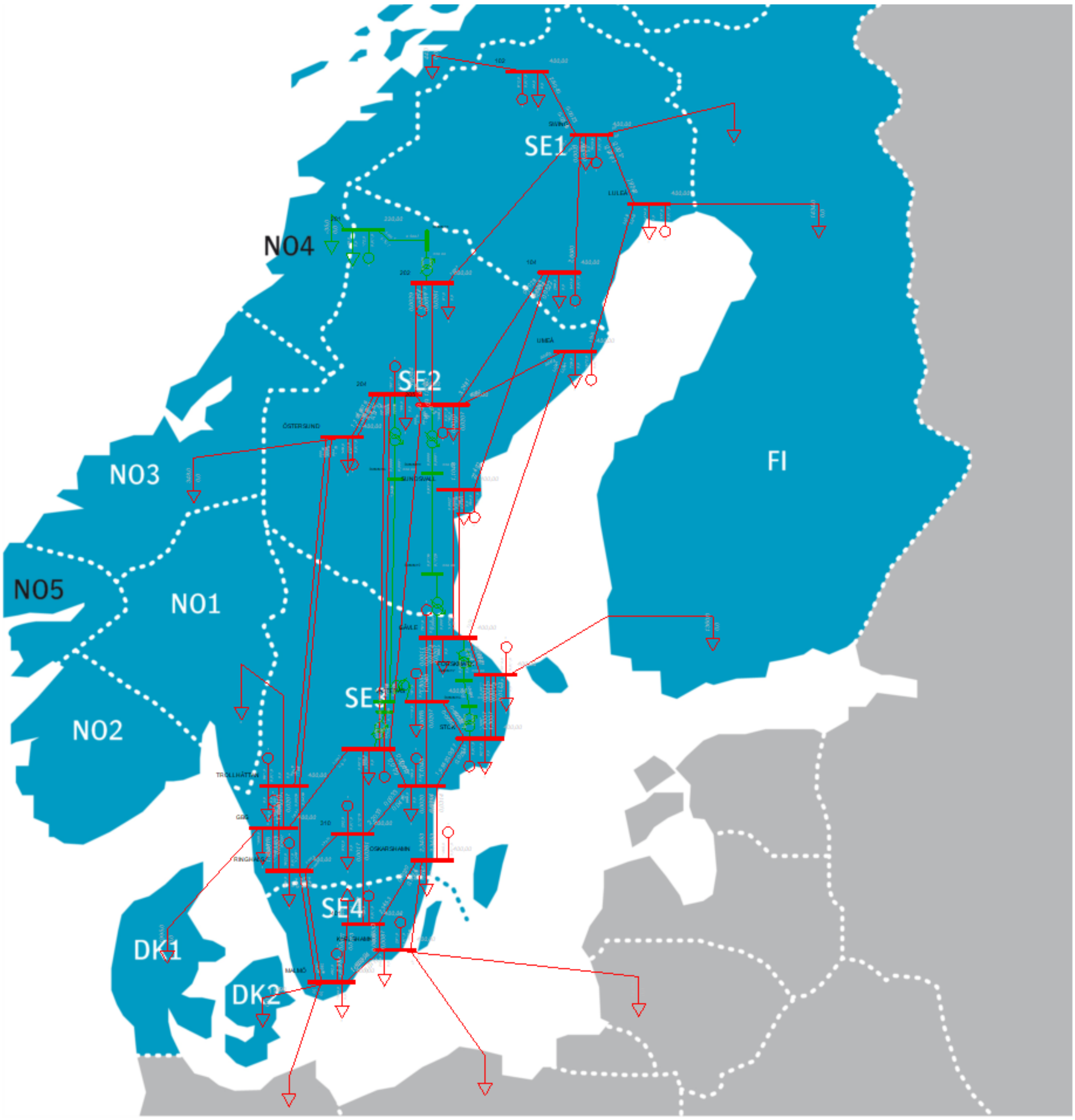

The potential of demand-side management in optimizing the development of the Swedish electric grid

Master of Science Thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2019

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Abstract

Due to an increase in both non-dispatchable renewable energy production and the overall electricity demand, the current Swedish electric grid is at risk of not being able to fully match its electricity demand with its generation. Expanding the transmission system is an expensive and time-consuming enterprise and hence the electric grid is in peril of not being able to supply its loads with its distributed generation at all times. Demand-side Management (DSM) might be part of the solution as new lines are under construction.

The aim of this thesis was to develop two realistic Swedish transmission system models in order to identify the main bottlenecks of the grid and to evaluate the effectiveness of DSM techniques in alleviating these grid congestions.

Several simulations were run in order to shift daily peak demands at SE3 and SE4, but also in the Malmö and Stockholm areas specifically. Additionally, a future scenario where nuclear power was phased out was also illustrated. The latter, to comprehend the necessity to expand the electric grid even if DSM were to be implemented at a large scale.

The results obtained indicated that different levels of DSM were desired depending on how the load was distributed to the valley hours. When the load was redistributed evenly to all off-peak hours, it was found that a 5% of the SE3 peak moved from 6 hours was optimal. Similarly, a 6% of the SE4 peak from 6 hours was found most beneficial. However, when the energy was moved unevenly, the percentage could be drastically escalated. Simulations on local flexibility demonstrated that reducing the load at Stockholm's area was 200% more effective in ameliorating the bottleneck at corridor SE2-SE3 than reducing the same load across SE3. Likewise, DSM strategies at Malmö were 66% more effective in decongesting corridor SE3-SE4 than reducing the same load at SE4, in addition to also helping decongest corridor SE2-SE3. Last but not least, the scenario of closing-down nuclear power inferred the necessity of grid expansion regardless of whether DSM techniques are broadly implemented in the future or not.

Keywords

Demand-side management, demand response, transmission system, Swedish electrical grid.

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Contents

Abbreviations

ADR Automated Demand Response. 20

CIGRE International Council on Large Electric Systems. xi, 22, 23
CPP Critical Peak Power. 20

DER Distributed Energy Resources. 1
DSM Demand-side Management. iii, 1–4, 16, 19–21, 38, 42–44, 46, 50–53, 55, 58–61, 65
DSO Distribution System Operator. 6, 20

ENTSO-E European Network of Transmission System Operators. 14
EV Electric Vehicle. 1, 16, 18, 20, 43, 58

FCR Frequency Containment Reserves. 11, 21

GENCOs Generation Companies. 6

HVDC High-Voltage Direct Current. 12

NTC Net Transmission Capacity. 25, 41, 44–46, 48, 52, 60

PSS/E Power System Simulator for Engineering. xi, 2, 24, 34, 37, 46
PV Photovoltaic Panels. 14, 19, 29, 58
PVC Polyvinyl Chloride. 62

SCB Statistiska Centralbyrån. xi, 25, 27
SVK Svenska Kraftnät. 6, 12–14, 21, 23, 25, 31, 34, 37, 41, 46, 49

TSO Transmission System Operator. 6, 11, 12, 52

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1 Introduction

1.1 Background

The emission of greenhouse gases to the atmosphere is one of the main causes for the current anthropogenic climate change. Non-dispatchable renewable energy sources are slowly but steadily taking over the fossil fuel power generators used to provide power in a centralized manner. At the same time, new loads are being introduced everyday which increases even further the current energy need. These upcoming changes pose new challenges to the development of the Swedish power grid. How can the current grid develop in such a way that future renewable energies can be accommodated in a cost-effective manner?

Another well-known challenge is the variable electric demand that occurs throughout a day. At present, energy peak demands determine the dimension of the cables and lines that make up the Swedish electrical grid. However, this is not an optimal solution as most lines are used at low capacity factors for the major part of the day. This phenomena could potentially be aggravated as Distributed Energy Resources (DER) constitute a larger share of the energy mix whilst new electrical loads, such as Electric Vehicles (EVs), data centers or heat pumps, proliferate.

A promising solution to smoothen out these demand peaks is to employ DSM techniques. DSM aims at involving consumers so that their consumptions patterns are shifted in order to adjust, to the extend that may be feasible, to what fits best for the grid and the available generation at every particular point in time [3]. DSM can therefore be a potential solution to cope with a less flexible production caused by intermittent renewable energy sources. Additionally, DSM is becoming a more and more enticing power management strategy due to several factors: new loads, such as plug-in electric vehicles, gain popularity; the grid becomes smarter i.e more data is acquired, processed and communicated (smart grids) [5]; and, last but not least, consumers become more willing to take their share in order to combat global warming [2]. All in all, by implementing and taking DSM into account for future developments of the grid, the dimensioning of future transmission and distribution lines could potentially be optimized.

1.2 Aim

The aim of this thesis is to investigate the potential of DSM in the current Swedish electrical grid. In particular, identify where DSM could be most beneficial for uncongesting the current transmission system.

1.3 Main task

This thesis comprises several tasks:

1. Perform a comprehensive literature review regarding the current state of the Swedish electrical system, the electricity market in which it operates and its transmission system. Thereafter, the potential of DSM will be investigated. Such investigation will focus on identifying the dormant potential of demand flexibility and its aggregated potential at the transmission level.

2. Quantify the percentage of load-shifting that can be accomplished at transmission level by using demand flexibility techniques. This will be performed by analyzing previous studies on households, industries and the distribution grid and extrapolate the results to the transmission level. Any studies of the effect of DSM directly to the transmission grid will, naturally, also be taken into account if any exists.

3. Design and set up two different models to analyze the current congestions that occur at the Swedish transmission system. The first model will focus principally on the exchanges between electricity market areas taking into account the available net transfer capacities of the grid. The second model will delve more specifically in the lines constituting the grid and hence will entail a larger degree of accuracy.

4. Analyze the power flows of Sweden by simulating the two constructed models of the Swedish transmission grid (comprising the 400 and most of the 220 kV grid). This will be realized with the support and supervision of Pöyry. The software to be used will be the Power system simulator for engineering (PSS/E) from Siemens.

5. Once the main bottlenecks of the grid have been identified, different levels of demand flexibility will be utilized to investigate how much the grid can be alleviated. These will be performed at electricity market areas but also locally applying DSM at specific nodes to examine its effect. The levels of DSM utilized will be put in contrast with the current state-of-the-art literature.

6. Discuss the desirability of DSM at the transmission grid by looking into how the grid can draw benefit from it. Particularly, identify where DSM would be more valuable and even analyze a future scenario.

7. Finally, draw conclusions on the potential effect of DSM strategies in order to influence transmission system congestions and potentially even future investment plans. Assumptions, limitations and potential future works will also be stated at this stage.

1.4 Scope of work

The scope of the work is to investigate how the transmission system in Sweden can benefit from the utilization of its potential load flexibility. This thesis will contemplate the potential of DSM by building two representative models of the grid whereby different levels of DSM will be applied. The first model will encompass the effects of DSM between the different Swedish electric areas whereas the second model will look inside each area as well as analyze the lines connecting those areas. Aditionally, DSM will be applied in particular nodes to examine its benefit compared to applying DSM over an electricity price area.

This thesis will rely on past data from 2018 in order to obtain results and draw conclusions thereof. The models will contain the entirety of its 400 kV lines and the majority of its 220 kV (specially those that cross two different bidding areas or when no 400 kV line interconnects two different nodes). DSM will thereby not be investigated at the distribution or subtransmission level (regionnät). Instead, studies on DSM at the distribution will be investigated in so far as they inevitably also influence the transmission system due to their aggregated effect.

1.5 Outline of the thesis

Chapter 1 presents the topic of this thesis: its background, aim, main tasks and scope of the work.

Chapter 2 consists of a comprehensive literature review encompassing all necessary concepts required to follow the methodology, results and discussion of this thesis. These mainly consist of four main pillars: How the Swedish electricity system is characterized, how the electricity market operates, how the transmission system planning is carried out and finally what DSM is and its relevance to the Swedish transmission system.

Chapter 3 makes up the first part of the method. It introduces and depicts the two models of the transmission system constructed. First, the 4-nodes model and later a more detailed and comprehensive model of 33 nodes.

Chapter 4 consists of the second part of the method. It presents the software utilized and how the simulations have been conducted regarding its workflow.

Chapter 5 comprises all simulation results for both models, realized based on a day's data. Different DSM levels are applied at different electricity market areas as well as particular nodes. Additionally, a future scenario where all nuclear power is removed is illustrated. Finally, the results obtained are put into perspective with the data for a whole year.

Chapter 6 discusses the results obtained during chapter 5 and contrasts them with the current literature examined during chapter 2. This chapter also includes all environmental and social implications of this work.

Chapter 7 covers all conclusions of the study as well as its limitations and potential future work that could follow this thesis.

2 Literature review

2.1 Deregulation of the electricity market

The deregulation of the electricity sector during the 1990s in North America and Europe, including Sweden, has profoundly changed the way in which the grid is operated, managed and planned [19]. Traditionally, electric utilities were responsible for the expansion and operation of the electric grid, in addition to providing for the vast majority of the generation. Such scheme allowed the utility to contemplate new investments in both generation and grid expansion in a holistic manner. The transmission and generation of power could be planned in parallel to fulfill each other's needs, that is, to guarantee an adequate level of transmission capacity to new power stations and upcoming loads. Furthermore, the scheduling and dispatch of generation could easily be performed taking into account physical, economical, reliability and security constraints. Such model, however, was suspected to be inefficient economically speaking. As electric utilities had the full monopoly of generation, transmission and distribution of electricity, there was no economical incentives to optimize their activity. Whatever inefficiencies in the system may have been, these would be passed down to the customer in the form of an increase in electricity prices. Additionally, the rise of fossil fuels costs exacerbated this problem leading to utterly high electricity prices [19]. Finally, it was noticed that the creation of power pools would bring about the possibility of interchanging power between utilities. This would, in addition to bring down energy costs, increase reliability and security of the electric grid. An ever increasing electricity demand and the need for a more reliable supply led to questioning the status quo of the current model that had prevailed until then. Because of all these factors, deregulation of the electricity market began to take place starting in North America and most European countries such as Sweden.

In short, the liberalization of the electric market thus had three main objectives:

1. To increase the efficiency in electricity supply
2. To provide with more customer choice and market competition overall
3. To lower the cost of electricity to customers

Such liberalization broke down the one-entity utility into several actors that would focus on certain functions with the electric market.

2.1.1 Swedish electricity market actors

The market deregulation gave place to several new actors [13]. These mainly consist of:

- **Generation Companies (GENCOs)**, responsible for the production of electric energy. They may bid directly to the whole market or supply local loads or be connected to the distribution system if not big enough. In Sweden, some of the largest GENCOs include Vattenfall and E.ON.

- The **Transmission System Operator (TSO)**, responsible for the safety operation of the grid and new investments to guarantee an adequate capacity level between all parties. In Sweden this role is taken by Svenska Kraftnät (SVK) who owns all 400 kV and most 220 kV lines in Sweden.

- The **Distribution System Operator (DSO)**. Similar to the TSO, the DSOs are responsible for regional and local distribution grids encompassing both their safety operation and their necessary expansions. Two examples of a DSO in Sweden are Göteborg Energi and Ellevio.

- **Electricity retailers** aggregate several customers and bid in the electric whole market as a single entity. Electricity consumer, have in most cases, the possibility to choose between different retailers which distinguish themselves by offering different electricity tariffs and potentially selling electricity from certain types of generation (whether renewable or non-renewable sources).

- **Electricity customers** may buy electricity from a retailer or purchase their energy needs directly from the whole market if their energy needs are large enough. These large customers may consist of factories and big industries.

- Finally, any power pool requires a **market operator**. The market operator is responsible for matching supply and demand bids on the basis of the price that they are willing to offer and take respectively. The market operator is an independent entity which cannot, thereby, participate in the market by bidding in it as a GENCO or retailer. In the Nordic market, Nord Pool is the main responsible for the market brokerage.

2.2 The Swedish electric system

The Swedish electric system is characterized for having high amounts of generation, mainly hydropower and a substantial amount of wind power, situated in the north. Conversely, the biggest consumption is situated in the southern parts of Sweden where most of the population is located. This has motivated, since the inception of the Swedish electric grid, the deployment of long transmission lines interconnecting the northern and southern parts of the country [8]. Additionally, Sweden is divided into 4 electrical bidding areas commonly referred as SE1, SE2. SE3 and SE4. These areas have been strategically delimited in order to reflect this excess of energy production in the north (SE1 and SE2) and the ever increasing demand in the southern parts (SE3 and SE4). The geographical delimitation of these areas can be seen in Fig. 2.1

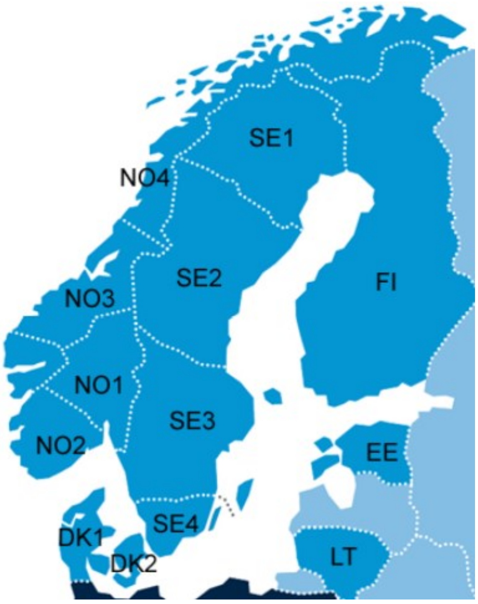

Figure 2.1: Electricity price areas in Sweden and its neighbouring countries [26].

2.2.1 Energy production

The energy produced in Sweden in 2018 by technology and area can be seen in Table 2.1.

Table 2.1: Swedish electricity production mix per technology and area in 2018 [18, 39]

Area\ Energy [TWh]	Solar	Wind	Hydro	Nuclear	Gas Turbines	Other Fuel-based	Others
SE1	0,00	1,54	19,06	0	0	0,47	0,00
SE2	0,01	5,86	33,37	0	0	1,56	0,00
SE3	0,10	5,57	8,31	65,92	0,01	10,47	0,08
SE4	0,04	3,72	1,02	0	0,00	2,41	0,21
Total	0,15	16,69	61,76	65,92	0,01	14,9	0,29
[%]	0,1	10,5	38,7	41,3	0,0	9,3	0,18

As can be seen in the table, the current energy mix in Sweden mainly consists of hydro power and nuclear power which each accounts for roughly 40% of the total energy consumption [18]. The rest of the energy is provided by wind turbines, accounting roughly for the 11% of the energy mix, and the rest from fuel-based power plants, which fuel consists primarily of biomass and gas. A very small but increasing proportion of solar power can also be noticed. Conversely, in terms of power, the current power installed capacity per electricity price area can be seen in Table 2.2.

