socially and politically in Sweden and its neighborhood. Consequently, policy actions beyond power system measures and the responsibility of Svenska kraftnät are needed to avoid such scenarios from occurring.

From a societal perspective, the impacts of wildfire and other extreme weather events can be significant, not only related to electricity supply but also other perspectives, such as private properties, ecological and economic aspects. Meanwhile, it could be stated that it is difficult to foresee and safeguard against all types of events related to security and extreme weather, as well as pure accidents. An example of the societal vulnerability to such events is the substation fire in northwest London, UK in early 2025, that closed Europe's largest airport Heathrow for an entire day [41]. This highlights the importance of preventive actions to both avoid and mitigate threat scenarios.

Finally, there are also other plausible scenarios, where two collocated lines, substations and power plants can be threatened simultaneously. Therefore, collocations and the risk of N-2 cases need to be considered when developing power grids in the future. However, this also involves trade-offs with other aspects, which will be discussed further in the following section.

6.4 Discussion

When designing power grids there are many aspects, interests and stakeholders to consider. This is particularly relevant today, as the Swedish power system is undergoing a major expansion to enable the energy transition, while reinforcing the system against security threats. Therefore, this section will address the trade-offs, synergies and different dimensions of sustainability when designing power grids.

In Sweden, power grids are built with great consideration of nearby people and the environment. To minimize the impact on the surroundings and facilitate the permitting process, it is common to collocate new lines and substations with existing ones. However, this implies a trade-off with security of supply, as the risk of simultaneous interruptions increases with collocations, both for security and extreme weather events. For security of supply, the solution would rather be to build new lines on unexploited land, with a higher environmental and social impact as a result. Consequently, if a severe threat scenario take place, the functionality of the power system is probably more important to the society than environmental and esthetic aspects, especially in Sweden which is more dependent on a reliable power system than other countries. Therefore, it can be concluded that the future grid design depends largely on the perspective and scenarios applied during grid development.

Meshed grids are a promising concept that can address and accommodate both security of supply as well as environmental and social aspects. For example, meshed grids can be built with geographically collocated lines that are topologically distanced from each other, which is an effective compromise. In addition, meshed grids are also highlighted as a good operational solution to avoid grid congestion and bring synergies with the new flow-based model, which aims to increase socioeconomic benefits. In grid development this link is also strong, with mutual cost- and security incentives to reinforce vulnerable nodes. In this way, synergies are captured between security of supply and all the dimensions of sustainability in grid development.

Chapter 7

Conclusions and Future work

This chapter concludes the findings of the thesis. In addition, limitations, future work and reflections to the project will also be presented.

7.1 Conclusions

The overall aim of this thesis was to identify threats and vulnerabilities in the Swedish power system, related to security and extreme weather events. In addition, the impact on security of supply has been investigated through power system simulations of threat scenarios.

The threats to the Swedish power system have increased in recent years, primarily as a result of the evolving security situation in Europe, but extreme weather have also become increasingly relevant. Identified threat events with high impacts on security of supply include cyberattacks and sabotage towards power plants, substations and lines. In particular, threats targeting vulnerabilities can have a major impact, such as events towards the digital control system, major production units and nodes near congested parts of the grid. Finally, threat scenarios with high impact to the power system would probably also have a major social and political impact on society.

The scenario analysis demonstrates that threat scenarios can impact the power grid and its customers differently. Scenario A and B could have a significant impact on both the transmission grid and its customers, through overloads, violations and ENS. In contrast, Scenario C and D would have a limited impact. However, there are uncertainties in these scenarios, primarily related to the timing and execution of the events, where the most severe scenarios in the worst case could trigger cascading effects resulting in a major system blackout.

Measures to mitigate the impact of threats vary between the scenarios, but generally deployment of more grid stabilizing resources and PSS would benefit security of supply in all scenarios. Specifically, measures to voltage violations include more reactive resources, such as SVC and STATCOM, and to avoid ENS during supply interruptions, more local and procured power reserves are necessary. However, to have an optimal level of security of supply there is a trade-off between the damage cost and measures. To conclude, security of supply to a high extent exists in the intersection between social and economic aspects, by continuously providing fundamental service at reasonable cost for society.

In the long term, reinforcements of vulnerable nodes are needed to mitigate the impacts of threat scenarios. This is underway, for example with the major investment package NordSyd. A highly meshed grid design also allows multiple values between security of supply and aspects related to economy and sustainability. A strategy is also needed on how much of future solutions are made dependent on the control system, otherwise it risks increasing this vulnerability. Beyond the power system, political actions and technological solutions are also needed to strengthen the protection and monitoring of critical infrastructure to avoid threat scenarios from occurring.

7.2 Limitations

What limited this thesis is primarily related to confidentiality, as vulnerabilities and threats to the power system is sensitive information that could harm Swedish interests if made public. The balance between defining sensitive information while providing new insights to the general knowledge horizon was therefore an important aspect in this project. Consequently, this thesis does not publish any site- or power system specific information but aims to highlight a relevant topic in energy research that will be important to society for a long time.

