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Industrial Electrical Engineering and Automation

# Virtual power lines in the future Swedish power system

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# Preface

This thesis, for the degree of Master of Science in Engineering, has been carried out at the Department of Industrial Electrical Engineering and Automation at the Faculty of Engineering, Lund University.

There are several people we would like to thank for their contribution to this work. Firstly, our supervisors Professor Olof Samuelsson and PhD student Martin Lundberg, who have provided excellent guidance, support and inspiration. We would also like to thank PhD student Henrik Nordström at KTH, who provided the script which allowed us to separate the aggregated data for renewable power production into different categories, and Dr Emil Hillberg at RISE, who were our advisor regarding changes to the Nordic44 model. We would also like to thank Dr Alexandra Nikoleris at LTH for introducing us to the concepts of scenario work.

Last but not least we would like to thank Pontus Herrmann and Julia Jonasson for the collaboration in developing the Nordic46 network model. Without their contribution the model would not have become what it is today.

This work has been carried out in close collaboration between the two authors and it is not possible to distinguish their separate contributions.

*Lund, May 2023*
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# Abstract

The transition towards renewable energy and electrification is expected to accelerate in the coming decades. This change is being studied by several actors, in Sweden most notably by Svenska kraftnät, the Swedish TSO. They have recently constructed four different scenarios, two of which explore a future with a doubling of electricity consumption from year 2022 to year 2045. These two scenarios have been studied in this thesis work in the context of challenges in the underlying power system.

There is currently a lack of transmission capacity between the Swedish bidding zones, which could worsen if the electrical power usage doubles in the future. Building new power grid infrastructure is a slow process, where new transmission lines can take 10-12 years to complete. A rapidly growing demand for electricity combined with long lead times to reinforce an already strained system is problematic since it slows down the rate of the electrification of society and increases electricity prices. One part of a possible solution to this dilemma is virtual power lines. These grid connected battery energy storage systems can reinforce already existing infrastructure by increasing power transmission capacities. Virtual power lines use battery storages which work in pairs where the demand side storage discharges during hours of congestion in the transmission system, at the same time as the supply side storage charges, thus virtually increasing the power transfer capacity. During low load hours in the transmission system, the supply side storage recharges the demand side storage.

The main objective of this thesis work is to examine if virtual power lines can be a part of the solution to the lack of transfer capacity across the Swedish bidding zone borders. This is done through simulations in PowerFactory in an updated version of the Nordic44 network model depicting the Nordic synchronous area in year 2045. The control of the virtual power lines, ie the decision of when the virtual power lines should charge or discharge is also modeled through conditional logic in a Python script.

The results of the simulations show that virtual power lines can benefit the Swedish transmission system. It is also concluded that virtual power lines should not be the only solution to reduce congestion in the grid, as the battery energy storage systems in the virtual power lines would in some cases need to be 100 000 MWh or more. A common result for both studied scenarios was that bidding zone border 1 in the north of Sweden would benefit the most from a virtual power line, with reductions in the number of overloaded hours of around 50% in some cases and a reduction in MWh overload of around 40%. When studying cases with delayed reinforcement projects in the power grid, virtual power lines could in some cases reduce both the number of overloaded hours as well as MWh overload with over 80%. These results were acquired using virtual power lines with energy ratings of 1 000-10 000 MWh. Additionally, factors that should be considered when dimensioning virtual power lines include how much of the overload energy that needs to be covered as well as utilization time.

# Populärvetenskaplig sammanfattning

Omställningen och elektrifieringen av samhället för att nå klimatmålen går fort och takten väntas öka de kommande decennierna. Det är inte omöjligt att elanvändningen dubbleras under de kommande 20 åren. Eftersom det redan finns flaskhalsar i det svenska elnätet och det tar 10–12 år att bygga ut stamnätet kan en dubblerad elanvändning leda till problem. Virtuella ledningar skulle kunna vara en lösning på det här problemet.

En virtuell ledning består av två stora nätuppkopplade batterilager som arbetar synkroniserat. De kan vara placerade i varsin ände av en elledning, men också längre ifrån varandra än så. I en enkelriktad virtuell ledning, som är det som studeras här, finns en behovssida, där mer el behövs, och en tillförselsida, där ett överskott på el finns. Mellan dem är transmissionskapaciteten begränsad, vilket innebär att ledningen inte alltid räcker till för att föra över så mycket el som behövs på behovssidan. Under perioder då ledningen är full kan batterilagret på behovssidan ladda ur för att bidra med mer el där det behövs. Samtidigt laddar lagret på tillförselsidan upp, och lagrar den el som inte kunde skickas på ledningen eftersom den var full. När plats sedan åter finns på ledningen laddar tillförselsidan ur, så att den elen kan skickas till behovssidan, som laddar upp för att vara redo för nästa tillfälle med brist på överföringskapacitet. Genom att använda virtuella ledningar kan alltså mängden överförd el öka utan att nya ledningar byggts till.

För att undersöka hur virtuella ledningar kan användas i det framtida svenska elnätet görs omfattande datorsimuleringar i en elnätsmodell där Sverige, Norge och Finland finns med. För att kunna göra dessa simuleringar används data från två framtidsscenarier från Svenska kraftnät, som är den myndighet som är ansvarig för Sveriges stamnät. Scenarier är påhittade versioner av framtiden som kan vara antingen sannolika, möjliga eller önskvärda. De är därmed inte förutsägelser av framtiden, utan snarare arbetsverktyg. Av de två scenarier som används har ett av dem en helt förnybar elproduktion år 2045. Det andra scenariot inkluderar även kärnkraft. Båda scenarierna antar att elanvändningen dubbleras till år 2045.