Table 2.2: Swedish electrical power capacity installed for each technology and area by 2018 [18]

Area\ Capacity [MW]	**Solar**	**Wind**	**Hydro**	**Nuclear**	**Gas Turbines**	**Other Fuel-based**	**Others**
SE1	4	523	5 207	0	0	264	1
SE2	11	2 378	8 046	0	0	522	2
SE3	159	2 178	2 581	8 586	942	3 104	10
SE4	80	1 621	347	0	620	1 542	2
Total	254	6 700	16 181	8 586	1 562	5 432	15

It is worth noting, that Sweden is in the process of phasing out most of its nuclear power. A nuclear plant of 870 MW is to be decommissioned by the end of 2019 (Ringhal2) and another of 860 MW by the end of 2020 (Rinhal1) [48]. This reduction in power capacity in SE3 may pose a challenge on the Swedish electric system as more power will be needed to be transferred from north to south and/or increase energy imports.

The comparison of Table 2.2 with Table 2.1 is relevant as it shows two different phenomena:

- The energy system extracts a large amount of power from its nuclear reactor. By phasing out this technology, large amounts of wind power will be necessary to compensate for the energy loss. At the same time, some sort of demand management will be necessary in order to compensate for wind fluctuations.

- Despite the amount of gas power installed, these are mainly utilized as back-ups and peak power providers. In connection to the previous point, if decarbonation of the energy system is desired, some sort of demand management, energy storage or other solutions will be necessary to cover those peaks.

Another relevant piece of information is the energy consumption at each bidding area. This can be seen in Table 2.3. It can be observed that most of the energy demand is located in the south and hence the necessity of a strong transmission grid in order to transmit the bulk of the electric power. This is problematic for several reasons. First and foremost, because such long transmission lines are incredibly costly. Second of all, they take long time to be constructed and it is hard to get concessions for them. Finally, as power demand increases in the south so do the losses that occur due to power transmission [37]. Moreover, as will be explained later in more detailed, the main problem of the grid does not generally consist of supplying the energy demand at each area, but rather that the instantaneous power varies greatly depending on the time, season and weather conditions.

Table 2.3: Energy consumption, average hour consumption and peak hour consumption for each electricity price area in Sweden

Area	**Consumption (TWh)**	**Consumption (% of total)**	**Avg hourly consumption (MWh)**	**Peak hourly consumption (MWh)**
SE1	4	523	1 128	3 548
SE2	11	2 378	1 874	4 801
SE3	159	2 178	10 003	17 088
SE4	80	1 621	2 770	4 921
Total	254	6 700	15 776	26 558

2.2.2 The Nordic electrical market

An understanding of how the electricity market operates in the Nordic countries may help understand the current challenges that the Swedish electrical system needs to tackle.

The Swedish electricity market has been integrated with a common Nordic electricity market called Nord Pool [38]. Besides Sweden, countries that participate in this electricity market consist of Norway, Finland, Denmark, Estonia, Latvia, Lithuania, Germany and the UK. Nord Pool is an independent entity responsible for providing a reliable platform for trading electricity and is, as for 2019, the largest electricity market in Europe. Several markets can be found within the Nord Pool platform. The main and largest one consist of the day-ahead market, also called Elspot. Apart from the Elspot, there is an intraday market called Elbas, a regulating power market and the possibility to arrange bilateral future trades in the financial market. How Nord Pool interacts with its market players and the system operators is summarized in Fig. 2.2.

2.2.2.1 Elspot: The day-ahead market

The Elspot consists of a bilateral electricity trade which takes place between 36 and 12 hours prior to the energy exchange. At 12:00 CET, all sell and purchase orders are aggregated into two different curves per each hour of the day [38]. At this point the offer and demand is matched by taking first the purchases willing to pay the most and the seller willing to be paid the least. The last purchase and sell bid will coincide in the amount that one is willing to pay and the other to accept. That becomes the clearing price of the market. From this point onward, all purchases are paid that price regardless of their initial willingness to accept a smaller amount. Similarly, all buyers pay the clearing price

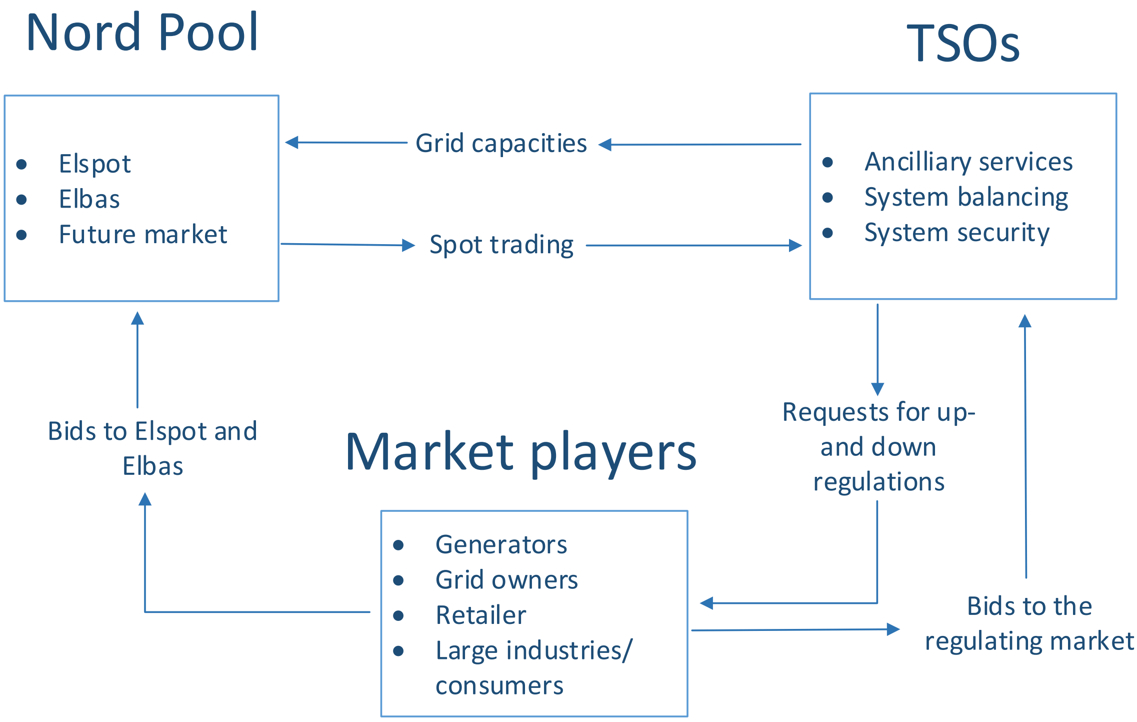

Figure 2.2: Market flow dynamics. Interaction between market players, system operators and the market broker (Nord Pool)

in spite of the fact that they had been willing to pay a higher amount. This difference between the amount that seller gets paid minus what it would have accepted in the worst case is called the seller surplus. Likewise, the consumer's surplus is the difference between the amount that it would have been willing to pay minus what it actually had to pay. The sum of these two surpluses is called the global welfare. Nord Pool, or in fact any market for that matter, aims at maximizing this welfare which essentially quantifies the benefit that arises from the trading.

As mentioned, the clearing prices of each area depend on the supply and demand of electricity at each hour. However, the ideal energy trade may not be feasible due to congestions taking place in the system or other diverse causes such as the need of ancillary services or safety and reliability constraints. In this case, two different scenarios can be identified:

- **Structural bottlenecks**, that is, common well-known bottlenecks due to lacks of transmission investment, are dealt with market splitting. Market splitting consists basically of splitting the country into areas (in Sweden that is the 4 aforementioned bidding areas) and the energy dispatch is realized independently. Consequently, different clearing prices arise: the area with a higher clearing price would benefit from the cheaper energy from the other areas but capacity constraints prevent further transferring. This market splitting motivates the TSO to expand the transmission system across areas while encouraging new generation in those areas where clearing prices are higher, and thereby where more power is desired.

- On the other hand, if the bottleneck is not structural but rather of **Temporal** nature due to a particular circumstance, counter trade is utilized. The TSO will buy or sell bids in the balance market in order to guarantee that capacity limits are not surpassed.

In any case, congestions in the system reduce the economic welfare of the system which is undesirable. Congestions may hinder the inclusion of new renewable energy investments, endanger the energy supply to a urban area or, at worst, jeopardize the stability of the system by initiating a partial or total blackout.

2.2.2.2 Regulating power

Besides the power exchanged in the spot market and the financial market, additional reserves are maintained in stand-by [34]. This additional power helps compensating for load and generations mismatches which directly influences the frequency of the grid. Generators can only operate within strict frequency margins and thereby protecting systems could potentially disconnect them from the grid if the system frequency were to drop or rise from the expected frequency range. The regulating power is hence the last one to take place and so it does it within each hour with the purpose to harmonize power unbalances.

The regulating power can be classified in different manners. For the primary frequency regulation, the Frequency Containment Reserves (FCR) is used which in turn can be divided in

- FCR-N: Frequency support when changes in frequency occur within acceptable levels i.e. ± 0,1 Hz
- FCR-D: Frequency support when changes in frequency are larger than 0,1 Hz

These reserve providers may consist of gas peakers, load-shedding, fast hydro generators and so on. For both the secondary and tertiary frequency control, another regulating power called the Frequency Restoration Reserves (FRR) is instead called.

2.2.2.3 Other markets

Apart from the Elbas and the regulating market, two additional markets are available which need to be taken into account when analyzing bottlenecks in the grid. These are the Elbas and the Financial market.

Elbas: The intraday market The Elbas functions in a similar manner as the Elspot as it also consists of a bilateral trading system. However, the Elbas operates between a time-frame between 33 and 1 hour before the power exchange occurs. Moreover, capacities are determined by the respective TSO in view of the results of the day-ahead auction. These capacities are being updated as intraday trades develop.

Financial market In addition to the spot market which comprises both the Elspot and Elbas, there is also the possibility of arranging future contracts between a producer and a consumer. The main purpose of these contracts is to hedge against unpredictable electricity prices both for the producer and consumer of electricity. When the day of the exchange arrives, if the producer cannot deliver the promised amount of energy, it will rely on the spot market to purchase the promised energy and therefore deliver what the contract states. The same applies for the consumer who would resell the energy obtained through the contract onto the spot market.

2.2.3 Transmission system planning

The Swedish transmission grid in 2017, by courtesy of SVK, can be seen in Fig. 2.3. In it, all 400 kV, 220 kV and High-Voltage Direct Current (HVDC) lines are presented. Sweden is connected to Finland, Norway, Denmark, Lithuania and Poland with whom Sweden exchanges power on a regular basis via Nord Pool.

Prior to the deregulation of the electric market, investments in transmission and generation took place in a coordinated manner so that maximum economic welfare could be delivered to society [19]. Transmission system planning has hence become more challenging than before as transmission investments need to foresee not only changes in the demand such as population growth or new industries, but also upcoming investments in generation. These poses several challenges to transmission system operators. On one hand, they need to continually monitor the current state of the grid while predicting future trends and scenarios. On the other hand, an ever more interconnected grid must take into account interconnections to other countries which add further variables and uncertainty into the system.

Investments in the transmission grid are characterized by being capital intensive investments. In addition, the expansion of the transmission grid is, generally speaking, time-consuming both due to the long constructing times needed but also because of the required studies to support the necessity of such investment. These long permitting processes may extend to about 10 years [41] which in turn add uncertainty to the system due to its evolution. New investments in the transmission grid should aim at facilitating competition, promote the proliferation of renewable energies and ensure overall reliability [41].

Figure 2.3: The Swedish transmission grid containing all 400 and 220 kV and its connections to neighbouring countries [32].

2.2.3.1 Development of the transmission system

In Sweden, the responsible for transmission system planning is SVK. SVK is responsible for all connection at 400 and 220 kV including their respective transforming stations and interconnections to other countries [33]. The current developments in the Swedish transmission grid can be summarized in four main pillars.

- First, new investments in generation consist mainly of wind power. These investments are expected to be predominant on the north as weather conditions are more favorable. As a result, it encourages reinforcements in the transmission grid to be able to transfer these new generations to the main points of energy consumption in the south.

- Second, the European market integration is promoting new interconnection between Sweden and their neighbouring countries, but also with continental Europe.

- Third, a considerable growth in energy demand is expected in the largest urban areas. This due to a growing population in those cities as well as the deployment of power-demanding data servers. This, together with the phasing out of most nuclear power in the coming decade, urges to strengthen the capacity to these areas in order to guarantee a proper and secure energy supply.

- Last but not least, the expansion of the transmission grid is driven by the fact that the current transmission grid is rather old. The oldest parts of the grid may no longer be simply maintained but rather need to be renewed during the next decade.

Besides these pillars, the deregulation of the electric market together with the interconnection between countries has prompted the need of transmission system designs beyond traditional national approaches. SVK is a member of the European Network of Transmission System Operators (ENTSO-E) and hence operates within its regulatory framework. ENTSO-E was formed with the intention to coordinate future developments of the European transmission system in order to satisfy agreed European goals [9].

2.2.4 The instantaneous power challenge

Sweden has enough power to provide for its energy demands and maintain a considerable amount of reserve energy [34]. In that sense, energy does not constitute a problem for the Swedish energy system but rather the instantaneous power does.

Sweden is characterized for having different electricity demands depending on yearly season (a temperature dependent demand) and varying throughout the day (a hourly variability demand) [45]. As for the seasonal variability, there is a higher electricity demand in winter compared to summer as can be seen in the Swedish demand of 2018 in Fig. 2.4. Due to the harsh cold temperatures, Sweden necessitates large amounts of heat power which are delivered in the form of centralized heating or other electric-based solutions such as heat pumps. During summer, on the other hand, the prevailing mild temperatures translate into few air conditioning apparatus needed. Moreover, since there is plenty of day-light, the demands of artificial lightning also diminish while Photovoltaic Panels (PV) generate more energy.

Regarding the daily variability, Sweden experiences higher demands during the day compared to the night. Habitually, two demand peaks occur during the day. The first takes place around 07:00-09:00 when most people have waken up and start their day. The

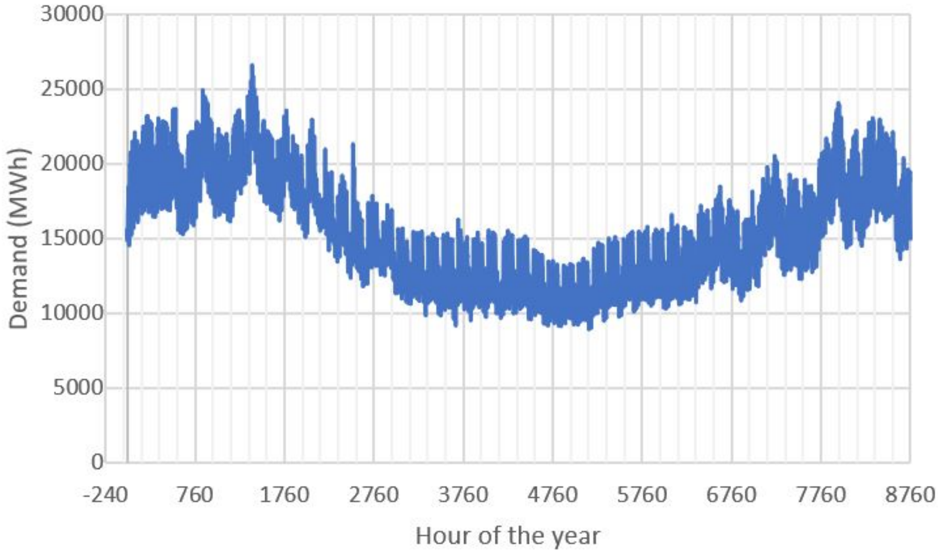

Figure 2.4: Electric demand in Sweden for each hour of 2018. Data source [39]

other around 17:00-18:00 when the majority of people arrive home from work. This pattern is known as the "duck curve". An example of the Swedish demand on a winter day and hence of the aforementioned "duck curve" can be seen in Fig. 2.5.

This curve may even become more accentuated as solar power installed increases. This phenomena has already happened in countries or regions where solar power provides a substantial amount of power. An example of this is the state of California, USA [29]. As more solar power is installed, the energy demands during daytime decrease. That, a priori might sound appealing and desirable for the Swedish system. Nonetheless, the peaks at those two hours would be ever-more prominent as no sun-light is available at those hours during the darkest hours of winter.

Finally, Sweden is shiftily transition into a carbon-free electric system by investing heavily on wind power. As this takes place the power intermittency due to weather dependant generation will pose new challenges when tackling these power peaks.

The instantaneous power challenge may be confronted by different strategies. One possibility is to expand the transmission and distribution system so that variability is dampened out. In other words, transfer power from where energy excesses emerge to those parts where energy is needed. The second possibility is to manage the demand by storing excessive energy which, as for today is still quite expensive, or by shifting the peak demands towards other hours. The latter can be accomplished by using demand-side management.

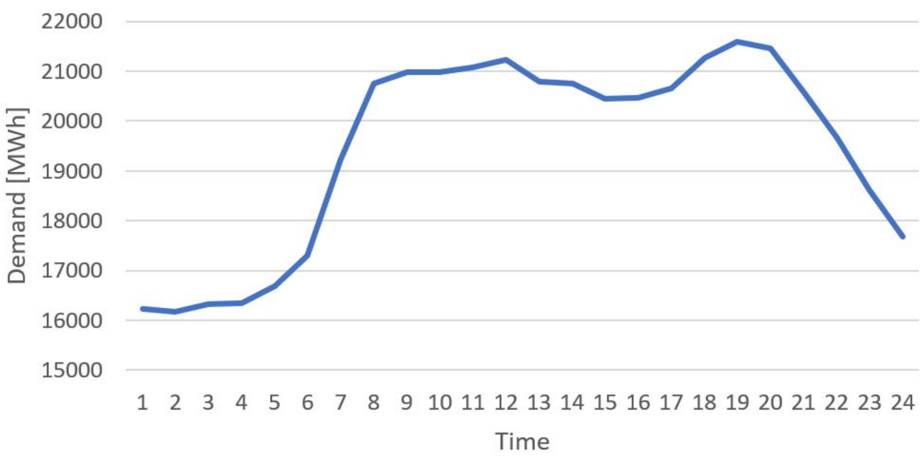

Figure 2.5: Electric demand in Sweden on the 13th of March 2018. Data source [39]

2.3 Demand-side management (DSM)

There is a perpetual need to maintain a constant balance between the electricity demand and generation at all times. Such endeavour is foreseen to gradually become more and more challenging [50]. With the advent of huge amounts of intermittent renewable power being installed, and political efforts to be less dependant on fossil fuel power stations; novel approaches to power balance are necessary. Energy storage at a grid level is, as for today, still costly to be implemented at a large scale; although a few test projects are already available [4]. Expanding the electric grid is, on the other hand, an expensive enterprise with usually long leading times ranging from 10 to 15 years [41]. Moreover, new grid investments should, in so far as possible, take into account future electric demands and, perhaps more importantly, their respective peak demands. This is where DSM may play a crucial role in the future.