To integrate security and extreme weather threats with grid development at Svenska kraftnät, the method to simulate threat scenarios with PSS/E was applied. However, despite that PSS/E is one of the most widely applied power grid simulation software tools it was challenging to perform detailed analysis, and the software also limited the selection of threat scenarios. For example, related to cyber threats, boundary conditions for extreme weather events, analysis of blackouts and the risk of cascading effects. However, a more suitable software for this thesis project has not been identified, and given the confidentiality more detailed results could not have been published either. Nevertheless, this highlights the limitations of quantitative tools, while the use of qualitative methods and risk matrixes is justified when analyzing power system threats.

7.3 Future work

Given the delimitations of this thesis and the increased relevance of the topic, there is plenty of scope for future work on how threat scenarios could impact the power system. A continuation of this thesis could have been to analyze security and extreme weather events in more detail. Both regarding the impacts of other threat scenarios or a deeper analysis of the selected scenarios. It would also be useful with a comprehensive comparison of the costs and benefits of implementing different measures. In addition to security and extreme weather, there are also other threats, such as technical faults, accidents and external factors that need further investigation.

This thesis project has focused on events with high impact on short-term security of supply, where the analysis period of the scenarios varies from seconds to hours. Consequently, there is a need to analyze both shorter-term events at millisecond level, but also long-term evolution over years. For example, this includes the risk of a widespread power system blackout like the one on the Iberian Peninsula in 2025, and the risks associated with ageing infrastructure and predictive maintenance, which becomes increasingly important in weather-dependent power systems.

When analyzing threats to the power system there is also a need for complementary methods of risk management beyond the traditional N-1 criterion. For example, security threats can increase the risk for parallel events, which require enhanced preparedness and analysis with N-2 criterion especially at vulnerable nodes. To address resource efficiency while ensuring an optimal level of security of supply, probabilistic risk assessments (PRAs) have also become increasingly popular as a useful tool for both grid development and asset management.

7.4 Reflections

Recurring extreme weather events and the security situation in Europe have highlighted the need for reliable electricity supply in modern societies. Although these threats are undesired, it has at least contributed to increased societal awareness and the fact that power grid investments to a higher extent involve security aspects. This is not only beneficial for security of supply in power systems, but from a broader perspective also ensures the long-term resilience and prosperity of the Swedish society.

In the future, security of supply in power systems will become even more important as societies become more digitalized and electrified. Meanwhile, prioritizing security of supply does not have to compromise with other aspects. Identifying and capturing synergies which benefit both security, economy and sustainability are therefore important in grid development. In this context, Svenska kraftnät also has a key role in leading and coordinating the transition.

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Appendices

A. NordSyd program

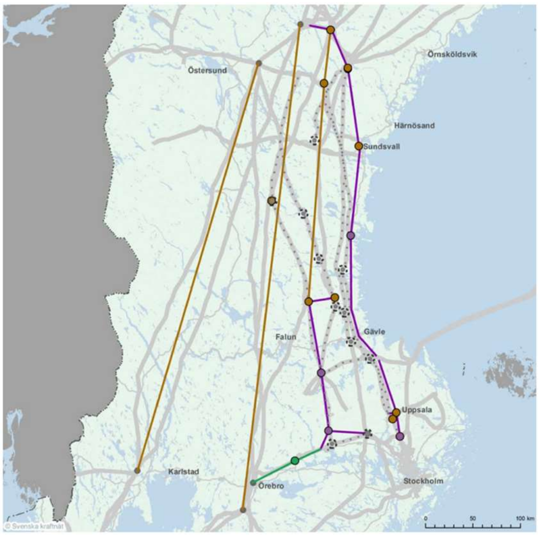

Figure A-1: *Map illustration of the NordSyd program [17]*

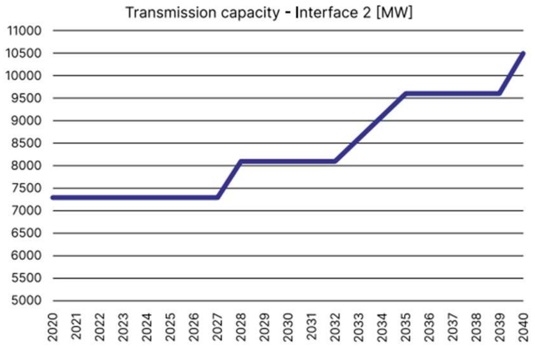

Figure A-2: *Planned transmission capacity development at interface 2, between the electricity price areas SE2 and SE3, through the NordSyd program [17]*

B. List of vulnerabilities

This is a list of vulnerabilities to the electricity supply in Sweden. The extent of vulnerability is described using the terminology; very low – low – high – very high. This terminology should be interpreted as a relative rating between the listed vulnerabilities, which are all of a considerable character. The vulnerabilities are also represented in Figure B-1.