DSM can be defined as the array of activities to alter utilities' load shape and/or energy consumption patterns [14]. DSM may be used as a means to hedge against high wholesale market prices, increase the reliability of the grid or even delay grid investments [6]. DSM's gain in popularity has partly been due to advancements in grid communication which, in turn, are transforming the current grid into an ever smarter grid. An example of this is the extensive rollout of smart meters which automatically measure and send consumers' electricity usage to electricity suppliers [1]. Second, the apparition of the prosumer actor (a consumer that can at certain times be a consumer or a supplier of electric power), local energy storage in the form of battery technologies, EVs, and communication-powered smart appliances have motivated even further the study of the DSM potential.

2.3.1 How can DSM be accomplished

Conceptually speaking, demand flexibility can be accomplished depending on the nature of the load in question as summarized in Fig. 2.6. Three main characteristics allow for providing flexibility to the system [12]:

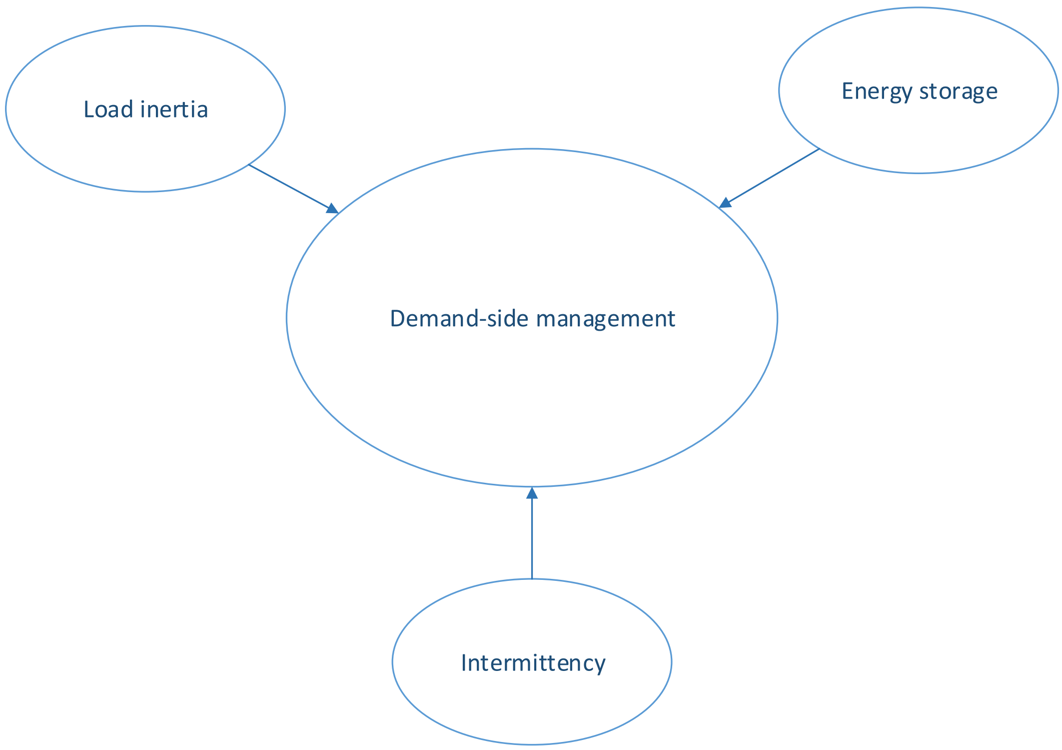

Figure 2.6: The three factors that allow a load to provide flexibility to the system

- Inertia: There are certain loads that may be temporally disconnected or turned down provided that a certain degree of inertia exists. This is true for instance for heating systems. The temperature of a building does not vary drastically in the span of seconds and hence heating systems may be temporally disconnected in order to provide flexibility.

- Storage: Energy storage systems such as batteries or fuel cells may provide flexibility by consuming exceeding energy in the system and releasing it when electric demand surpasses its generation.

- Intermittency: Particular loads are not run on a 24/7 basis but instead are discreetly connected and disconnected throughout the span of a day, week or month. These are loads that can be shifted to hours of low electricity cost i.e. during non-critical hours.

Similarly, flexibility can be provided by either large industries, or individual households and/or aggregated small consumers based on these three principals.

2.3.1.1 Flexibility through large industries

Demand flexibility is already being utilized in Sweden for specific large industries [34]. These industries are willing to provide a reduction in their consumption i.e. pause certain electrically-driven processes, in order to balance the system within the reserve market. Demand flexibility coming from energy intensive industry has been estimated to be of around 16 GW only in Europe [35]. Such flexibility is already being being exploited in Sweden which had 185 MW of power reduction in reserve during the winter 2017/2018 [34]. In [44], it is estimated that the share of peak demand that industry could shave in Sweden could be up to 8,5%.

2.3.1.2 Flexibility through households

Nowadays, flexibility at the household level is hardly being utilized even though its potential is slowly coming to light. The main identified flexible load consists of the heating system [21]. This in turn can be divided into space-heating and hot water. The former has gained considerable attention due to the growing popularity of heat pumps as means for space-heating and the large amount of heating demand in cold countries such as Sweden. According to [44], the share of peak demand that households with electrical heating could shave could be as high as 20,4% in Sweden.

Additionally, other loads that could contribute to flexibility consist of the ventilation system and, although only for a few seconds or minutes, freezers and refrigerators. Last, washing machines and other electric appliances could be scheduled to run at hours of low demand assisting in smoothing out the demand during the day and even accruing small economical benefits for the customer if they had an hourly variable tariff.

2.3.1.3 Electric vehicles (EV)

The advent of plug-in EVs signifies a completely new electrical load for the electrical system to supply. In [28], it is shown that uncontrolled charging, that is charging as soon as the EV is plugged in to a charging station, will with all likelihood coincide with household demand peaks. Notwithstanding, such loads may have a large degree of flexibility allowing their integration without comprising the current transmission and distribution capacity. In [36], data analysis of measured data revealed that 59% of the aggregated load due to the charging of EVs could be shifted up to 8 hours. Moreover, 16% of that load could be moved up to 24 hours. This can be accomplished through use of smart chargers which could contribute greatly to congestion management.

2.3.1.4 Energy storage

The installation of battery systems at both grid level and household level provide an additional degree of flexibility to the load. Inclusion of new electric loads such as electric vehicles and the popularization of heat pumps will undoubtedly increase the electricity demand of households. Such increase may, however, have a positive effect on the economic value of PV and battery systems [46], which in turn could promote their extensive deployment. Battery technology allows to shift the demand from hours of maximum demand and less irradiance to hours of minimum demand and maximum irradiance. In economical terms, that is to shift demand to hours of cheaper electricity. An example of this, it was accomplished reductions of the peak power of about 10% for 4 hours [10].

In Fig. 2.7, A household with a high degree of flexibility is represented. The house consists of a certain amount of controllable loads such as heat pumps and electrical appliances which are constantly exchanging information with the grid, a charger for electric vehicles, PV and a battery system.

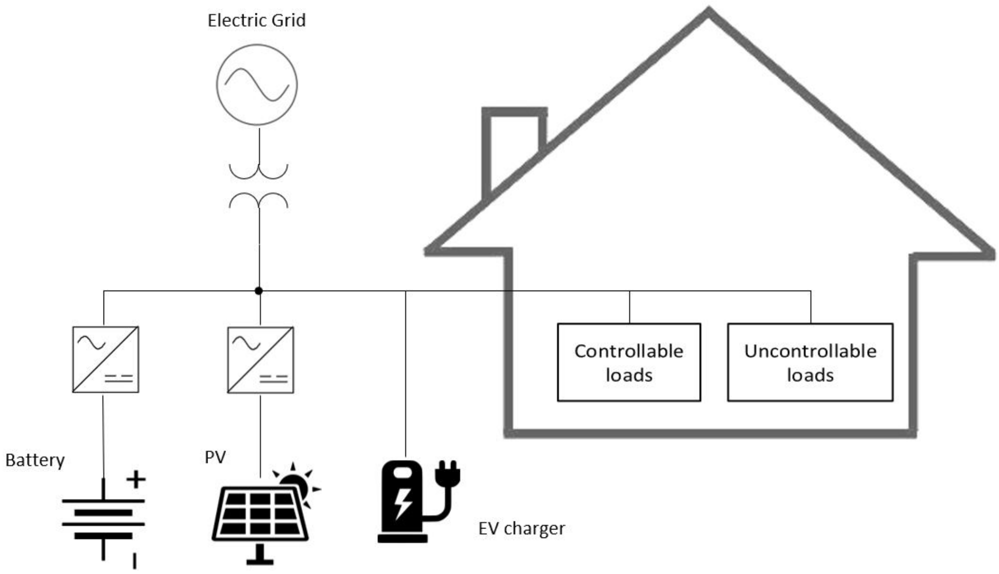

Figure 2.7: Household with a high degree of load flexibility

2.3.2 Demand-side management at the distribution level

There are several studies regarding DSM at a distribution level. One common approach is to analyze the demand flexibility on a household and extrapolates those values assuming a definite number of houses. For instance, in [30], a practical case study is about to be examined. It consists of the "Coordinated Power Control" power project, "Växlande Effektreglering" in Swedish, more commonly known as the VäxEl project. The VäxEl project, started in January 2017, has gathered different market actors as well as smart grid server providers, research institutes, governmental regulatory entities and local grid owner with the purpose of creating a cost-effective optimization of a smart distribution grid. The project is being carried out in Uppland, Sweden, and has, as for now, focused on reducing Critical Peak Power (CPP) by connecting its heating systems to Upplands Energi electric grid. The project features a notable amount of power flexibility allocated among its several householder. More specifically, it consists of 200 kW of rooftop solar power installed, 36 kW of electric vehicle charging, 70 kWh of home energy storage and 500 connected water-based heat systems. By running a scaled-down simulation of the VäxEl project, a 10,3% average reduction in CPP is achieved within a span of three days. Such feat is attained by utilizing an Automated Demand Response (ADR). This ADR employs real data from the previous day house consumption to estimate the demand of each day. By doing so, the charging and discharging of the house batteries were optimized by cutting down, consequently, the CPP of the system. When smart EV charging is incorporated to the model, the average CPP reduction increases to 11,1%. As for February 2018, the controlling of installed heat pumps in the project allowed a reduction of between 1 to 1,8 kW of power of CPP which prevented the DSO to exceed the 60 kW power subscription limit from the regional grid, which corresponds to a fee of 48 500 €.

Another study performed at Malmö pointed out that the potential regarding power flexibility could amount to the 25 % of the city's maximum power peak [23]. That is a reduction of 109 MW during four hours which is shifted to other hours of the day. Such flexibility is deemed to be potentially available in households specially regarding the heating strategies utilized.

2.3.3 Demand-side management at a transmission level

There are several locations in Sweden where transmission capacity is reaching its limits or even that has already been surpassed. The Stockholm area, Uppsala and other major cities are examples of this. Malmö, for instance, is an illustrative case [22]. The city has grown enormously in the past few year resulting in an increase in electric demand. Additionaly, since Öresundsverket, a power station of 400 MW situated close to Malmö, was closed down, the need for transmitted power at critical hours - for example during cold hours and when wind does not blow much- has augmented enormously. Malmö is connected to the regional substations of Sege and Arrie which supply power to the vast majority of Skåne. The aggregated power available at these substations is of 650 MW. Nonetheless, this limit was exceeded 638 hours during 2016-2017. This situation requires an immediate action to alleviate the current lack of power. New transmission lines are estimated to be available by 2026 but the current lack of transmission capacity requires of more immediately additional measures such as the implementation of demand flexibility.

Despite the multiple studies of the effect of DSM at a household or even at the distribution level both in Sweden and worldwide, there are few studies regarding its effect at the transmission level. To combat that, this thesis aims at exploring the effects that DSM may have at shaving these peak powers in Sweden. In other words, to investigate the possibility of alleviating the current transmission system but also to investigate its potential in the upcoming future.

2.3.4 Market integration possibilities for DSM

DSM could be mainly integrated into two different markets. The first one, and the one used for this work, consists of the Elspot, previously described as the main electric market in the Nordic countries. In the Elspot, a certain agent called "aggregator" could gather enough households so that their aggregated flexibility would be inserted into the market as a bid to either increase or decrease their demand. If this were so, however, there should be an economical incentive for the customers to utilize DSM. According to [1], customers' electricity bill could be down to a 35% lower when utilizing an electricity tariff following Elspot (having an electricity hourly cost) and being able to shift their energy consumption to the cheapest hours. Indeed, demand response could even be more economically interesting if it could participate in other markets such as the reserve market [40].

This suggestion seems to be confirmed in [31]. SVK identified demand flexibility as a means to enlarge the current competition within the FCR, principally within the FCR-N. However, the current regulations limit the inclusion of that group. Among others, the minimum bidding power amounts to 0,1 MW. Pilot tests are being carried out to comprehend the feasibility of DSM as a new reserve power provider and to quantify its effect on the other reserve power providers such as hydro power stations.

3 Modelling the Swedish transmission grid

In order to analyze how the Swedish transmission system could take advantage of demand flexibility, at least a model of the Swedish transmission system was needed. To begin with, a pre-study of the current existing models was carried out. Thereafter, due to the lack of an available model that was comprehensive enough for the study, two custom-made model were confected.

The Swedish transmission grid consists of all 400 and 220 kV lines. Depending on the complexity and the purpose of a study, different models can be used to represent the Swedish electric system or even the Nordic one.

3.1 Pre-study: Existing models

In this thesis, several models were considered which will now be presented.

3.1.1 The 4-nodes Swedish system

A relatively simple model is to represent Sweden as four nodes which reproduce the four bidding areas into which Sweden is split when congestion arises between areas. Apart from the simplicity of the model, the 4-nodes system is commonly utilized as there are vast amounts of public and open information available. Among these, data can be found on the generation and demand within areas and power flows between them. The generation and demand for each area are thus aggregated in a symbolic node and the equivalent transfer capacities between areas is calculated on the basis of thermal and stability limits. The main drawback of the model is also its principal advantage: it does not provide any means to look into what occurs within each area.

3.1.2 The CIGRE Nordic-32 test system

The Nordic-32 test system was designed with the purpose to run voltage and transient stability analysis in Sweden. This model which can be seen in Fig. 3.1, was drawn as a result of a voltage collapse in 1983. About a decade later, CIGRE published and made this model publicly available so that further studies on voltage stability could be undertaken. The model does not exactly match the Swedish electric grid but rather has a behaviour in terms of voltage stability that resembles the Swedish national grid.

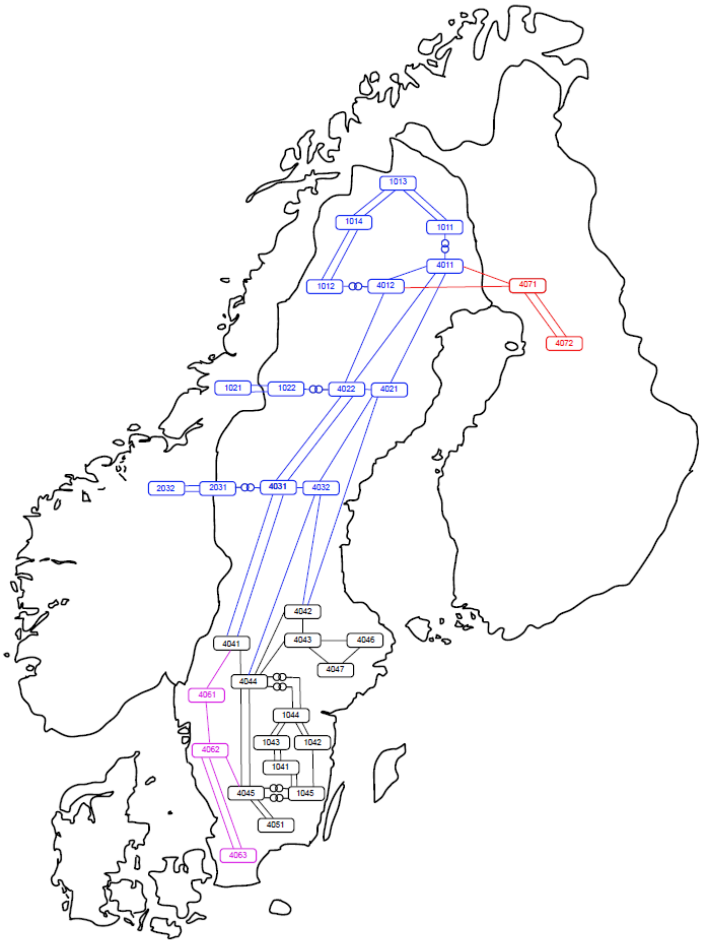

Figure 3.1: CIGRE Nordic 32 test model [11]

The main drawbacks of the model are, first, its antiquity. The model does not encapsulate the many new transmission investments that have taken place in the past two decades, particularly, the several interconnections with neighbouring countries. Second, even though the model is focused on voltage stability, the transmission capacities are not stated. Because of these drawback and the additional need to calculate how the load was split into each node, this model was discarded. Although modifications of the Nordic-32 have also been constructed, by expanding it for specific purposes [51], none specifically was deemed suitable for the task at hand.

3.1.3 More accurate models

There are more accurate models such as the ones used by SVK on the ARISTO and SPICA platforms. These models, however, are not publicly available and hence were not an option.

3.2 The 4-nodes Swedish system

In order to obtain as accurate results as possible, a study with a 4-nodes Swedish system was first employed. This simple model can be seen in Fig. 3.2. This model was used with several end-goals. First of all, it allowed for a quick investigation on how the flows took place between areas. Second, it provided with a test-bed to integrate the software PSS/E with Python which is further discussed later. Finally, the model could, when exchanges between electricity price areas was concerned, be used for comparison when running the same scenarios with the 33-nodes model.

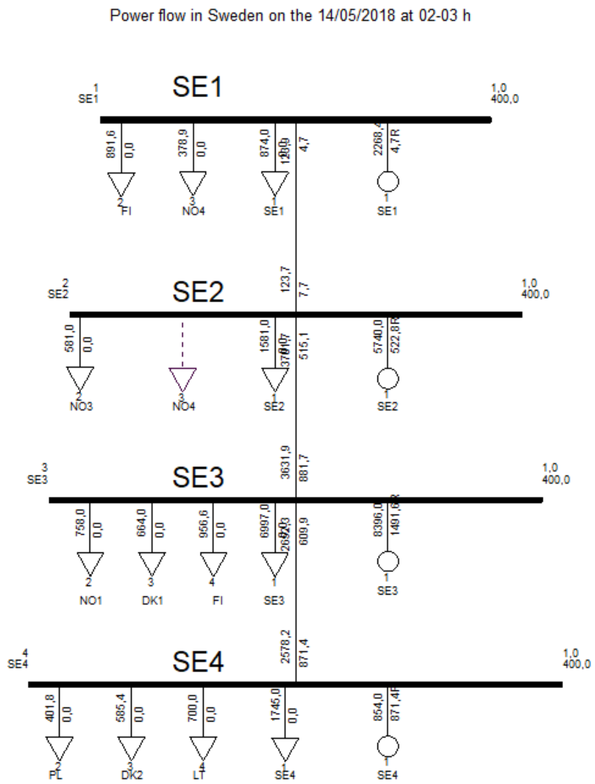

Figure 3.2: The 4 nodes model used for simulations

3.3 The 33-nodes model

Two models were designed, built and utilized for the resolution of this thesis. The first one is based on the 4-nodes concept described above. The second is the more comprehensive and custom-made model that covers both intra-area connections and the main interconnections between areas.

3.3.1 Constructing the model

This second model was essentially based on the current 400 kV transmission grid diagram publicly available at SVK website. The model took into account the main population areas and hence big electricity demands, the location of the largest generation units and points of interconnection in the transmission grid. The model was somewhat inspired by the original Nordic-32 test system although with several modifications as to include new interconnections that have taken place in the past two decades. Moreover, ongoing conversations with Pöyry and Chalmers served as a means to identify potential bottlenecks so that the model did not neglect any conflicting point.

In total, there are 33 nodes, 8 of which dummy buses used for interconnecting the step-up and step-down transformers from 400 to 220 kV and vice versa. Each node has a three digit identifier. The first digit identifies the node with each bidding area. For example, the node 201 is situated in area 2 and so does 202. Dummy buses are identified by starting with the digit "5" regardless of the area in which they are located. Some nodes have, in addition, an assigned name which refers to the closest city they have. Both node identifiers will later be employed for showing and discussing the results obtained. In this model, in contrast to the Nordic-32 test system, neighboring countries have not been represented as additional nodes. Instead, all exports and imports are included as increments or decrements of loads at the nodes in which these countries connect to Sweden. After several iteration, the final model can be seen in Fig. 3.3. Note that only one connection is shown even if multiple lines connect two nodes.

3.3.2 Note on general data

The data for generations, consumptions, energy exchanges and Net Transmission Capacitys (NTCs) are compared with the available Nord Pool and SVK data which defines the aggregated data in each bidding area. Within each bidding area, this data has been attained through available public data on the internet and, in a few cases as explained below, through data kindly provided by Pöyry and Chalmers. Certain estimations have been made when no clear available data was provided. Last, note that dummy buses are not shown in any table due to them not having any load or generation associated.

3.3.3 Load data

The load at each area and hour was extracted from the Nord Pool database. However, since Nord Pool only indicates the demand per area, the loads at each node were assigned by looking into where the population is located. Statistics on Swedish demography are found in SCB which is the official governmental organization that compiles and shares public statistics in Sweden [42]. The biggest electricity demands were hence estimated to be in the largest metropolitan areas. Although population by city, municipality and region were available and used in specific cases, Fig. 3.4 shows the population density according to municipalities which gives a broad idea of where the biggest electricity con-

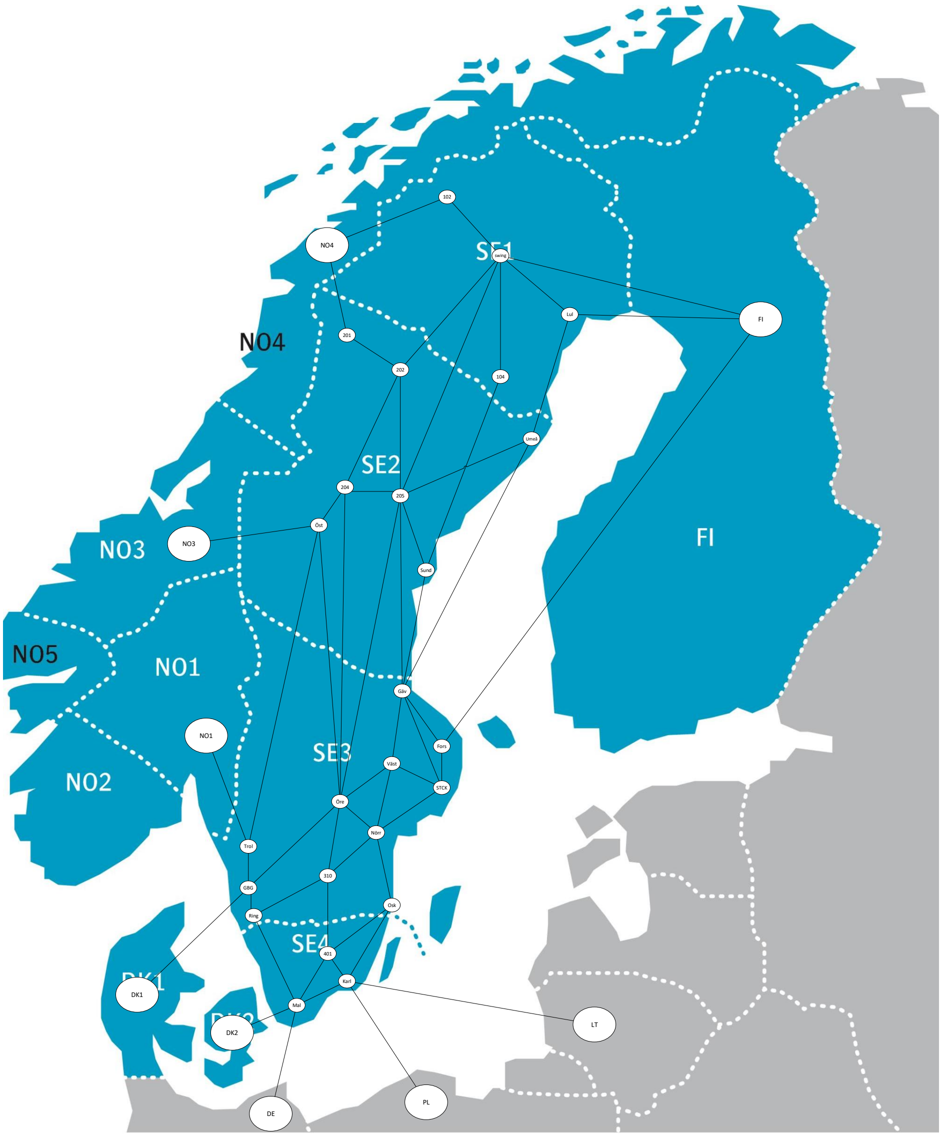

Figure 3.3: Simplified model of the Swedish transmission grid based on the current 400 kV grid.

sumptions should be found.

The demand at each node was thereafter been assigned percentually. That is, at each hour the demand at one electricity price area is distributed to each node in that area

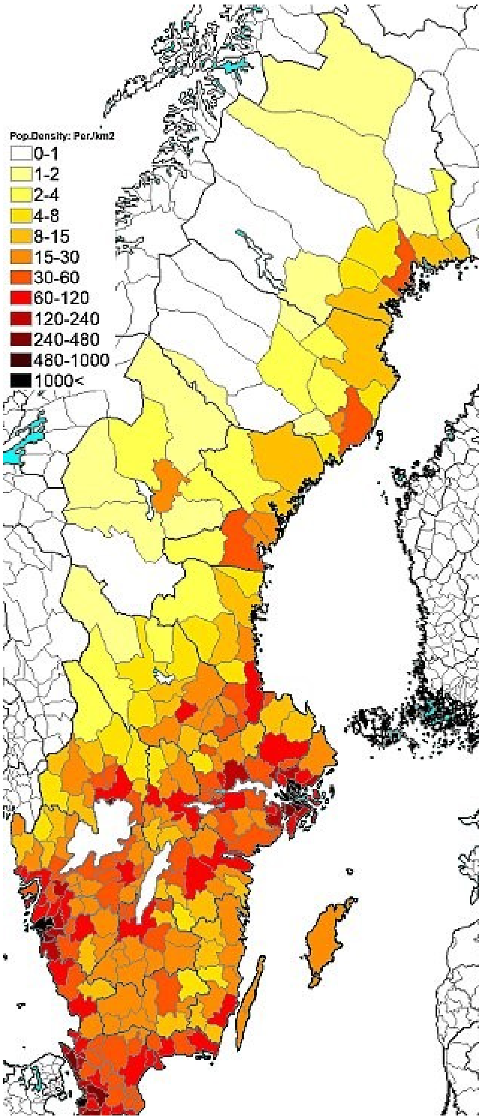

Figure 3.4: Population density in Sweden divided into municipalities. Data source: SCB [42]

according to the predefined percentage. Such percentages are summarized in Table 3.1 Additionally to the national load, imports and exports to other neighbouring countries are represented as decrements or increments of loads located at the nodes closer to the point of connection. These interconnections can be seen in Table 3.2 and the energy exported at each hour is taken from the Nord Pool database.

3.3.4 Installed capacity data

The data from the capacity installed in each node come from different sources presented below. The kind of generations considered consist of: wind, solar, hydro, nuclear, thermal units and "unspecified".

Table 3.1: Percentage of the area's demand per each node

Node	Node's name	Area	Percentage of area's demand
101	SWING	1	10
102	102	1	20
103	LULEÅ	1	50
104	104	1	20
201	201	2	1,8
202	202	2	3,5
203	UMEÅ	2	28,2
204	204	2	6,4
205	205	2	7,1
206	ÖSTERSUND	2	22,1
207	SUNDSVALL	2	30,9
301	GÄVLE	3	5,6
302	FORSKMARK	3	7,0
303	VÄSTERÅS	3	7,0
304	STCK	3	33,1
305	ÖREBRO	3	4,2
306	NÖRRKÖPING	3	5,6
307	TROLLHÄTTAN	3	5,0
308	GBG	3	17,2
309	RINGHALS	3	4,2
310	310	3	5,9
311	OSKARSHAMN	3	4,9
401	401	4	8,6
402	KARLSHAMN	4	27,0
403	MALMÖ	4	64,5

3.3.4.1 Wind power

There are multiple sources regarding the installed wind capacity in Sweden that keeps growing almost on a daily basis. There are specific maps showing in a visual manner where all wind farms in Sweden are located. These can be seen in the appendix specifically in Fig. A.1 and Fig. A.2. Wind farms, contrary to for instance nuclear reactors, tend to be of a smaller size (in terms of generating capacity) and spread out all over the country at favorable wind locations and where permissions are granted. Hence, a visual approach to identify where wind power was located was suggestive but yet deemed insufficient.

In [15], a report on wind power installed per area, region and municipality is available. In particular, a map consisting in the amount of windpower installed per region has been used as reference. Such map can be seen in Fig. 3.5.

Table 3.2: Interconnections between neighbouring countries and the nodes

Node	Node's name	Area	Interconnections
101	SWING	1	SE1-FI
102	102	1	SE1-NO4
103	LULEÅ	1	SE1-FI
104	104	1	-
201	201	2	SE2-NO4
202	202	2	-
203	UMEÅ	2	-
204	204	2	-
205	205	2	-
206	ÖSTERSUND	2	SE2-NO3
207	SUNDSVALL	2	-
301	GÄVLE	3	-
302	FORSKMARK	3	SE3-FI
303	VÄSTERÅS	3	-
304	STCK	3	-
305	ÖREBRO	3	-
306	NÖRRKÖPING	3	-
307	TROLLHÄTTAN	3	SE3-NO1
308	GBG	3	SE3-DK1
309	RINGHALS	3	-
310	310	3	-
311	OSKARSHAMN	3	-
401	401	4	-
402	KARLSHAMN	4	SE4-PL & SE4-LT
403	MALMÖ	4	SE4-DK2 & SE4-DE

A third source was also used. Since, in some cases, several nodes were located on a single region, the map per region was not accurate enough. A list of electric certificates in Sweden is publicly available at [16]. In it, all wind farms appear and can be isolated and classified per municipality. This was used to fine-tune the amount of wind power available at each node. The results were compiled and the final distribution of wind power per node utilized is shown in Table 3.3.

3.3.4.2 Solar power

Only photovoltaic solar power has been taken into account for being the most prominent in the country. Since the solar power installed in the country is, as for 2018, very small compared to the other energy sources. Furthermore, since most of PVs have mainly been installed for personal use, the solar power has been equally distributed to all nodes

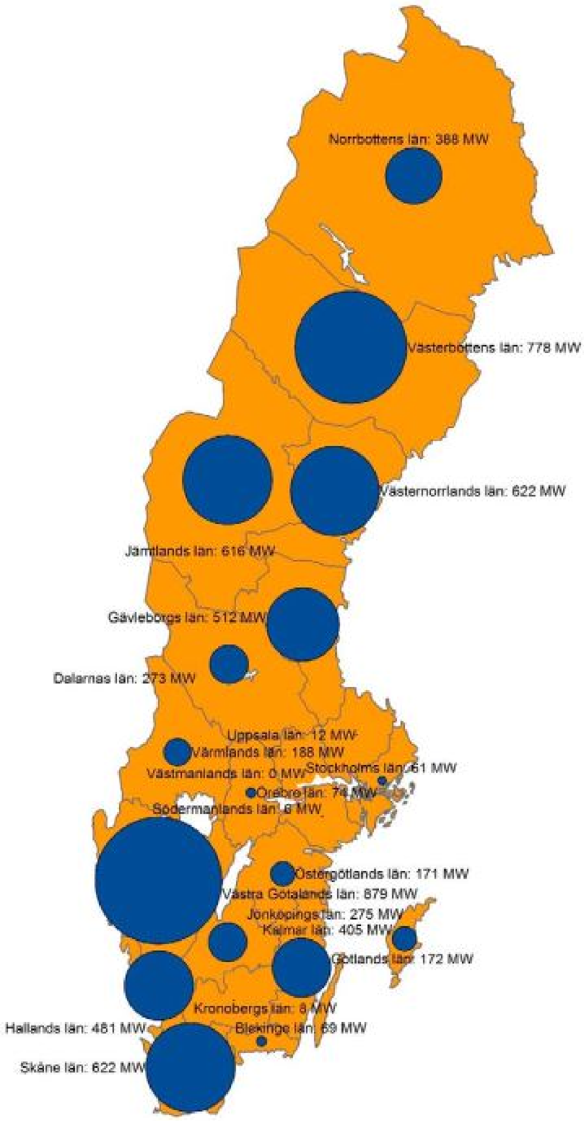

Figure 3.5: Wind power installed per region [15]

taking into account the amount of installed solar power per electricity price area as stated in [18].

3.3.4.3 Hydropower

Similar to wind power, several sources have been employed in order to determine the percentage of hydro power installed at each node. First of all, a map of all hydro power stations was found. This can be seen in Fig. 3.6. All hydro power installations over 20 MW are listed in [17]. These installations have been located and cross-checked with the list of electric certificates in [16] also employed for wind power. Finally, the hydropower distribution per node was calculated shown in Table 3.4

Table 3.3: Percentage of area's wind power installed at each node

Node	Node's name	Area	% Wind power
101	SWING	1	20
102	102	1	5
103	LULEÅ	1	45
104	104	1	30
201	201	2	10,9
202	202	2	4,9
203	UMEÅ	2	19,4
204	204	2	1,6
205	205	2	20,6
206	ÖSTERSUND	2	16,8
207	SUNDSVALL	2	25,8
301	GÄVLE	3	10,5
302	FORSKMARK	3	0,5
303	VÄSTERÅS	3	0,0
304	STCK	3	2,7
305	ÖREBRO	3	22,5
306	NÖRRKÖPING	3	7,2
307	TROLLHÄTTAN	3	33,1
308	GBG	3	1,0
309	RINGHALS	3	3,1
310	310	3	12,0
311	OSKARSHAMN	3	7,3
401	401	4	15
402	KARLSHAMN	4	30
403	MALMÖ	4	55

3.3.4.4 Nuclear power

Nuclear power in Sweden is situated in three different locations. The largest nuclear power station consist of Ringhals with an aggregated power of 3 730 MW and Forsmark with a total installed power of 3 276 MW. A third reactor is located in Oskarshamn with a total installed power of 1 450 MW as for 2018. It is worth noting, however, that one of the reactors at Ringhals is to be closed down in 2019 (870 MW) and another in 2020 (860 MW). All nuclear power is confined within the third bidding area as can be seen in Table 3.5.

3.3.4.5 Thermal units

Unfortunately, SVK clusters all kind of thermal units regardless of whether the energy comes from biomass, gas turbines, oil or coal. The splitting of power in each area is,

Figure 3.6: Map of hydro power installed stations in Sweden which surpass 20 MW [43]

furthermore, more complicated than the other energy sources. This is because there is not a single centralized source of information where all thermal units appear. Different approaches have been utilized in order to split up each area's energy production into every node. The resulting percentages of thermal units per bidding area can be seen in

Table 3.4: Installed percentage of each area's hydro power capacity per node

Node	Node's name	Area	% Hydropower
101	SWING	1	65
102	102	1	20
103	LULEÅ	1	2,5
104	104	1	12,5
201	201	2	1
202	202	2	5
203	UMEÅ	2	24
204	204	2	25
205	205	2	25
206	ÖSTERSUND	2	10
207	SUNDSVALL	2	10
301	GÄVLE	3	40
302	FORSKMARK	3	0
303	VÄSTERÅS	3	5
304	STCK	3	0
305	ÖREBRO	3	2,5
306	NÖRRKÖPING	3	2,5
307	TROLLHÄTTAN	3	15
308	GBG	3	15
309	RINGHALS	3	15
310	310	3	2,5
311	OSKARSHAMN	3	2,5
401	401	4	33,3
402	KARLSHAMN	4	33,3
403	MALMÖ	4	33,3

Table 3.5: Percentage of installed area's nuclear power per node

Node	Node's name	Area	% Nuclear power
302	FORSKMARK	3	39
309	RINGHALS	3	43
311	OSKARSHAMN	3	18

Table 3.6.

The energy coming from thermal units at area SE1 has been divided according to population. Two main assumption were made. First, there is a very small proportion of thermal units in that area which are probably and supposedly used mainly for central heating. Second, the amount of biomass installed in SE1 follows this "population" pattern [7]. This motivated the idea of applying the same principle for the other thermal units.

At SE2, it is known that no coal, oil nor barely any gas are installed leaving biomass as the only thermal units existing in that area. The percentages have thereby been assigned in accordance to the biomass map of Sweden of 2018 [7].

SE3 is probably the hardest area to dimension. Oil, coal, gas and biomass coexist in that region. However, the information available on the internet is rather limited and ultimately it has been decided to split the production according to population. This assumption is deemed to be reasonable as electricity is usually produced in parallel of district heating and due to the huge energy demands of highly populated areas.

Finally, SE4 contains both biomass and gas-fuelled power stations. The latter are localized through the UNIPER webpage [47] which owns almost the totality of such gas production. Combining the existing biomass plants along with the gas power stations, the percentage of thermal units at each node is calculated.