Digital control system: Control systems is a core part of the power system, and since they have become digitized, operations have been improved through higher integration between information technology (IT) and operational technology (OT), improving efficiency and control. However, the digitization has made the system more vulnerable, as more control have been centralized to the control room. Consequently, in the wrong hands major disruptions and damage can be caused. Like other IT systems, control systems can be targeted through intrusion or cyberattacks and given its centralized function, it is among the most valuable to protect from antagonistic actors. The vulnerability of the digital control system is therefore considered very high. [31]

To manage this vulnerability, Svenska kraftnät takes several actions in its IT systems. In addition to protection against cyberattacks from outside, barriers are also built to protect the system from agents on the inside. It is also assumed that there could be a “resting presence” that creates the ability to disrupt the system in the future. However, apart from the TSO control system there are multiple DSOs with separate systems mitigating the risk. [31]

Price area interfaces: Electricity price areas exist as a result of limited transmission capacity at the interface between two areas. These structural bottlenecks are vulnerabilities in the power grid, where failure in a substation, line or HVDC cable across the interface could have larger impact than components elsewhere in the grid. In general, the vulnerability at the interfaces is considered to be low, but at some nodes and operational cases the vulnerability can be considered high. [12]

Managing bottlenecks in the transmission grid is a priority for Svenska kraftnät, as there are both socioeconomic and reliability benefits in avoiding congestion [17]. According to [12], some vulnerable nodes at the interfaces are also mitigated through the NordSyd project. In general, Svenska kraftnät also has a strategy of building a meshed grid, enabling alternative lines and flows during contingency. Further, the new flow-based model will allow electricity to find other paths when congestion or failures occur. [17]

Local grids: Local grids account for more than 80% of the total length of power lines in Sweden. A significant difference compared to high voltage grids is that the redundancy in local grids is lower, as there is usually only one line to the users. In addition, narrower line corridors also increase the exposure to falling trees, which overall means a vulnerability of local grids, especially in rural areas where distances are longer. This vulnerability was demonstrated during Gudrun in 2005 and other subsequent storms, but has been addressed by extensive implementation of underground cables. Topologically, the local grid is also connected to fewer users than the high voltage grid, which means that outages are less extensive. Therefore, the vulnerability of local grids can be considered as low, but was higher in the past. [33]

Centralization & decentralization: Both extensive centralization and decentralization of electricity generation bring vulnerabilities to the power system [11]. In recent years, the share of decentralized intermittent renewables has increased significantly in Sweden, causing fluctuations that need to be compensated by dispatchable sources that are often large centralized power plants. These can become cost-ineffective as a result of the reduced production, which contributes to shutdowns and further decentralization that increases operational complexity and makes it difficult to maintain the power balance, voltage control and system stability. [31]

Conversely, high centralization to a few large power plants also represent a vulnerability, as an outage of one plant can be difficult to compensate for the rest of the system. This is particularly the case for nuclear power plants, where each reactor accounts for a significant share of the electricity supply. Moreover, the impact risks being greater if the situation is already strained [11]. Centralized power plants can also be targets for potential provocations, disturbances or attacks, contributing to additional vulnerabilities. [10]

Other: There are many other vulnerabilities in the power system. The dynamic between supply and demand is one of these. In recent years, the system has become more volatile, partly as a result of higher intermittent power generation combined with evolving consumption patterns with electric vehicles, heat pumps and coming large hydrogen electrolyzers. Another vulnerability linked to operational dynamics is the structure and design of the power grid. As generation and demand changes, the grid is loaded differently and requires adaptations, both at national and local level to address vulnerabilities. Finally, foreign ownership of Swedish energy infrastructure is also a vulnerability. Like supply chains of natural gas, for example, electricity infrastructure is an asset that is important to control in order to mitigate the risk of pressure from foreign powers [31]. For example, the Chinese government owns almost a fifth of Swedish wind power. All the listed vulnerabilities and how they have changed recently are summarized in Figure B-1. [42]

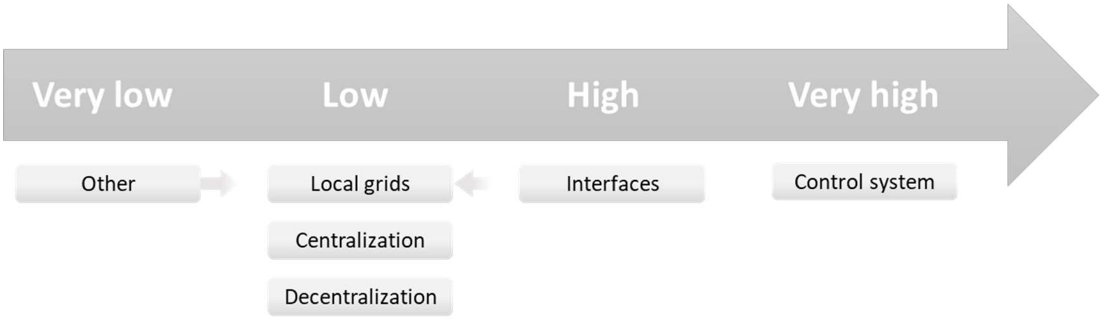

Figure B-1: *Summary of vulnerabilities in the power system*

C. List of threats

This is a list with the main threats to electricity supply in Sweden, focused on security and extreme weather. The probability and impact of the threat events will be assessed using the terminology: very low – low – high – very high. This terminology should be interpreted as a relative rating between the listed threats, which are all of a considerable character. Below the list, the threats are summarized in Figure C-1.