3.3.4.6 Unspecified

A last power production type in SVK is indicated as "unspecified". Since no information on this generation is provided, all energy generated from this category has been distributed equally to all nodes.

3.3.5 Lines

PSS/E simulates a transmission line by using a pi-model where the total resistance, line reactance and shunt capacitance are given as inputs for the program. Such configuration can be seen in Fig 3.7

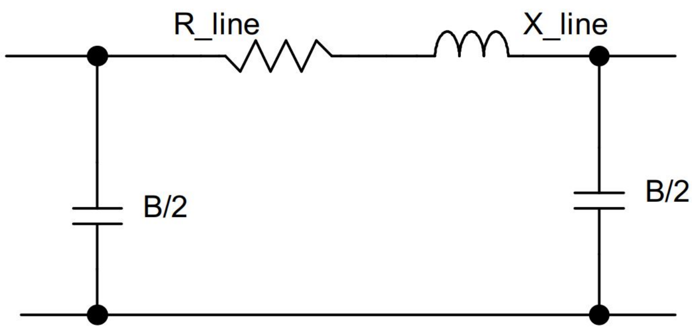

Figure 3.7: Pi-model utilized in PSS/E

However, for long transmission lines, usually defined as lines exceeding 150 km in length, this line representation is not accurate enough. The line parameters need be adjusted to

Table 3.6: Percentage of installed area's heat power per node

Node	Node's name	Area	% Thermal power
101	SWING	1	10
102	102	1	20
103	LULEÅ	1	50
104	104	1	20
201	201	2	0
202	202	2	0
203	UMEÅ	2	29,929
204	204	2	0
205	205	2	0
206	ÖSTERSUND	2	2,676
207	SUNDSVALL	2	67,395
301	GÄVLE	3	5,639
302	FORSKMARK	3	7,048
303	VÄSTERÅS	3	7,048
304	STCK	3	33,127
305	ÖREBRO	3	4,229
306	NÖRRKÖPING	3	5,639
307	TROLLHÄTTAN	3	5,004
308	GBG	3	17,198
309	RINGHALS	3	4,229
310	310	3	5,921
311	OSKARSHAMN	3	4,934
401	401	4	2,742
402	KARLSHAMN	4	40,504
403	MALMÖ	4	56,754

take into account the effect of distributed line parameters [20]. In order to do so, first, the propagation constant of the line is defined as:

$$\gamma = \sqrt{yz} \tag{3.1}$$

where "z" is the line impedance consisting of the line resistance and line reactance whereas "y" is the admittance corresponding to the shunt capacitance of the line. The corrected line impedance is then:

$$Z_{corr} = zl\frac{sinh(\gamma l)}{\gamma l} \tag{3.2}$$

And the corrected shunt admittance is:

$$Y_{corr} = zl\frac{tanh(\gamma l/2)}{\gamma l/2} \tag{3.3}$$

It is worth pointing out that the criteria for loading transmission lines depends on the length of the line [20]. For relatively short lines consisting of up to 80 km the thermal capacity is the only limiting factor. For 80 to 250 km, the main limiting factor becomes the voltage drop that occur between terminals. For even longer lines, stability limitations become crucial and must also be taken into account. In this work, thermal capacity limits have been employed for all lines within an electricity price area. For the lines connecting SE2 and SE3, the capacity limits stated on Nord Pool are employed in parallel with the line thermal ratings as will be seen in the simulation results. In such fashion, the capacity available at each hour embraces all transmission line constraints.

There is not much publicly available data on the material and thickness of the lines. In [8], information dealing with most transmission lines erected prior to 1960 is available. Discussion with SVK were fruitful in order to find out the most common topology for newly-build lines. When the line-type was unknown, certain assumption were taken

- Most new lines built nowadays consist of alloys Fe-Al of 910 mm^2 and triplex. Thus all lines built after year 2002 are assumed of that kind.

- A very common line topology in the past consists of the triplex Curlew 593/68. This topology has been employed for all unknown topology lines built prior to year 2002.

- 220 kV lines have been included in the model only if they transferred power from one area to another or if they were the only lines connecting two nearby nodes. In such cases, the line topology of those lines has been assumed to be of a Duplex 593/68 Curlew.

Other topology lines included in the model consist of the duplex Curlew 593/68 and the triplex 774 Ripa. A summary of all lines' parameters used for the model can be found in the appendix in Table A.1.

3.3.6 Other relevant data

All transformers included in the model are assumed to be ideal i.e. no losses occur in them and a negligible reactance of 0,0001 pu. The dummy buses employed for the 400-220 kV transformation and viceversa have neither loads nor any kind of generation connected. In that way, all generation and demand is aggregated at the 400 kV buses.

4 Implementation of the model in PSS/E

Once the model was constructed, a specific software was needed to implement it. Once that was decided, the procedures or workflow of the thesis were orchestrated as discussed in the following points.

4.1 Software selection

Two main softwares were taken into consideration. Originally, GAMS was regarded as the most attractive option as it would have allowed to run optimal power flows and determine how the system alters as certain conditions of the system are modified. The main problem overall remained in that the marginal costs of generators are not publicly available. Furthermore, the process of building the model would have been much more time-demanding and, last but not least, no expertise was available at Pöyry (company in which this theses was carried out). Moreover, PSS/E, being the second option, provided with a much more user-friendly interface which was deemed to facilitate troubleshooting and the subsequent possibility of analyzing more scenarios. In parallel to PSS/E, Python programming was also used in order to run power flows for several hours. Other softwares that were considered but discarded at an early phase consist of Matlab and its power flow module MATPOWER, and programming everything directly into Python with the pylon library for power flow analysis.

4.2 Workflow

The workflow starts from collecting the data at SVK's webpage, mainly power generations and the demands, and power flows and international exchanges at the Nord Pool database. The information for the day in question is compiled and stored in a single Excel file. Next, a Python script is written so that all the data is read and processed so as to adjust to the PSS/E model. The same script initiates PSS/E, opens the relevant case and updates all necessary parameters. The model is run and the results stored in a file. Finally, the script loops throughout a whole day i.e. for 24 hours, and keeps storing all the results in a file. Once all the simulations have been run, work is done to interpret the results obtained and define any further simulation scenarios (for example, employing a certain degree of demand flexibility). A block diagram can be seen in Fig. 4.1 illustrating the flow of work just described.

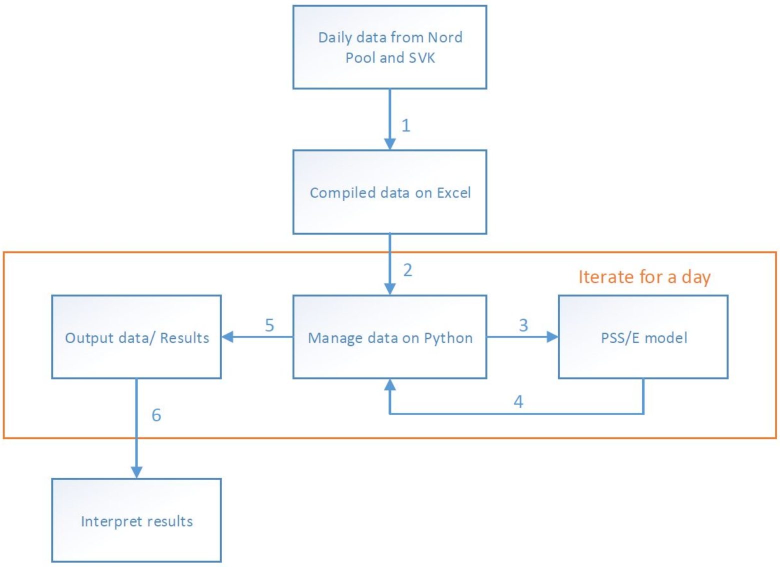

Figure 4.1: Workflow in order to gather data, process it, run the simulations and collect the results

The python script developed allows for running both the 4-nodes and the 33-nodes for either an hour or a day, and for running the model with or without DSM. For the 33-nodes model, additional steps are required such as translating the input data into the demand and generations for the 33 nodes. How the script processes and executes all these tasks can be seen in the work flow in Fig. 4.2.

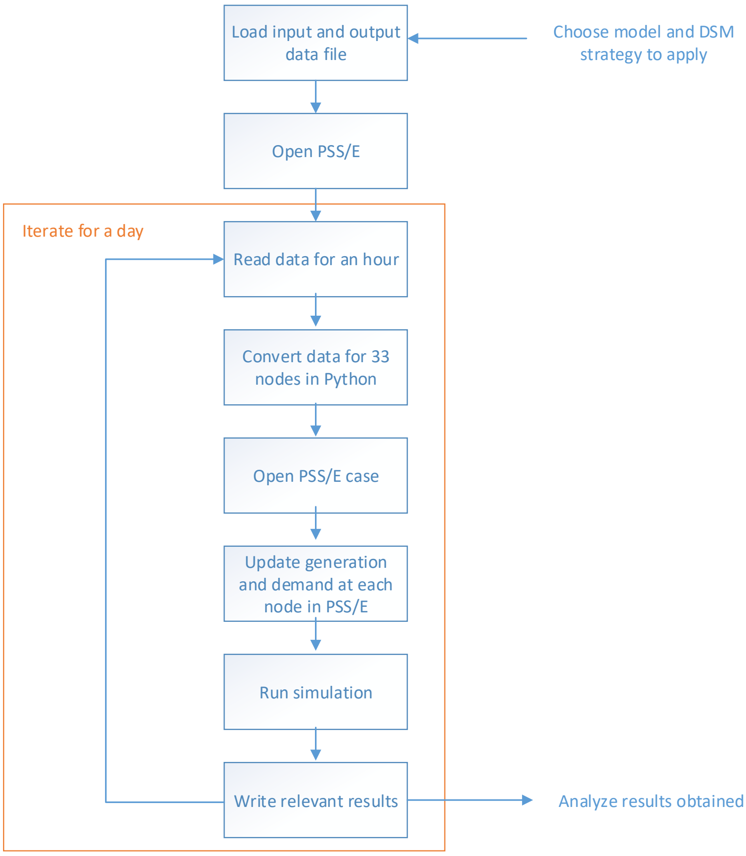

Figure 4.2: Complete workflow of the Python script for the 33-nodes model

5 Simulation results

5.1 The 4-nodes model

As a first approach, the 4-nodes model was utilized to analyze how demand-side management could alleviate congestions between electricity price areas.

5.1.1 Validating the model

An hour without congestion was run and the results analyzed to see that the model worked as expected. Specifically, the model was run using the data for the 08/05/2018 from 21:00-22:00. The hour choice was rather arbitrary although it was selected considering:

- Prices between electricity price areas within Sweden and between the Swedish and neighbouring electricity price areas were the same. That is to say, no congestion occurred during that time frame.
- The price per MWh was considerably lower than the yearly average being an indicator that nothing out of the ordinary was taking place at that hour. For instance, the tripping of a transmission line or generator.
- Sweden was only exporting energy and not importing it. This, again, pointed towards a favourable hour for the Swedish electric system which did not suffer from an apparent lack of power production at that hour.

In order to verify the validity of the system and hence move on to simulate a whole day the following points were verified:

- Check that a solution was found with no or very little power mismatches. For this case, a power mismatch of 0,00 MW was accomplished.
- Verify that the generation at the swing bus was the same as the expected generation in view of the Nord Pool data.
- The power transferred between bidding areas was the same as stated by Nord Pool

All points were met and hence a scenario with congestion was analyzed.

5.1.2 Scenario with congestion

It is not uncommon that a congestion occurs between SE2 and SE3. An example of this is the 28/11/2018. Until 06:00, the area price for all regions coincided and grew progressively as it approached that hour. At 06:00, the prices between SE1 and SE2 continued to be the same as did the one between SE3 and SE4. But because of a line congestion, the market was split, being the price at SE3 and SE4 higher (SE3 would have liked to import more power whereas SE2 would have benefited from exporting more). This congestion was alleviated at 10:00 but resurged at 14:00 until 18:00 at which point the market price between SE2 and SE3 remained the same until the end of the day. Similarly, congestions between SE3 and SE4 took place from 09:00 until 13:00 and from 16:00 until 18:00.

The 4-nodes model was run with the data from that date. In so doing, the flows between the four electric areas were analyzed comparing them with the NTCs provided by SVK at that day which was 6.500 MWh. The power transmitted and the loading percentage are shown in Table 5.1.

In short, it was observed that the system was heavily congested from 6 am to 10 am as the different electricity prices between areas suggested. Additionally, at 18 the system showed a clear congestion even though the market was not split. The latter is possible as there is always a certain uncertainty on what the total demand and generation at each point can. This, due to small errors in weather forecasts, generators not providing the exact agreed amount of power to the system or even small variations in customers energy consumption in contrast to what the prognosis predicted. Moreover, a small overloading of the lines is possible so long as it does not persist for a long period of time.

5.1.3 Demand-side management in SE3

To alleviate the congestions occurring during the 28/11/2018, a demand-side management strategy was put forward. Such strategy is assumed to be included within the Elspot market. Two main points needed to be addressed:

1. If the load at SE3 was decreased during a certain number of hours, the energy "saved" would be moved into the valley hours. How much flexible the system could potentially be was a subject of investigation. Nonetheless, certain studies, as presented in the subsection "Demand-side management at a transmission level" in the "Literature review" chapter, provided an estimate of that and therefore were used as references in the discussion chapter.

2. Any reduction or increment of the load would bring about a reduction or increase of power generated. This was an intricate problem as whatever generation that got or did not get dispatched was fully dependable on the market.

Delving into the kind of generations that were dispatched that day, it was noticed that,

Table 5.1: Loading levels between electricity market areas on the 28/11/2018

h	Apparent power SE2-SE3 (MVAh)	Loading (%) of NTC
0-1	3 854	59,3
1-2	3 101	47,7
2-3	3 163	48,7
3-4	2 888	44,3
4-5	3 216	49,5
5-6	4 603	70,8
6-7	6 572	101,1
7-8	6 600	102,5
8-9	6 614	101,7
9-10	6 513	100,2
10-11	6 289	96,7
11-12	6 173	95,0
12-13	6 117	94,1
13-14	6 425	98,8
14-15	6 296	96,9
15-16	6 151	94,6
16-17	5 984	92,1
17-18	6 319	97,2
18-19	6 520	100,3
19-20	6 189	95,2
20-21	5 368	82,6
21-22	4 492	69,1
22-23	3 785	58,2
23-24	2 053	31,6

as the peaks approached, hydropower from SE2 and SE3 increased considerably. Hence, it was assumed that, if the demand decreased so would the hydro energy generated. Similarly, if the demand increased so would the hydropower too. A question that remained was from where this hydropower would come from. It was observed that both hydro from SE2 and SE3 ramped up drastically as the peak hours approached. The assumption made here was that both hydropower generations in SE2 and SE3 had similar marginal costs and hence, if demand were reduced, the energy generated from hydro in SE2 and SE3 would be reduced in equal proportions i.e 50% each of the demand reduction. The same reasoning was used when demand increased due to demand-side management. A last assumption implied that imports and exports at SE3 would not be substantially affected and thereby were not modified in the model when DSM was introduced.

A final point that needed to be addressed was: If demand was reduced due to demand flexibility, how was that demand to be redistributed to the other hours? In this thesis, two main alternatives of demand-side management were utilized for the 4-nodes and 33-

nodes model to visualize how the congestion was partially alleviated. First, a constant percentage of DSM was applied at specific hours moving their peaks into the other off-peak hours uniformly. The second alternative contemplated a more flexible case. In it, flexible percentages of DSM were employed at different hours while also redistributing the shaved peaks in an ununiformly manner.

5.1.3.1 DSM with even distribution of load in SE3

5.1.3.1.1 A 5% demand-side management in SE3

A first approach was to apply a demand flexibility of 5% of the maximum peak in terms of power which was a realistic percentage in comparision to [23]. Analyzing the consumptions per hour at SE3 during 2018, it was found that its highest peak corresponded to 17 000 MWh. A 5% of that peak corresponded therefore to 850 MWh. DSM was applied to all hours with congestions (over 100% loading) and in fact also those above 98% loading (which were about to be congested). The shaved peaks were moved to the other hours proportionally (each hour took the same amount of extra energy). Running the simulation, the new flows obtained are summarized in Table 5.2

The hours where DSM was applied were alleviated and thereby constituted no longer bottlenecks for the system. Notwithstanding, there were several hours that had reached high levels of loading such as from 10-11 with a 98,9% and from 17-18 with 99,4%. This indicates that a 5% DSM was not optimal taking into account how the load was redistributed later. A smaller level of DSM was hence employed.

5.1.3.1.2 Optimal DSM level with even distribution of load

Running several levels of DSM between 0% and 5% and including or excluding more hours, it was revealed that a DSM of 3% onto the hours 6:00, 7:00, 8:00, 9:00, 13:00 and 18:00 was the optimal iteration. In so doing, the maximum loading was kept at 98,5% which is a 4% lower than the maximum loading hour without DSM. This DSM level was optimal in so far as the load shaved is redistributed in equal parts among the off-peak hours. A natural question that arose was: could a higher DSM be applied if the load shaved could be moved to certain hours of the day? For example, to move part of the diurnal load to the night? This will be discussed later in the discussion chapter.

5.1.3.2 DSM with uneven distribution of load in SE3

It is not trivial how the aggregated load in a whole bidding area can be shifted across time. Until now, it has been assumed that shaved demand peaks would be uniformly distributed among the rest of the hours. This was indeed a conservative approach since several loads could absolutely be shifted to later hours in order to take maximum advantage of load flexibility. An example of this, as discussed in previous chapters, are EVs. Most EVs could be easily be charged during off-peak hours at night avoiding overloading

Table 5.2: Loading levels between electricity price areas on the 28/11/2018 when a DSM of 5% is applied and the load is shifted to all hours equally

h	Power SE2-SE3 (MVAh)	Loading (%)
0-1	3 995	61,5
1-2	3 243	49,9
2-3	3 305	50,8
3-4	3 024	46,5
4-5	3 358	51,6
5-6	4 745	73
6-7	6 147	94,6
7-8	6 235	95,9
8-9	6 189	95,2
9-10	6 088	93,7
10-11	6 430	98,9
11-12	6 314	97,1
12-13	6 258	96,3
13-14	6 000	92,3
14-15	6 438	99
15-16	6 292	96,8
16-17	6 125	94,2
17-18	6 460	99,4
18-19	6 095	93,7
19-20	6 330	97,4
20-21	5 509	84,8
21-22	4 633	71,3
22-23	3 926	60,4
23-24	2 194	33,7

the transmission lines during the daylight hours.

This new scenario, thereby, explored what the maximum DSM in percentage could be applied onto the transmission system regarding the congestion occuring between SE2 and SE3. In this scenario, several combinations of hours and percentages were utilized in order to approximate the maximum benefit that the transmission system could extract from an optimized DSM strategy. That is, to smooth out the loading of the line to avoid overloading at certain hours.

After several iterations, by utilizing a DSM percentage fluctuating between 16% and 10,5% at different hours, a 82% maximum loading and 78% minimum loading of the NTC during an entire day were obtained. An average DSM of 13,5% was calculated among all hours where DSM is applied. Hence, were the system capable of moving its peaking loads to any hours, then a DSM of average 13,5% (between 10% and 16,5%)

could be used to homogenize the loading of the system with a 4% difference between the most loaded hour and the least loaded hour of the day.

5.1.4 Demand-side management in SE4

The procedure followed for this case mirrored what was done for the DSM in SE3. Generations were reduced in both SE2 and SE3 when DSM was applied and the same generation was increased when the load was augmented. The explanation for this was the following. The amount of hydro energy output in SE4 did rise during peak hours. However, the amount of hydropower installed in SE4 is insignificant in comparison to the ones in SE2 and SE3. Moreover, and as a natural result of that, it was observed that the variations in hydro power in SE4 were negligible compared to those occurring at SE2 and SE3.

The scenarios examined were also akin to the ones applied in SE3: First the load was equally distributed among all off-peak hours whereas, in a second approach, the load is assumed to be flexible enough so as to be moved to the hours of less loads i.e. the load was redistributed in an uneven manner. It is worth mentioning that the peak demand at SE4 in 2018 consisted of 4 920 MW, and hence all percentages of DSM, for the following scenarios, are in relation to this figure.

5.1.4.1 DSM with even distribution of load in SE4

The hours selected to apply DSM were those where the loading was above 86 % of the NTC levels. That is from 10:00, 11:00, 12:00, 13:00, 14:00 and 15:00.

Iteratively, it was found that, for SE4, the maximum DSM level applicable in order to minimize the hours where the loading level was above 86% was 6%. At such percentage, the hours exceeding 86% of the NTC limit were reduced from 6 to 3. At the same time, the maximum peak hour was reduced from almost a 93% of its NTC limit to a 89 % i.e a 4% reduction. Moreover, this 4%, which corresponds to a reduction of 190 MWh every hour where DSM was applied, half of that energy was also relieved in the interconnection SE2-SE3. Since the hours where SE2-SE3 and SE3-SE4 were congested were quite alike, applying DSM in SE4 seemed to have an intrinsic positive effect on the loaded SE2-SE3 lines. That is, for each MWh that is relieved in SE3-SE4, half MWh was also relieved in the SE2-SE3 connection.

5.1.4.2 DSM with uneven distribution of load in SE4

Distributing the load in an uneven manner the loading of the line can be greatly evened out as seen when applying DSM in SE3. For this scenario, the hours chosen were expanded to the 14 hours where the loading exceeded 75%.

The DSM applied varied from a maximum 32,5% DSM to a 15 % DSM level with an average of 23%. The difference between the maximum loading to the minimum was shrunk to 4 % with the maximum at 72% and the minimum at 68 %. Additionally, as a "rebound effect", the maximum loading between SE2 and SE3 went down from a 106% to a 98% of its NTC which reinforced the idea that applying DSM at SE3 could benefit the other main structural bottleneck of the Swedish transmission system.

5.2 The 33-nodes model

The 4-node model has been tested and verified. Likewise, the potential of demand-side management in order to alleviate the structural bottleneck between SE2-SE3 and SE3-SE4 has been put forward. In this section, the 33-nodes model is introduced. Similar scenarios are tested on the new model for both SE3 and SE4. Thereafter, the effect of applying DSM on specific nodes is introduced in order to see which lines benefit the most from such load shifting. Finally, a case-study where a future scenario is depicted is presented and its power flows analyzed.

5.2.1 Validating the model

Before running day-simulations, the model was run for one hour and the results compared to the values provided by Nord Pool and SVK. The final PSS/E model can be seen in Fig. 5.1.

Two cases were put forward. First, the model neglecting any kind of line impedances. Second, the model with the calculated and respective line impedances.

5.2.1.1 Model with lossless lines

In order to validate the simulation model in a gradual manner, the model was run with lossless lines in addition to generators being capable of providing or consuming whatever reactive power necessary to stabilize the system.

The model was run using the data for the 28/11/2018 from 08:00-09:00. All data utilized for the aggregated load at each node in addition to their generation can be found in SVK's and Nord Pool's websides

In order to verify the validity of the system and hence continue to implementing further constraints, the following points were investigated:

- Check that a solution is found with no or very little power mismatches. For this case, a power mismatch of 0,00 MW was accomplished after four iterations

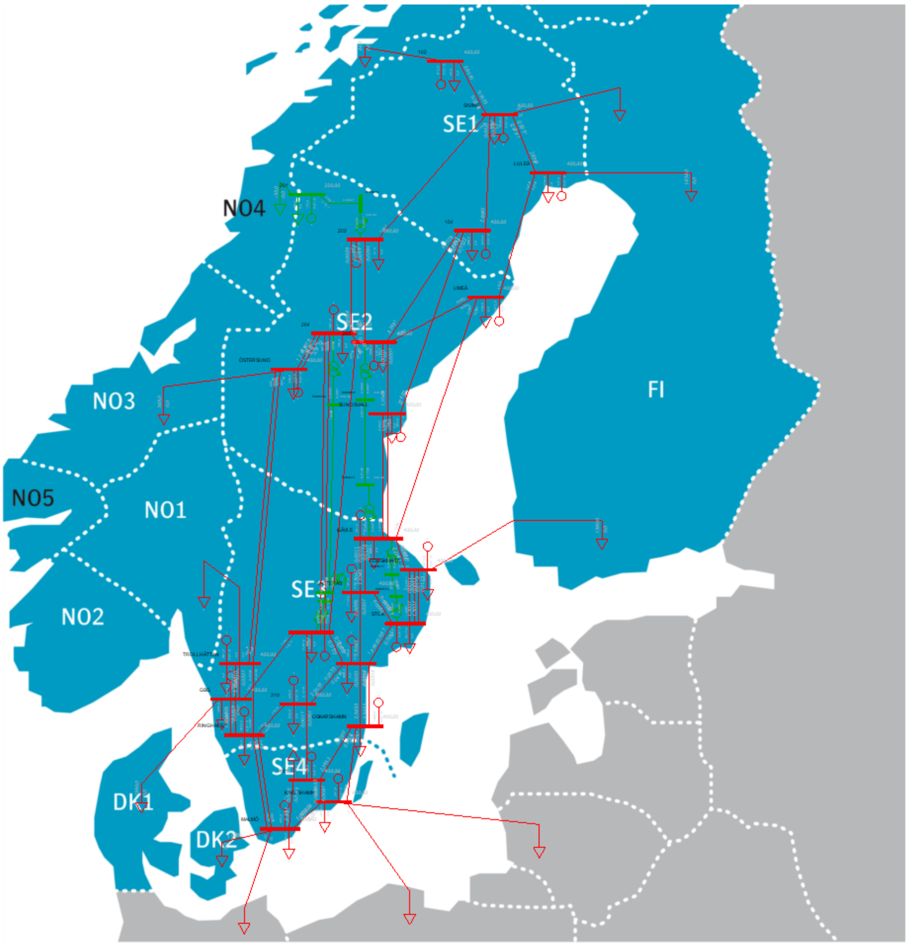

Figure 5.1: PSS/E model of the Swedish transmission grid

- Verify that the generation at the swing bus was roughly the same as the one stated by the Nord Pool data. The noted difference is of 2 MWh which corresponds to a negligible error of 0,08 %.

- An area based report was run to cross check that the flows between Swedish bidding areas were close to the ones stated by Nord Pool. Again, the differences amounted to 1 MWh which is a negligible amount compared to the power transferred

These results were deemed to be accurate enough and therefore to represent reality.

5.2.1.2 Model with line impedances

The real impedances for all lines and thermal ratings were at this step introduced. Essentially, it was desired to locate those lines that were most heavily congested. Moreover, those lines that crossed two different areas would be further scrutinized so as to put them into perspective with the congestions seen in the 4-nodes model.

Running the same day and hour as for the uncongested case, it was observed that none of the lines surpassed the 100% loading level. This is not surprising in spite of seeing a congestion in the 4-nodes model for the same hour. The reason for this lies in that the 4-nodes model utilizes the NTCs between areas. The NTC does not only take the thermal ratings into account but also voltage and angle stability. Consequently, the NTC is, in effect, more limiting than a thermal limit. Nonetheless, there are clearly certain lines that are more loaded than others. These lines can be seen in Fig. 5.2 and will now be described:

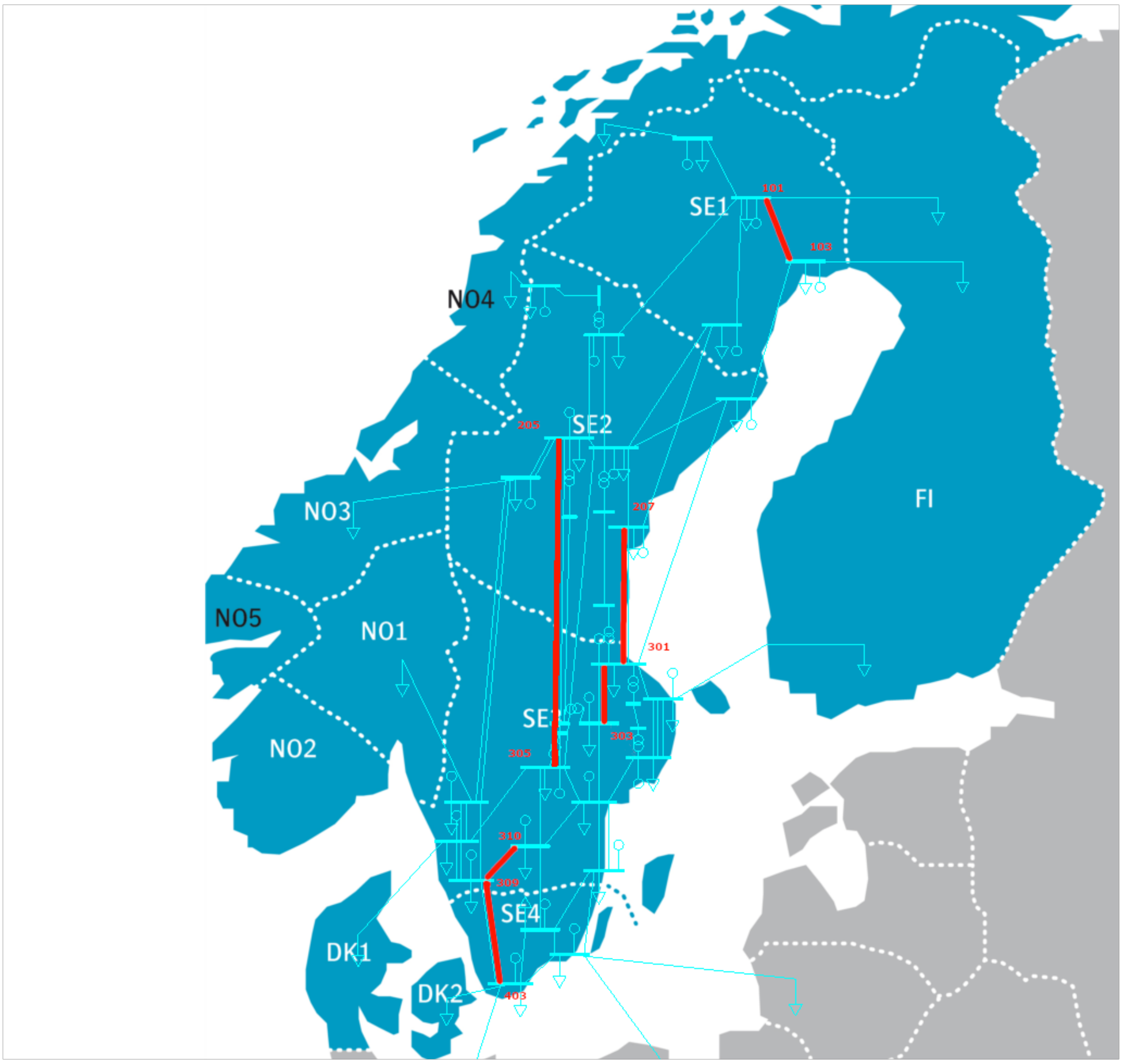

Figure 5.2: Representation of the most loaded lines on the transmission system model according to the hour 8:00-9:00 during the 28/11/2018

- At SE1, the line connecting buses 101 and 103 (The swing bus in the middle of SE1 with the node representing Luleå and its surrounding) was 77% loaded. This mainly due to the power exports to Finland. According to the transmission lines map of SVK, a new line is being built from 101 to Finland which would be motivated in view of the loading level found for that line.

- The aerial lines crossing areas SE2-SE3 were loaded at different levels. The most heavily loaded line corresponded to one of the lines connecting buses 207 and 301 (from a node close to Sundsvall to a node near Gävle). To be more precise, this line corresponds to the commonly known as CL5. Its loading level at that hour was 85 %

- The second most loaded line crossing SE2 and SE3 turned out to be the branch that connects buses 205 with 305 (between a node surrounding Kilforsen and another close to Örebro). This is a rather old line commonly known as CL4. Its loading level at that hour is 69%

- At SE3 two lines surpassed a loadability level of 80 %. The branch connecting 301 with 303 (roughly Gävle to Västerås) loaded to a 80,8 % and, the second one, 309 to 310 (Ringhals to a node around Jonköping's area) with a 83,6 %.

- Last but not least, crossing SE3-SE4 there is the line connecting 309 to 403 (Ringhals to Malmö's metropolitan area) loaded to 87,7 %. In this case, a line between 310 and 403 is currently being built which could potentially be motivated by such loading.

5.2.2 Scenario with congestion

Running the system for a congested hour constitutes a snapshot of how the system looks like in a congested situation. In essence, it aimed at presenting the most potentially critical bottlenecks of the system. Proceeding this, and to reinforce such proposition, the system was run for a whole day. The end-goal of doing the latter was not only to verify such proposition but also to visualize into which hours the demand peaks could be moved into.

For the sake of comparison, the same day, namely the 28/11/2018, was chosen. All lines that showed loading levels above 80% of their thermal rating have been drawn in Fig. 5.3. From a tie line report, the following aspects are brought to light:

- From 00:00 to 05:00, no line was loaded with more than 80% which goes in line with the fact that price differences between SE2-SE3 coincided and, furthermore, the overall Swedish demand was low compared to other hours of the day.

- The first line to show signs of being notably loaded was the line connecting buses 309 to 403 (Ringhals to Malmö). At 05:00 the line was already loaded at 80,6% reaching its peak at 13:00 and 14:00 with a loadability level of 106%. From 15:00 the loading of the line started to slowly decrease until 20:00 when the line was finally below 80% of its thermal limit.

- The second line most loaded consisted of the one connecting 309 with 310 (Ringhals to a node close to Jonköping). This line was maximum loaded at 17:00 with a 87,5% loading dropping its loading level to below 80% after 19:00.

- The 207-301 connection (roughly Sundsvall to Gävle) showed a loading level over 80% after 07:00 until 14:00. Its peak was found at 11:00 with a 85% of its thermal capabilities.

- The most heavily loaded line at SE2 was the 301-303 (Gävle-Västerås). It showed a loading level of 80,2% at 11:00.

- Finally, the most congested line in SE1 consisted of the 101-103 (swing bus in the middle of SE1 to Luleå). It showed a loading above 80% from 10:00 to 12:00 and again at 15:00. The maximum peak was found at 11:00 with a loading of 88%.

5.2.3 Demand-side management in SE3

For this section, the same levels of demand-side management used for the 4-nodes model were employed for the 33-nodes model and its results compared. Again, this DSM strategy is assumed to be participating within the day-ahead market and not in other potential markets such as the regulating power market. In those cases where different results were obtained, for example if one level of DSM was optimal for one model but not for the other, then additional simulations were run. In the discussion section, all these results are analyzed in more detail and conclusions are drawn thereof.

5.2.3.1 DSM with even distribution of load in SE3

This scenario considers the possibility of shifting a 3% of the peak demand as was done for the 4-nodes system. For the sake of consistency, the same procedure was implemented here: A 3% DSM was applied at the same hours and unto all nodes in SE3, whereas the load was redistributed evenly onto the off-peak hours.

Looking at the loading levels of the most congested lines, it was observed that the line 207-301 (which was the most loaded at corridor SE2-SE3) was alleviated by about 3%. In addition, the line 309-310 was also alleviated with a 1,1% of its thermal limit and even the power transmitted to SE4 through 309-403 was shrunk by a 0,5%. Finally, to a less extent, the power flow in line 101-103 also showed a mild reduction of 0,3% of its

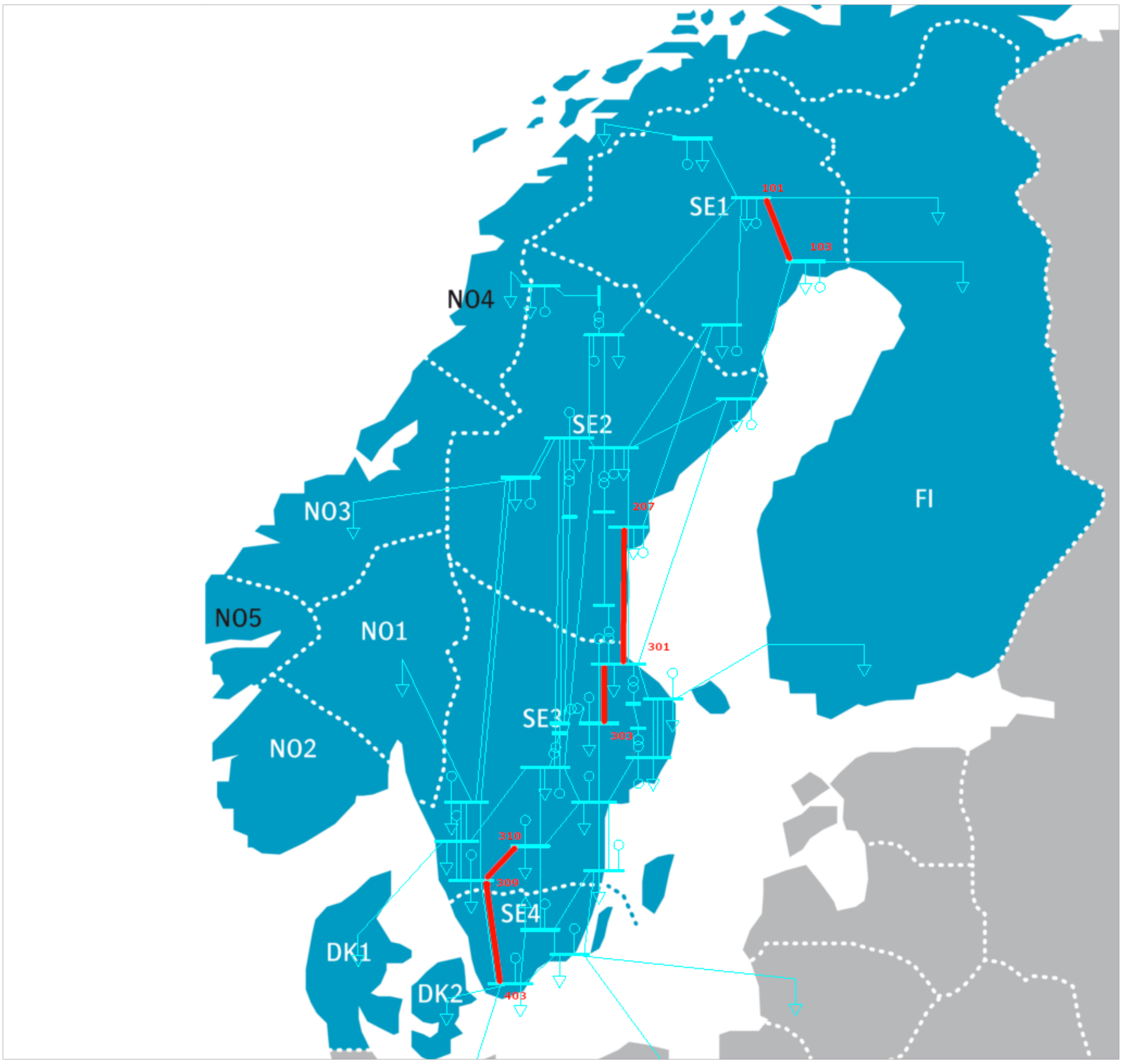

Figure 5.3: Representation of the most loaded lines on the transmission system model constructed

total thermal capacity.