Cyberattack: Related to the vulnerability to digital intrusions are the threats of cyberattacks [31]. Overall, the number of cyberattacks has increased in recent years and affects most sectors [43]. As control systems are digitized and other operations move to the digital world and becomes increasingly complex to manage, both the probability and impact of cyberattacks will increase [11]. In particular, intrusion into the control system have the potential for major impacts on the power system and by extension on society. To mitigate the risk, Svenska kraftnät is taking several measures in its IT systems to protect themselves. As Svenska kraftnät considers cyberattacks to be one of the most likely threats overall, the threat is considered high. [31]

Heat wave: During the summer, heat waves are expected to become more frequent and severe as a result of climate change. Heat waves lasting for days or weeks can contribute to reduced transmission capacity in lines and, at particularly high temperatures, also to the breakdown of components and materials, which can bring power shortages and outages, primarily at local level. Indirectly, heat waves also affect the risk of extreme droughts and wildfires, as well as the cooling water temperature for nuclear power plants, with a range of consequential effects [22]. The probability of heatwaves is certainly increasing. However, the impacts of heatwaves as such are uncertain and hard to determine. The threat from heatwaves alone is therefore considered low, but their consequential impacts may be high. [33]

Extreme drought: Sweden's electricity supply is dependent on hydropower, both as an energy source and storage, since it accounts for around 40% of annual electricity generation and the balancing of supply and demand. Extreme droughts could therefore have a major impact on the power system, especially given that neighboring countries would also be affected by the drought, limiting the import possibilities. However, the overall threat of drought is considered to be low, but in combination with other events it could be high. [22]

Wildfire: The combination of hot and dry weather increases the risk of wildfires, which can spread rapidly in favorable terrain and wind conditions. The cause can be human or natural such as barbecues, sabotage or lightning strikes and is most likely to occur in southern and central Sweden [22]. The risk of wildfires is particularly high in south-eastern Sweden, but is expected to increase in most parts of the country [44]. Given that electricity in Sweden is usually transmitted in a north-south direction, the impact of a wildfire in central Sweden could be high if critical nodes are affected. However, wide line corridors, steel poles and wires high above the ground mean that transmission grids generally have lower risks than regional and local grids, so the threat from wildfires alone can be considered low. [33]

Heavy precipitation: Heavy precipitation include rain, snow or ice storms. In general, the impact of precipitation is largely determined in combine with other environmental conditions such as temperature and wind. Climate change with warmer winters and increased precipitation will result in more fluctuations around 0°C with wet snow and freezing rain in northern and central Sweden. This increases the threat of build-up and icing of lines, causing mechanical stress and breakdowns. However, the impact on electricity supply is considered low [33]. Meanwhile, given that Sweden's power grid is built to withstand large amounts of rain the threat of heavy rainfall can be considered low. However, it can bring consequential effects as high flows, landslides, floods and dam failures, together having higher impacts. [22]

Floods & Dam failure: Related to precipitation are also floods and dam failures that can be caused by heavy water flows. Flooded rivers and dam failures can cause local problems with water-filled substations, fallen power lines and major destruction of other infrastructure downstream of the dam. Ageing hydropower stations and heavier rainfall increase the probability of failures, but as the impacts are mainly local, the threat to the power system is considered very low. [22]

Lightnings: Today, lightning strikes are the most common cause of failure in the power system, resulting in flashovers and fires in, for example substations. Longer and warmer summer seasons also increase the probability of lightning strikes. Lightning also interacts with higher temperatures, droughts and wildfires, which contribute to increased threats. The impact of thunderstorms is also highest in the transmission grid where poles are higher. Although the probability of lightning increases, the threat is considered low due to the preparedness, but can have significant impacts in combination with other weather events. [33]

Storm: Storms have historically caused some of the largest outages in the Swedish power system, particularly affecting local and regional grids with narrower line corridors and lower poles [9]. Going forward, the probability of storm winds is expected to remain unchanged. However, the combination of unfrozen, wet ground and storms is expected to become more common, which consequently increases the probability of fallen trees. However, nowadays large parts of the local grids consists of underground cables as a measure after previous storms, reducing the overall risk despite more favorable weather conditions. Overall, the impact of storms is considered to be reduced from high to low, despite the increased probability of fallen trees. [33]

Extreme cold: Svenska kraftnät has assessed that there is an import dependency during hours in a normal winter, which would increase during extreme cold. If the cold weather conditions which implies high loads also affect neighboring countries, import possibilities are expected to be limited [22]. However, the probability of extreme cold is expected to decrease as winters become warmer [33]. Furthermore, Sweden has power reserves that can handle the high loads during extreme cold. The risks of extreme cold are therefore considered to be very low. [31]

Intermittent shortage: Under normal conditions, low intermittent electricity generation is managed without problems. However, in combination with for example high loads during winter, unexpected loss of generation, transmission or limited import possibilities problems could arise and occurs for example in Germany, so-called “dunkelflaute” [45]. Although the probability of intermittent shortages increases in a more weather-dependent power system, the threat can be considered very low. [22]

Nuclear outage: Nuclear power accounts for around 30% of Sweden's electricity generation and given that each reactor accounts for a significant share of electricity supply, the impact of an outage could be high. In addition to a large amount of energy, nuclear power also provides power quality services. During the summer when most nuclear power is maintained, outages at remaining reactors can cause problems with reactive power, voltage stability and cascade effects, and during high loads in winter, load shedding may be necessary in the worst case. To mitigate the risk of nuclear outages, safety measures are taken at several levels [22]. Furthermore, the war in Ukraine have actualized the physical protection of power plants, as they become legitimate targets for antagonistic actors. Such threats can likely be transferred to a Swedish context [10]. There have also been reports of drones flying close to Swedish nuclear power plants [32]. Beyond security threats, there are also threats related to extreme weather, where heat waves could bring warmer cooling water temperatures resulting in reduced nuclear generation. Overall, the probability has increased from low levels, while the impact of the threats to an entire power plant can be considered high. [31]

HVDC sabotage: As part of the deteriorating security situation, there have been several events of potential sabotage of infrastructure in the Baltic Sea. The explosion of the Nord Stream gas pipeline is one of the most recognized, but there have also been breaches of the HVDC cable Estlink 2 and several internet cables [30]. Given the dependence on imports to southern Sweden during hours mainly in winter, an offshore HVDC cable sabotage could impact on the power system. The probability of these events has increased significantly, while the overall threat is still considered low. [22]

Parallel events: The threats described above can also occur simultaneously, causing an even worse situation. In some cases, this is more likely as there may be synergies, for example between heatwaves, droughts and wildfires [22]. It is also possible that security threats and extreme weather could interact, for example with antagonistic actors taking action when the system is already strained, such as sabotage or cyberattacks on a cold winter day [10]. Overall, the probability of parallel events is considered very low, but the impact could be very high. [22]

Other: In addition to the threats described above, there are other events related to safety and extreme weather. For example, space weather such as solar storms, volcanic eruptions with ash clouds, earthquakes, landslides, avalanches and tsunamis, whose threats to the Swedish power system are considered low or very low. Apart from security and extreme weather, there are other threats such as pandemics, system complexity and ageing infrastructure with risk for accidents that can bring unexpected and cascade effects with significant impact. All the threats and how they have changed recently are summarized in Figure C-1. [22]