Focusing on lessening the power transferred through SE2-SE3, a parallel simulation was also run applying a DSM of 3% at hours 07:00, 08:00, 09:00, 10:00, 11:00 and 12:00 which correspond to the hours of maximum power transferred for that line. The new strategy managed to reduce the number of hours where line 207-301 was above 80% loading from 6 to 2 hours. In fact, it was even seen that no off-peak hour line 207-301 became a peak hour after the power shift. Henceforth, in view of that, a 5% DSM was explored to see if better results could be attained. The new simulation managed to reduce the load at line 207-301 to less than 80% for all hours of the day. In addition, no other line seemed to be drastically affected from such strategy. Consequently, a 5 % DSM applied at those hours was hence deemed to be the optimal point in order to alleviate the constrained lines between SE2-SE3.

5.2.3.2 DSM with uneven distribution of load in SE3

To begin with, the same 13,5% DSM average was run shifting the load to the same hours as previously done in the 4-nodes model. The results, however, were quite unsatisfactory. A throughout examination of the results indicated that such DSM strategy brought about serious congestions in the transmission lines located within area SE3 rather than between SE2 and SE3. This indicates that the off-peak hours became critical hours as far as the transmission lines within area 3 are concerned. Such DSM level was hence excessively high.

Reducing the average DSM to a 10% made this problem no longer persist. At 10% DSM level, all power transferred of all lines connecting SE2 with SE3 were kept below the 75% of their thermal rating. Moreover, no congestions within SE3 arose while line 309-310 was easen by a 3% and the line 309-403 was alleviated by a 2% of its thermal rating. In that sense, the optimal DSM level was established for alleviating the congestions occurring between SE2 and SE3 while not aggravating other existing congestions in the transmission system.

5.2.4 Demand-side management in SE4

In view of the results for the 4-nodes model, the same 6% DSM identified as optimum is run on the 33-nodes model. The hours where DSM is applied are kept the same.

The results are congruent with what was previously found. The 309-403 line was relieved by a 4 % of its thermal rating when a 6% DSM is introduced. Unfortunately, however, the peak loading still remains above 100 % which is unexpected taking into consideration that the total loading SE3-SE4 is below the maximum allowed NTC. Such divergent was discussed with SVK. According to the Swedish TSO, the subtransmission lines connecting SE3 and SE4 influence substantially the NTC in corridor SE3-SE4. Since the model does not encompass subtransmission lines, the transmission lines in the model persisted to appear congested even when DSM was incorporated to the simulation. At any rate, the application of DSM in SE4 is proven to be effective in order to partially relieve such constraint, regardless of whether the bottleneck was fully eliminated or only partially alleviated.

5.2.5 Demand-side management at specific areas

Knowing which lines suffer from higher congestions than others, it is also possible to investigate the effect of DSM in certain locations. In this study two locations were studied. Namely at 403 (the Malmö region) and at node 304 (the Stockholms metropolitan area). The former was chosen in view of the congestion that occured from 309 (Ringhals) to 403 (Malmö) which was the most prominent of that day. The latter is chosen due to the high demand that Stockholm's area features and thus to investigate its influence onto the highly loaded line 207-301 interconnecting SE2 with SE3 as well as the 309-310 line.

5.2.5.1 DSM at Malmö's region

The peak demand at SE4 in 2018 was found to be 4 920 MW. Malmö's region, which in fact embraces almost half of Skåne's area, accounts for the 64,5% of that demand. Hence, the peak demand at that load was estimated to be of about 3 175 MW for the entire year.

The arranged scenario consisted of shifting a 6% of the peak demand in Malmö from the hours of maximum loading at 309-403 (10:00, 11:00, 12:00, 13:00, 14:00 and 15:00) to the off-peak hours in an even manner. The results, in line with what was seen when DSM was applied at SE4, succeeded in relieving the apparent constraints at 309-403. To be precise, the decrease in percentage amounted to a 3,5% of the maximum thermal rating for that line. This is particularly high since when applying the same level of DSM at SE4 the decrease was of only 4%. This result suggests that applying DSM in Malmö is crucial in reducing the congestion at 309-403. Moreover a 1,5% loading reduction at 207-301 was also accomplished thus suggesting applying DSM in that area.

5.2.5.2 DSM at Stockholm's region

As previously seen, the peak demand at SE3 during 2018 amounted to 17 000 MW. Stockholm's area is estimated to account for the 33,1% of that demand and hence it's peak is estimated to be around 5 630 MW.

A 3% DSM was applied at Stockhom area to the hours where line 207-301 is utilized at more than 80 %. The results showed that the hours where the line was used at more than 80 % was reduced from 7 to 3. Moreover, the maximum use of the line dropped from a maximum 85,1 % to a 83,3%. Also, line 301-303 is no longer above 80% at 11:00. Similar to the case where DSM was applied for the whole SE3, lines at SE4 were also alleviated but to a lesser degree, about 0,3% when DSM was applied. Last but not least, the line 101-103 reduced considerably its loadability with about 3,5% which was also beneficial to the system.

As last step, the 5% DSM that showed to be optimal when applied for SE3 in the 33-nodes model, was also applied to only Stockholm area. In other words, a 5% of Stockholm's peak demand was substracted to the hour consumptions of hours 07:00-13:00. The results were equally positive having reduced the amount of hours in which

207-301 was above 80% loaded from 6 hours to 1 and a reduction of 4,7% of its loading at each hour where DSM was applied.

5.2.6 Future scenario: closing-down of nuclear power

5.2.6.1 Case description

As previously observed, Sweden is expected to close down most of its nuclear reactors in the following years. At the same time, the amount of wind power installed has done nothing but escalate in the past few years which could suggest a mix energy transition from predominantly nuclear and hydro power to wind and hydro power. In view of such possibility, a new scenario was put forward in order to investigate how future power flows could be affected by such energy transition.

The investigation of such future scenario was done under certain constraints and assumptions.

- To begin with, all nuclear power was removed from the system and substituted by wind power. Such substitution is not trivial since, while nuclear power generates energy at a fairly constant rate, wind power is strongly dependant on whether conditions. Analyzing the situation for the 28/11/2018, it was found that nuclear power generated 2,4 times more energy than wind power. Hence, in order to provide, at least, the same amount of energy for a day, a 240% increase in wind power capacity was required. An increase of 250% of wind power capacity was in the end implemented to offer some margin for days of less wind speeds.

- Wind power was distributed among nodes in accordance to how wind power had been installed so far in reality and hence also in the simulation model.

- In order to correct for wind power productions, the flexibility of hydro power in SE2 and SE3 was used decrementing or incrementing their output power in discreet blocks of 250 MWh. This, to compensate for both favorable wind situations where wind power exceeds the supplanted nuclear generation, or conversely when there is a lack of wind power in which case hydropower needs to intervene in order to balance the power generated with the demanded one. When there was a surplus of wind power, the hydro power was decreased in equal parts for both SE2 and SE3 except when no more power could be reduced in SE3, in which case the reduction was continued in SE2. Only at 23:00 the power could not be reduced any further at SE2 and thereby the power balance was stabilized by the swing bus.

- Finally, any divergence smaller than those 250 MW was met by the hydro power located at the swing bus at SE1.

5.2.6.2 Simulation results

The simulation results showed various bottlenecks that were nonexistent in the previous scenarios. Looking at the hour 09:00, which is the only hour where hydro power scheduled was not modified in comparison with the other simulations, the effects of this replacement can be more clearly seen. A contour map of the scenario is presented in Fig. 5.4

Many congestions occurred around Stockholm's area and the lines coming from SE2 and delivering power to SE3. A reason for this is the fact that two out of the three nuclear power stations resided in the east part of SE3. The removal of such generators translated into more power coming from other parts of the country not only SE3 wind power but also from wind power coming from SE1 and SE2. Even a line connecting the area of Trollhättan with Gothenburg's was congested due to the large amount of wind power installed in the west coast but above Gothenburg. The necessity of transferring power from SE1 to SE3 brought about a congestion between 104-207 (120% of its thermal limit). The only positive remark is probably the decongestion of the 309-403 line feeding Malmö's area and the previously congested 309-310. This due to the large concentration of wind power close to the west coast at SE4 and Malmö region as can be seen in Fig. A.1 in the appendix.

Another simulation was performed allowing SE1 hydro power to participate in the power balancing along with the hydro power at SE2 and SE3. The maximum loadings decreased slightly but not enough to make a substantial difference. Moreover, the congestions appeared to be structural (they existed for most of the day) which disencouraged the idea of applying DSM on the whole.

5.3 Yearly implications

A Python program has been written to investigate the amount of hours and days in which congestions occurred between bidding areas. The intention was twofold. First, to analyze how congested the transmission system appeared to be during a whole year. Second, to comprehend to what extend the selected day for the simulations was representative of the congestions occurring during that year. The results of of all these are summarized in Table 5.3.

Table 5.3: Number of hours and days where congestions occurred between SE2-SE3 and SE3-SE4 during 2018 and the average price difference between these areas

	No. of hours	**No. of days**	**Avg price difference (€/MWh)**
SE2-SE3	374	65	7,25
SE3-SE4	1351	167	11,8

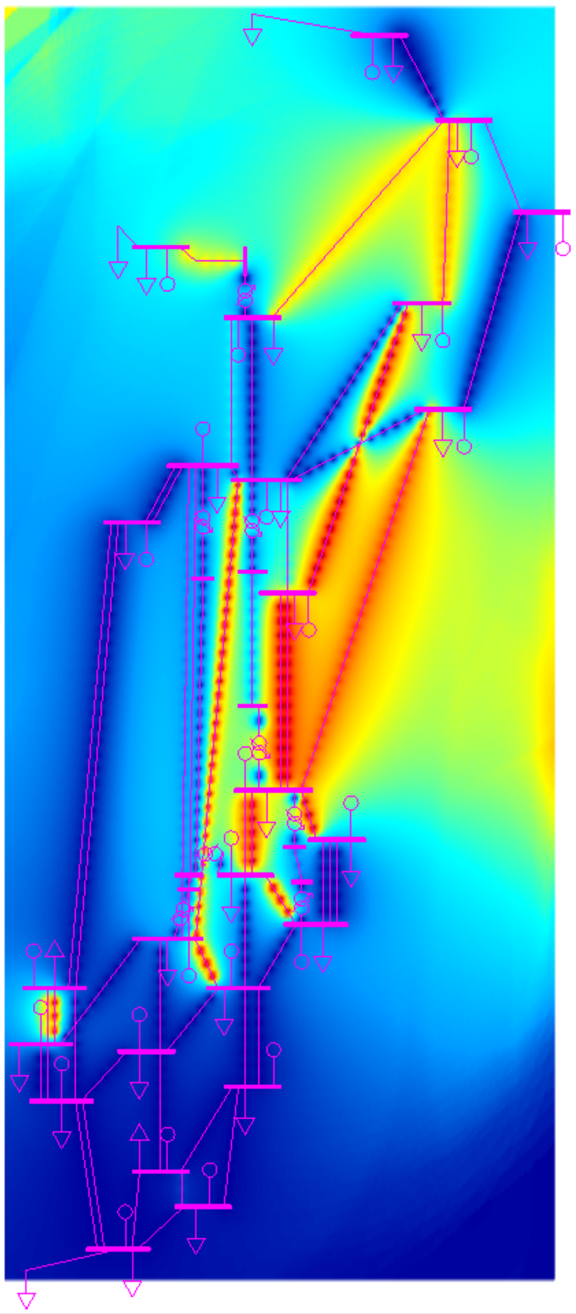

Figure 5.4: Contour of the power flows in relation to their ratings for the case where all nuclear power has been substituted for wind power. Red colours indicate a high utilization of the line (100% or above) and the darkest blue low loadings (60% or less)

Analyzing these values in terms of percentages, in 17,8% of the days a congestion between SE2-SE3 occurred for at least 1 hour, whereas 45,8% of the days suffered from a congestion between SE3-SE4. The average number of congested hours over congested days was 5,8 h and 8,1 h per congested day for SE2-SE3 and SE3-SE4 respectively. These two facts suggesting that bottlenecks at SE3-SE4 are not only more recurrent than bottlenecks at SE2-SE3, but also of longer duration (more hours of congestion when a congestion takes places during a day). Economically speaking, the average price difference between SE2-SE3, when a congestion occurs, is 7,25 €/MWh, whereas for SE3-SE4 amounts to 11,8 €/MWh. This price difference will be discussed in more detail in the discussion part.

The day selected for the simulations was characterized by being congested during 8 hours at SE2-SE3 and 6 hours between SE3-SE4. The day was thus not exceedingly far from the average values, although the congestion between SE2-SE3 was relatively more severe and the one at SE3-SE4 milder than what it would be expected from comparing the values with the average ones. Moreover, the congested hours were congruent with the ones observed in other days. The congestions usually arose after 06:00 in the morning and disappeared by latest 21:00 at night.

6 Discussion

6.1 Demand-side Management at inter-area level

6.1.1 SE2-SE3

It has been observed through the previous simulations how congestions between SE2 and SE3 can be alleviated by taking advantage of demand flexibility. The benefit from applying demand-side management was, nonetheless, strongly dependable on how the moved load could be redistributed. The most conservative case in this study assumed that all shaved load during the day would be equally distributed among the rest of the day. Under such assumption, it was noted that the system would in effect benefit from up to a 3% demand flexibility, according to the 4-nodes model results, and up to 5% according to the 33-nodes model. However, an increase of such percentage would not retrieve any additional advantage. As the percentage of peak load reduction rose so did the load that needed to be shifted. At a 3% and 5% for each model respectively, the highest peak would equal the off-peak hour with highest consumption. In other words, the valley hours would start becoming the peak hours. In terms of energy, a 3% DSM applied at 6 different hours corresponded to 3 060 MWh or 18% of the peak energy demand for a single hour at SE3, while a 5% was equal to 5 100 MWh and 30% of that peak energy demand .

The second scenario put forward consisted of applying DSM in a completely flexible manner. That is, different percentages of DSM were used for peak hours while shifting that energy in an uneven manner i.e. Those off-peak hours which had less congestion were loaded more heavily than those who had relatively high loading levels from the outset. The motivation for such scenario was twofold. On one hand, with the proliferation of the EVs, PVs and energy storage, the possibility of shifting loads to rather late hours at night may become all the more feasible. In other words, to shift loads to when consumption was at its minimum. On the other hand, even if such flexibility were not feasible with the current load topology, which will be examined shortly, it is of utter interest to comprehend how much DSM would assist the transmission system in evening out its capacity usage throughout a day.

This second scenario was fairly more optimistic and hence aimed at investigating how much DSM the transmission system could embrace. For this case, an average of 13,5% (DSM between 16% and 10,5%) of the annual peak demand was found optimal. Such percentage was within the maximum flexibility calculated in Sweden of between 15% and 30% in terms of power [44]. The amount of load flexibility employed was an amalgamation of the flexibility that could be provided from both industry and households being this susceptible to the duration of the DSM strategy. In other words, even though a reduction of 16% of the peak seemed to be altogether possible and supported by the literature available, another important aspect to look at is the amount of energy displaced. DSM was applied to a total of 14 hours with an average DSM level of 13,5 %. This resulted in a total energy of 32 130 MWh shifted during a whole day. This, in turn, corresponds to a 189% of the highest peak energy demand for one single hour during 2018. In [22], it is estimated that a buffer of a 100% of the peak energy demand of Malmö could be potentially available for demand flexibility (25% of the peak power demand for four hours in total). Consequently, this suggests that a DSM of 13,5% of average during 14 hours would, a priori, not be feasible. On the other hand, this also indicates that the transmission system, not only would benefit from using the dormant demand flexibility, but it could even benefit from more flexibility. Such flexibility could be attained, for instance, by promoting the use of energy storage both at distribution and transmission system such as batteries and fuel-cells among others. Finally, comparing the DSM percentages for the even distributed case with the same literature studies, it can be concluded that its implementation is currently feasible as well as desirable.

To summarize, the study suggests the desirability of accomplishing a DSM level even higher than the maximum dormant load flexibility in the system. This, so long as it is unevenly applied at different hours and the load can be freely redistributed across its valley hours. In a rather pessimistic scenario, where loads should be redistributed equally across hours, the system would still benefit from a DSM level of 3%-5% in terms of power and 18%-30% in terms of peak energy. This would reduce the number of hours that congestions occur while maximizing the use of the current transmission system infrastructure.

6.1.2 SE3-SE4

The results at SE3-SE4 pointed out that a DSM level of 6% applied at SE4 was optimal when redistributing the load evenly. This, in turn, corresponded to 1 770 MWh of energy or a 36% of the maximum peak energy in SE4 during 2018. Again, comparing the results with [23], this 36% is feasible considering the potential flexibility of the current loads.

Another relevant result was the fact that, by reducing the load at SE4, the loading between SE2-SE3 was also relieved. This suggests that reducing the load at hours where both SE2-SE3 and SE3-SE4 are congested would have a doubly positive effect. This is reasonable considering that there is very few generation in SE4: barely any hydro power and no nuclear power, while containing highly populated centers such as Malmö.