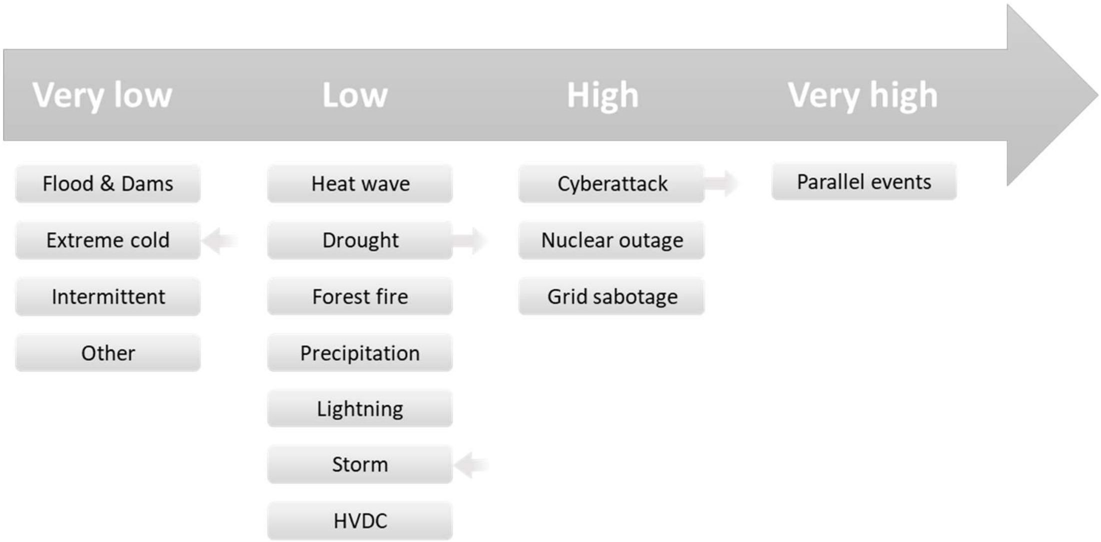

Figure C-1: *Summary of threats to the power system*

D. PSS/E

PSS/E is a power system simulation software owned by Siemens and widely used by TSOs in America and Europe. The power system is represented in a node-based network of lines, transformers, generators, loads and other components, where simulations are performed with a numerical algorithm using iterative linear calculations. The simulation solver has several available solution methods, such as Newton-Raphson and Gauss-Seidel, and settings on adjustment of taps and switched shunts, as well as control of area interchange and reactive power. The simulation software can also be run using phyton. Finally, the simulation functionalities include for example, power flow analysis, contingency analysis, dynamic simulations and optimal power flow.

E. Definition of quality criteria limits

Components in the power grid are graded with operating limits that they should stay within during operations to ensure system reliability and long-term performance of the components. For lines and transformers there is just an upper limit, while the bus voltage has a range with upper and lower limits. There are two main types of operation modes in the power grid, the first is normal operation and the other is operation during disturbance (called emergency). Therefore, there is operating limits for normal- and emergency operations respectively, where emergency operation limits are wider. Further, the grid should return from emergency- to normal operating limits within 15 minutes from the initial disturbance, according to operating procedures.

The analysis in this report is based in the normal operation limits, since the duration of the scenarios are longer than 15 minutes. The definition of overloaded and violated buses in this thesis are represented in Figure E-1 and E-2, where the red dots represent nodes that are overloaded and violated respectively. The aggregated average distance between the red dots and the normal operating limit represents the "AVERAGE" in Table F.1.

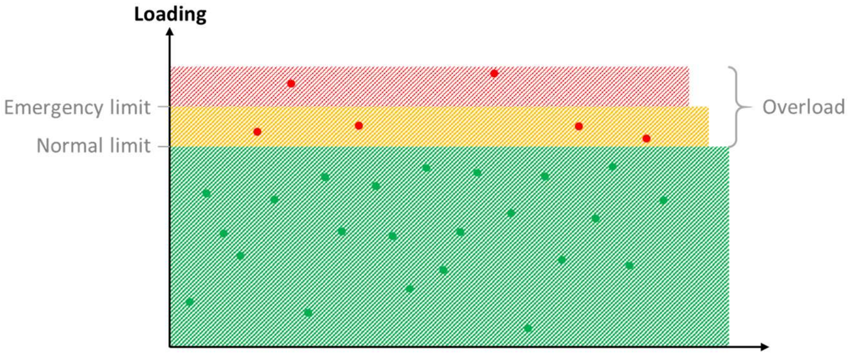

Figure E-1: *Definition of overload used for power quality results*

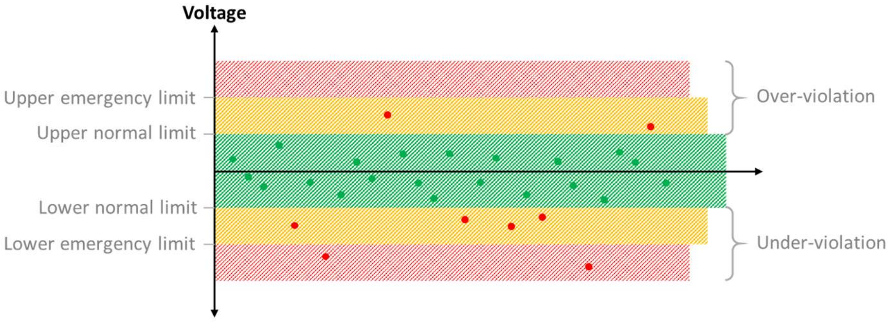

Figure E-2: *Definition of voltage violation used for power quality results*

F. Result templates

The result templates are common for all scenario results. Table F.1 is used for the power quality criteria, where #line, #trafo, #buses refer to the number of overloaded/violated units in absolute terms. The "% of total" correspond to the overload/violation as share of the entire transmission grid. The "avg%" is the average overload/violation of the lines/transformers/buses in percent.

Table F.1: Number of overloaded and violation lines, trafo's & buses in the transmission grid and average overload and violation of these components.

	LINES	**TRAFOS**	**BUS VOLTAGE**
NUMBER	#lines (% of total)	#trafos (% of total)	#buses (% of total)
AVERAGE	avg% overload	avg% overload	±avg% violation

As the duration of ENS is uncertain, it is presented for 1, 2, and 3 hours respectively, where the interrupted power is assumed to be constant and multiplied by 1, 2, and 3 hours respectively to achieve the ENS. The TIC is obtained by multiplying the ENS with the weighted average VoLL for the corresponding hour, shown in Table 2.1. The result template for ENS and TIC is shown in Table F.2.

Table F.2: Energy not supplied (ENS) and Total interruption cost (TIC) in the transmission grid

	1 HOUR	**2 HOURS**	**3 HOURS**	
ENS	X1	X2	X3	MWh
TIC	Y1	Y2	Y3	MSEK

G. Reference values

To anchor the results and enable comparisons, some values for typical situations and previous HILP events are summarized in this section, which also addresses the reliability and validity of this thesis project.

The annual electricity demand of nearly 140 TWh in Sweden corresponds to about 15 GW on average. The demand during high load is around 25 GW and during low load it is around 8 GW. The annual electricity supply around 160 TWh in Sweden has average powers above 7 GW from hydro, around 5.5 GW from nuclear, and around 4.5 GW from wind. Transmission capacities between the electricity price areas are around 3.5 GW at interface 1, 7.5 GW at interface 2 and 6 GW at interface 4 in north-to-south direction. Further, capacities in offshore HVDC cables amount 5.5 GW in total. The data is also shown in Figure G-1. [46]

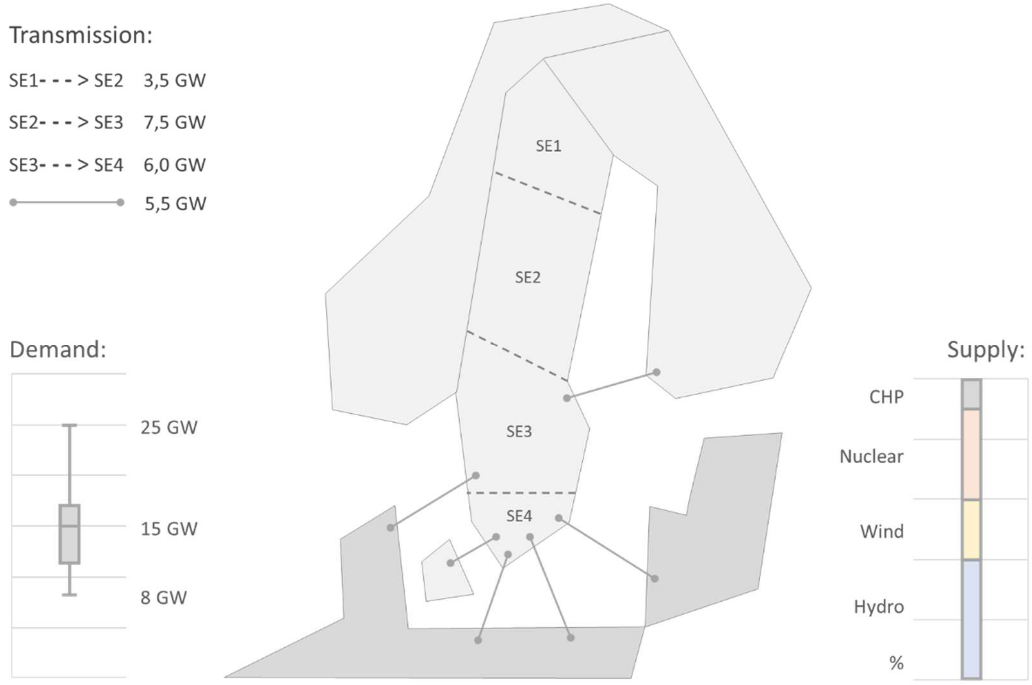

Figure G-1: Representation of the Nordic synchronous area and data for the Swedish power grid

The annual ENS in the Swedish transmission grid is 1.3 GWh [27]. Meanwhile, for the entire power grid the annual ENS have varied between 10 and 20 GWh, which is less than 0.02% of the annual electricity demand in Sweden. This ENS corresponds an estimated TIC at around SEK 1.5 billion annually [28]. However, for the storm Gudrun which is the most extensive HILP event in modern times in Sweden, the ENS was estimated at 111 GWh and TIC somewhere between SEK 4-5 billion at the time. [9]

To contextualize the relation between interrupted power and duration, and its impact on ENS, an average interrupted power at 1 000 – 1 500 MW and a duration of three days would correspond to an estimated ENS of 75-110 GWh and TIC around SEK 4-5.5 billion[1]. This means that both a high interrupted power and duration are required for any threat scenario to be comparable to Gudrun. The ENS and TIC for Gudrun, and the annual averages for the transmission grid and the total grid are shown in Figure G-2.