6.1.3 Yearly implications

It has already been mentioned that 17,8% of the days and 45,8% of the days are congested at some hour for corridors SE2-SE3 and SE3-SE4 respectively. This suggests that corridor SE3-SE4 is suffering, comparatively to SE2-SE3, from more frequent congestions. Additionally, the average market price difference between SE2-SE3 and SE3-SE4 are 7,25 €/MWh and 11,8 €/MWh. The latter, however, may not be enough to quantify the severity of the bottleneck. Whereas it is true that the price difference per unit of energy between SE3-SE4 is greater than the corresponding SE2-SE3, the amounts of energy exchanged are not the same. Currently, the maximum NTC of corridor SE2-SE3 is 7 300 MW whilst the NTC between SE3-SE4 is 5 400 MW (2 000 MW if energy is flowing from SE4 to SE3). Unfortunately, there is no public available data on how much extra capacity would be needed to fully relieve the bottlenecks. Regardless of that, the presence and frequency of those bottlenecks have been presented and the possibility to partially or totally solving them through DSM demonstrated.

6.2 Demand-side Management at intra-area level

The main overloaded/highly loaded lines were found to be the 101-103, 207-301, 301-303, 309-310 and 309-403 during a highly loaded day in 2018. Some of these lines were positively relieved by applying DSM such as the 301-303, 309-310 and 207-301 when the DSM was employed at SE2, and 309-403 and all the aforementioned lines when DSM was applied at SE4. Two points are worth being discussed.

First of all, some of the most congested lines such as 101-103 and 309-403 are about to be reinforced in view of the construction of new transmission lines in the area. However, as it is the case for the 309-403, the construction time may be high and probably no reinforcement will come into operation until 2026 [22]. This demands immediate action to sustain the current system until these new reinforcements come into picture.

Second, the majority of the SE2-SE3 lines were built under the 60s and need to be replaced at a near point in time. While this does not happen, due to the high costs and laborious process, structural bottlenecks have already arisen, principally at the 207-301 line. Moreover, the phasing out of nuclear power, which is as for today only located at SE3, can only aggravate the current lack of energy production at SE3 and thereby put more lines under stress, in peril of being severely congested at certain hours of the day/year. All in all, this should motivate the increasing use of DSM at this area.

6.3 Local flexibility

A couple of scenarios have been examined to visualize the effect of DSM in particular nodes on the transmission system power flows.

Analyzing the effect of applying DSM at Malmö's region, it was demonstrated that by reducing its load at critical hours, the effect on the congested line 309-403 is greatly relieved. Comparing figures, a 6% DSM reduction in SE4 (1 770 MWh) relieved a 3,4% of the line while a 6% DSM reduction in Malmö (1 140 MWh) relieved a 3,5% of the same line. Extrapolating these numbers, if the reduction of 1 770 MWh in SE4 had only been reduced in Malmö, the reduction of the line congestion would be of 5,6% instead of the accomplished 3,4%. This signifies that, applying DSM at Malmö's region is 66% more effective in alleviating 309-403 than it would be by reducing the load equally all over SE4. To conclude, such findings may suggest that implementing DSM strategies in Malmö may have one of the most positive effects for the current Swedish transmission system.

As for the Stockholm's case, it was revealed that by applying a 5% DSM the amount of hours where line 207-301 was loaded to higher than 80% was reduced from 6 to 1. This represented a loading reduction of 4,7%. In terms of energy this was equivalent of shifting 1690 MWh of demand. In comparison, with the 5% DSM in SE3 which moved 5 100 MWh and managed a reduction of 5,2% for the same line. If such energy had been reduced only in Stockholm's area, the loading reduction would have been of 15,7% instead of a 5,2%. That is 200 % more effective than reducing the load over the whole SE3 if the goal is to alleviate the most loaded line in SE2-SE3. This poses Stockholm as one of the most interesting places where DSM could be implemented to reduce the current bottleneck occurring at SE2-SE3. Last, it was observed that the power flow to SE4 was slightly reduced as DSM was applied. This is suspected to be due to loss reduction attributed to overall smaller flows in the system. A table summarizing these findings can be found in Table 6.1.

Table 6.1: Comparison of loading reduction for the same energy applied at areas 3 and 4 compared to Stockholm's and Malmö's areas respectively

	5% DSM SE3	**5% DSM of SE3 in STCK**	**6% DSM SE4**	**6% DSM of SE4 in Malmö**
Reduction 207-301(%)	5,2	15,7	0,7	3,1
Reduction 309-403 (%)	1	1,8	3,4	5,6

6.4 Future scenario

The scenario of replacing all nuclear power for an equivalent amount of wind power has been investigated. In it, the flexibility of hydro power was employed to balance the power generated and demanded at each hour.

The results pointed out that, if wind power were to be installed in the same locations as it has been until now, and no grid reinforcements in the grid took place; new bottlenecks would occur in the system. This is partially reasonable as the grid was not originally planned to accommodate such distributed generation. Furthermore, there are even studies that are skeptical of such transition, questioning the feasibility of replacing nuclear power for wind power both in economical and environmental terms [24]. In any case, this scenario depicts the need to rethink how the future grid should look like in order to foster a higher degree of renewable energies and decrease the dependency on fossil fuels and nuclear power. A well planned transmission system along with the utilization of the available demand flexibility should prevent the apparition of new constraints in the system, whilst providing the groundwork to combat climate change.

6.5 Societal, ethical and environmental implications

6.5.1 Environmental aspects

A higher degree of penetration from non-dispatchable renewable energies, such as solar and wind power, into the energy mix is paramount to combat climate change and fulfill the renewable energy prospects for the European Union [25]. Such enterprise calls for every actor in the energy system to take its share including: power suppliers, transmission and distribution grid operators and owners, and even energy retailers and energy consumers.

This thesis entails several environmental aspects as it aimed at optimizing power grid resources taking demand flexibility into account. In short, this thesis contributes in environmental terms by

- Providing the necessary background to understand how the current Swedish transmission system looks like by identifying the main bottlenecks. By decongesting these bottlenecks new opportunities for increasing renewable energy capacity could most likely arise.

- Presenting the potential of demand-side management as a means to cope with renewable energy sources variability as well as demand fluctuations.

- Certain materials for cables and transmission lines are not particularly environmentally-friendly. For instance Polyvinyl Chloride (PVC) is a non-degradable plastic widely used as an insulating material [27]. Thus, preventing the construction of unnecessary lines due to the utilization of DSM techniques may reduce the environmental impact of expanding the grid.

- Finally the implications of phasing out nuclear power have been presented when maintaining the transmission grid as it stands today. It was observed that, if nuclear power is to be greatly substituted by additional wind power, the grid will need to be reinforced as to accommodate such distributed generation.

6.5.2 Societal and ethical aspects

The societal and ethical aspects are limited and implicit in the optimization of the transmission network. An example of this could be to avoid the construction of additional power lines near populated areas if, for instance, demand-side management may suffice in shifting power peaks to hours of less energy demand. Additionally, the cost-benefit analysis, which is undertaken in each and every European transmission expansion plan, strives to maximize societal welfare. These analysis take into account several social, ethical and further specific environmental factors which are particular to each and every individual project [9].

7 Conclusions

7.1 Limitations and assumptions of the study

Several limitations are worth pointing out. First of all, some of the lines in the 33-nodes model were estimated both in terms of conductor section and whether they were duplex or triplex. Thus, this might have influenced the results to a certain extent. Moreover, the model does not contemplate reactive power limitations at the generation side. Ideally, shunt reactive power devices are situated at strategic positions in order to inject or absorb reactive power and hence contribute to voltage stability. The assumption that each node is capable of generating an ideal amount of reactive power is fictitious and simplifies reality to a considerably extent. Such simplification was made due to lack of public information on the matter, although net transfer capacities were employed for the 4-nodes model to capture that unknown factor.

Another assumption was how the redispatchment of energy was carried out. Even though it was observed that hydro power was undoubtedly involved in the power balance of the system, it is not straightforward to determine to which extent. For instance, it is unclear which hydro power would kick in and which one would shut down or decrease its production when DSM is applied. A similar observation can be made in regards to power exchanges with other countries. Without an all-encompassing model where all countries were represented in detail, it is hard to foresee how these exchanges would be altered as demands and generations inside Sweden are modified.

A partial solution to these question marks would be to run an optimal power flow which took into account the marginal costs of each unit at each country. Such approach, however, would not come without its own limitations as the possibility to get access to such information is highly unlikely due to confidential issues. In this study, hence, an empirical approach has been taken by observing what happened in the past and extrapolating those phenomena to accommodate different levels of demand flexibility.

Finally, it would have been of great interest to investigate several days to guarantee that no conclusion was reached on a weak ground/ without having a strong basis for that. In other words, if similar patterns were encountered in the majority of days where congestion occurred, a whole year could be run and recommendations based on a year's basis could be put forward.

7.2 Main conclusions

The purpose of this thesis was to investigate the potential of DSM in the development of the Swedish transmission system. By building two open source models of the Swedish transmission grid, the main bottlenecks in the grid were identified. Several DSM techniques were, thereafter, utilized and the results obtained compared in terms of how effective they were in relieving these congestions. Moreover, their feasibility in contrast to the current literature on the topic was also examined. A future scenario where nuclear power was substituted by wind power was also explored.

This study uncovered large divergences concerning how much DSM would be desirable in the transmission system. Whereas a higher degree of load flexibility is undoubtedly desired, it is paramount to acquire further knowledge on how the aggregated load could be shifted across time. The simulation results clearly indicated so. Shifting the peak loads to off-peak hours in an evenly manner had its own limitations: new peak hours eventually emerged as more and more energy was being shifted. Regardless of this, it was found that 5% of the SE3 peak could be moved during 6 hours to optimally support the transmission system. Similarly, a DSM level of 6% of the SE4 peak for 6 hours proved to be of maximum benefit. On the other hand, if peak power demands, on the contrary, could be freely moved to low consumption hours (generally speaking, night hours), the dormant potential of demand flexibility could be fully utilized. This, with great benefits to the transmission system which, in the best scenarios, pointing out to reductions of more than 20% of the thermal ratings for the most congested lines, without any apparent pitfall.

Local flexibility scenarios, moreover, uncovered the fact that applying DSM in Stockholm was 200% more effective in alleviating congestions between SE2 and SE3 than applying DSM all over SE3. Similarly, DSM in Malmö was 66% more effective in relieving the bottleneck at SE3-SE4 compared to applying DSM across SE4.

Last but not least, the conceived future scenario reflected on the necessity of expanding the electric grid. Whereas DSM managed to alleviate the current congestions in the grid, new investments will be necessary to accommodate upcoming wind power capacities if these are to successfully replace the current nuclear power in the future.

7.3 Future work

Future studies could focus on running similar simulations for different days and obtain illustrative results for a whole year. This would provide with a holistic outlook on the necessities of the system, taking into account every day of the year.

Furthermore, this thesis could be further expanded by analyzing more future scenarios. For instance, the effect of closing individual nuclear reactors, the inclusion of lines currently under construction, investigate future electric demand growths, the hypothetical deployment of battery energy storage at transmission level and so forth.

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A Appendix

A map showing where the majority of wind farms are located can be seen in figure A.2 and in figure A.1

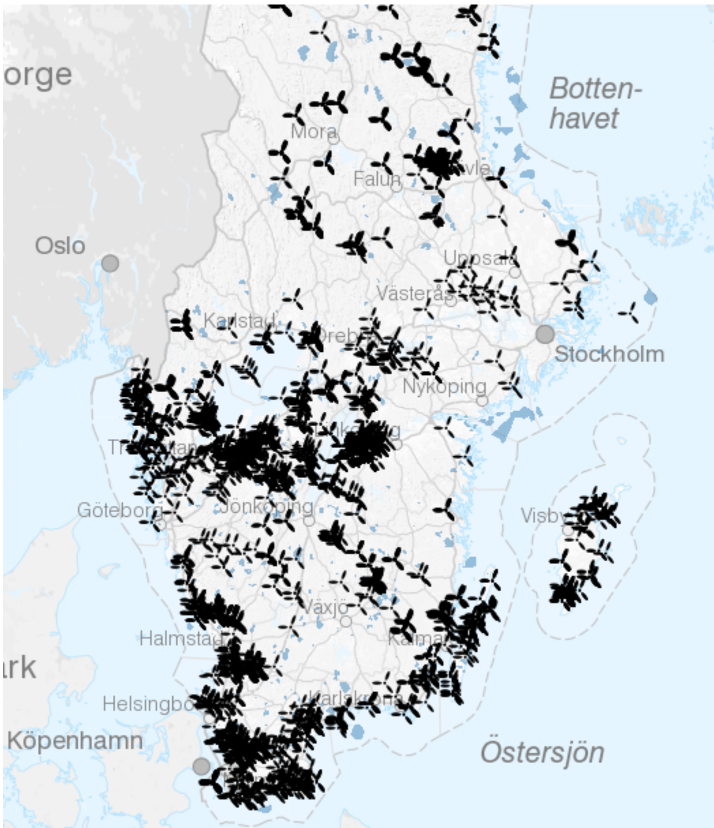

Figure A.1: Wind power installed in the southern part of Sweden corresponding to corridors 3 and 4 [49]

In Tab. A.1, all branches' parameters used in the 33-nodes model can be seen.

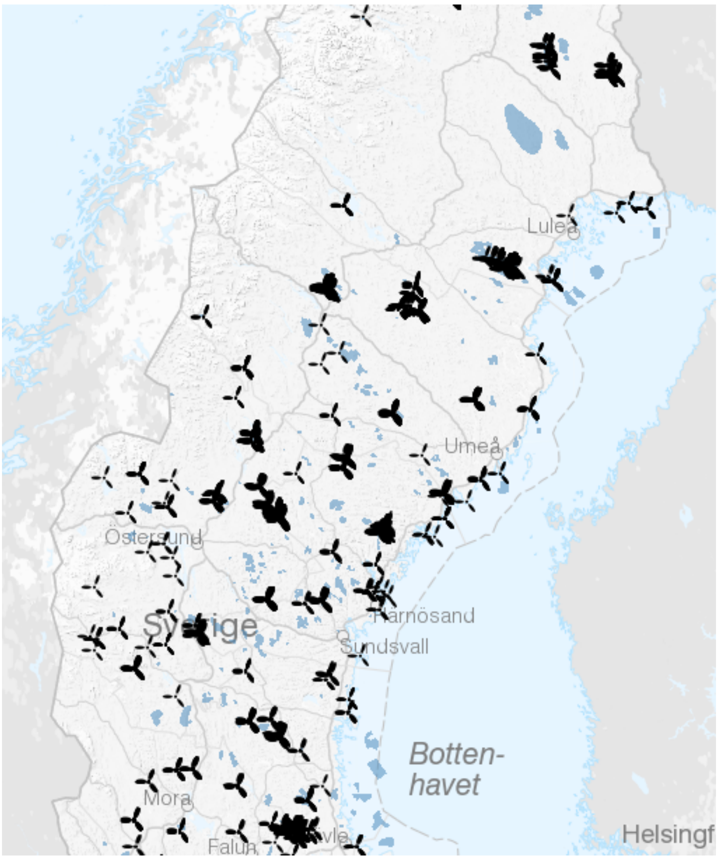

Figure A.2: Wind power installed in the northern part of Sweden corresponding to corridors 1 and 2 [49]

Table A.1: Data of all branches used in the 33-nodes model. All series compensation impedances consist of series capacitors

From Bus	To Bus	R(ohms)/km	X(ohms)/km	B(Mhos)/km	Length (km)	Capacity (MVA)	Series Compensation (ohms)
101	102	0,018	0,277	0,013	200	1719	0
101	103	0,018	0,277	0,013	150	1719	0
101	104	0,018	0,277	0,013	200	1719	0
101	202	0,026	0,33	0,011	300	1146	0
103	203	0,018	0,277	0,013	280	1719	0
104	205	0,018	0,277	0,013	250	1719	0
104	207	0,026	0,33	0,011	250	1146	0
201	501	0,026	0,33	0,011	150	630,3	0
202	204	0,026	0,33	0,011	180	1146	0
202	205	0,018	0,277	0,013	150	1719	0
203	205	0,026	0,33	0,011	200	1146	0
203	301	0,018	0,277	0,013	550	1719	65
204	205	0,026	0,33	0,011	80	1146	0
204	206	0,026	0,33	0,011	100	1146	0
204	206	0,018	0,277	0,013	100	1719	0
204	305	0,026	0,33	0,011	600	1146	71
204	305	0,018	0,277	0,013	600	1719	80
205	207	0,026	0,33	0,011	100	2406,6	0
205	305	0,018	0,277	0,013	500	1719	78
206	307	0,026	0,33	0,011	550	1146	86,2
206	307	0,018	0,277	0,013	550	1719	78
207	301	0,026	0,33	0,011	300	1146	43
207	301	0,0136	0,286	0,0124	320	1950,5	69,6
301	302	0,0136	0,286	0,0124	80	1950,5	0
301	303	0,026	0,33	0,011	100	1146	0
301	303	0,018	0,277	0,013	100	1719	0
302	304	0,018	0,277	0,013	100	1719	0
302	304	0,018	0,277	0,013	100	1719	0
302	304	0,018	0,277	0,013	100	1719	0
303	304	0,018	0,277	0,013	40	1719	0
303	306	0,026	0,33	0,011	100	1146	0
304	306	0,018	0,277	0,013	150	1719	0
305	306	0,018	0,277	0,013	100	1719	0
305	308	0,026	0,33	0,011	250	1146	0
305	310	0,0125	0,265	0,0141	150	2182	0
306	310	0,026	0,33	0,011	200	1146	0
306	311	0,018	0,277	0,013	180	1719	0
306	311	0,018	0,277	0,013	180	1719	0
307	308	0,026	0,33	0,011	100	1146	0
307	308	0,018	0,277	0,013	100	1719	0
307	309	0,018	0,277	0,013	250	1719	0
308	309	0,026	0,33	0,011	100	2182	0
308	309	0,026	0,33	0,011	100	2182	0
309	310	0,026	0,33	0,011	150	1146	0
309	403	0,018	0,277	0,013	230	1719	0
309	403	0,026	0,33	0,011	230	1146	0
310	401	0,018	0,277	0,013	150	1719	0
311	401	0,018	0,277	0,013	180	1719	0
311	402	0,026	0,33	0,011	200	1146	0
401	402	0,018	0,277	0,013	50	1719	0
401	403	0,018	0,277	0,013	100	1719	0
402	403	0,026	0,33	0,011	150	1146	0
502	503	0,026	0,33	0,011	150	630,3	0
504	505	0,026	0,33	0,011	180	630,3	0
504	506	0,026	0,33	0,011	600	630,3	0
507	508	0,026	0,33	0,011	250	630,3	0