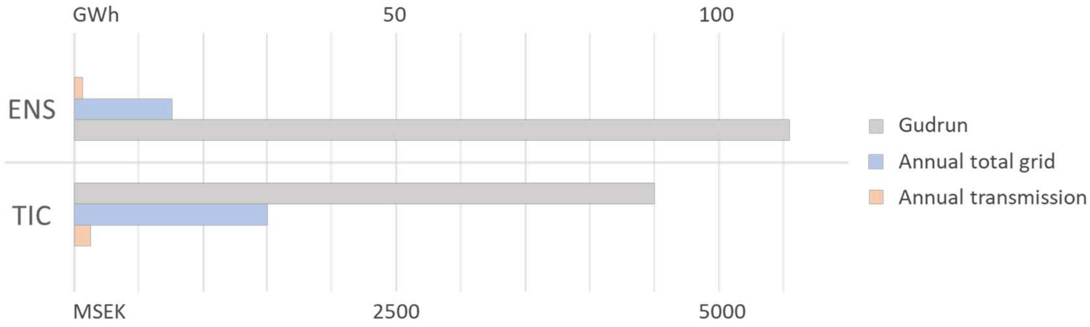

Figure G-2: Energy Not Supplied (ENS) and Total Interruption Cost (TIC) for the storm Gudrun and annual average for the transmission- and total grid in Sweden

The transmission grid is usually operated with a small overvoltage, mainly to reduce grid losses according to ohm’s law. This means that some buses with voltages deviating from the operating voltage limits can occur for short periods also during normal conditions. The operating limits varies between different buses, but can be ±3% and ±6% for normal- and emergency operating limits respectively. In fact, voltage is closely related to the reactive power, and lack of reactive resources usually bring voltage instabilities with violations as a result. [47]

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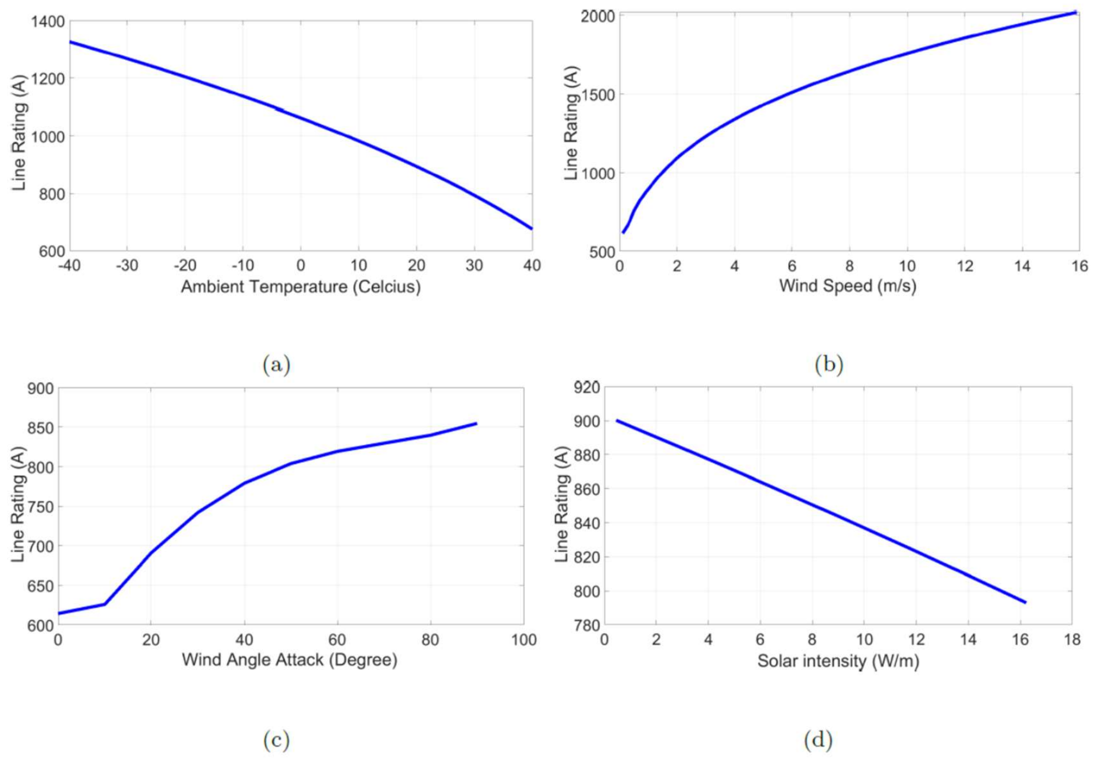
[1] Calculated based on 1 000 – 1 500 MW constant interrupted power and a duration of three days, using the same VoLL as during the storm Gudrun in 2005 (36 SEK/kWh) corrected to 53.3 SEK/kWh based on the CPI in 2024.

H. Dynamic load capacity of overhead lines



(a) (b)

(c) (d)

Figure H-1: Line load capacity as a function of ambient temperature (a), wind speed (b), direction of the wind compared to the line (c) and solar radiation (d) [38]

Key dynamics from the figures:

- Load capacity decreases with ambient temperature, reducing by half between -40 and +40˚C
- Load capacity increases with wind speed, especially for low wind speeds
- Load capacity almost doubles between no wind and 2 m/s
- Load capacity increases when the wind is more straight towards the line than parallel to it, around 40%
- Load capacity decreases with solar radiation, slightly above 10%

For the wildfire scenario:

- The thermal capacity in the grid is assumed to be reduced by 10%, considering that the line rating in Figure H-1(a) decreased about 10% when the ambient temperature increased from 20 to 30˚C.

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