Resultaten från simuleringarna visar att virtuella ledningar kan öka överföringskapaciteten mellan de svenska elområdena. De virtuella ledningarna kan bidra med mer nytta i scenariot med 100 % förnybar elproduktion. Det beror troligtvis på att elproduktionen är mer ojämn i det fallet, vilket ger fler tillfällen för de virtuella ledningarna att ladda upp och ladda ur. Potentialen för virtuella ledningar är störst mellan elområde 1 och 2 i båda scenarierna. Av resultaten framgår också att virtuella ledningar inte bör användas som enda lösning för att minska belastningen på elnätet, eftersom det skulle innebära att batterilagrena behöver vara gigantiskt stora. Om 100% av alla timmar med överbelastning mellan elområde 2 och 3 år 2045 skulle åtgärdas skulle batterier motsvarande 8 miljoner elbilsbatterier behövas! Om man nöjer sig med att minska överbelastningen i elnätet 80% av tiden skulle batterilagret bara behöva vara ungefär trettio gånger mindre. Detta är det mest extrema fallet, men det generella resultatet är att det inte är försvarbart att använda virtuella ledningar som enda lösningen. Ytterligare faktorer som behöver beaktas när en virtuell ledning dimensioneras är bland annat hur många timmar elledningen är full samt hur mycket den virtuella ledningen används.

Värt att notera är att det finns flera olika användningsområden för virtuella ledningar. Dels kan de implementeras istället för att bygga nya fysiska ledningar i de fall då tillräcklig överföringskapacitet saknas. De kan också användas för att avlasta elnätet under de 10–12 åren det tar att få en ny ledning på plats. Slutligen kan de även användas för att bibehålla överföringskapaciteten vid större underhållsarbete eller annat bortfall som gör att större ledningar i ett område inte kan användas.

# Contents

# Nomenclature

**AOEP** Accumulated overload energy peak

**BZB** Bidding zone border

**BZB1** Bidding zone border between SE1 and SE2

**BZB2** Bidding zone border between SE2 and SE3

**BZB4** Bidding zone border between SE3 and SE4

**BESS** Battery energy storage system

**$CO_2e$** Carbon dioxide equivalent

**CSE** Confederation of Swedish enterprise, *Svenskt Näringsliv* in Swedish.

**DK** Bidding zones in Denmark

**ERCOT** Electric reliability council of Texas

**EF** The scenario *Elektrifiering förnybart*, in English *Electrification renewable* from Svk.

**EI** Energimarknadsinspektionen, the Swedish Energy Markets Inspectorate

**EP** The scenario *Elektrifiering planerbart*, in English *Electrification dispatchable* from Svk.

**ESS** Energy storage system

**FI** Bidding zones in Finland

**HVDC** High Voltage Direct Current

**LMA** Long term market analysis

**NO** Bidding zones in Norway

**NTC** Net transfer capacity

**NTNU** The Norwegian University of Science and Technology

**PV** Photo voltaic

**SE1, SE2, SE3, SE4** Bidding zones 1, 2, 3 and 4 in Sweden, also called Luleå, Sundsvall, Stockholm and Malmö.

**Svk** Svenska Kraftnät, the Swedish TSO

**TRL** Technology readiness level

**TRM** Transfer reliability margin

**TSO** Transmission system operator

**TTC** Total transfer capacity

**VPL** Virtual power line

# 1 Introduction

For over 50 years, scientists around the world have known that extensive carbon dioxide emissions will affect the climate [1]. The August 2021 IPCC report AR6 stated that "*It is unequivocal that human influence has warmed the atmosphere, ocean and land*" [2]. In order to limit global warming to 1.5 °C according to the Paris Agreement, carbon emissions from all sources need to drastically decrease. This means that the energy system needs to transition from using fossil fuels to energy sources with low carbon emissions. One way to do this is by a widespread electrification of society, using electricity with a low carbon footprint. For Sweden, using electricity as an energy carrier for industry, transport, etc means that the Swedish energy system is facing a major change, even though the majority of the electricity is fossil free. Electricity production needs to increase, perhaps to more than double today's level, to meet these new needs, and this electricity needs to originate in sources with a low carbon footprint. This can be accomplished in many different ways, and it is not yet known which approach Sweden will take. In order to study and evaluate some of these different routes, scenarios of the future power system can be used.

A scenario is a made-up version of the future. It is not a forecast, but rather a tool to ensure that multiple outcomes of the future are considered. Scenarios concerning the Swedish power system have been developed by several different actors. One of them is *Svenska Kraftnät*, called Svk hereafter, the Swedish transmission system operator, TSO for short. The scenarios developed by Svk in their *Long term Market Analysis* from 2021 are not forecasts of the future, but rather tools used to take measures to counter future challenges that may occur in the grid. Of the latest collection of scenarios developed by Svk, two constitute a doubled electricity use in Sweden until 2045. In 2045, one of the two scenarios is a completely renewable power system, which includes a substantial increase in offshore wind power. The other scenario is also based on electricity generation with low carbon emissions but includes nuclear power in addition to the renewable power production.

The transmission system in Sweden stretches all the way from the south in bidding zone 4 to the north and bidding zone 1, see figure 1b. There is currently an uneven spread of population and power production, where the majority of people live in bidding zones 3 and 4, SE3 and SE4, whilst large portions of the power production is located in bidding zones 1 and 2, SE1 and SE2. This means that power is not always produced where it is needed, and hence there is a need for a transmission grid to transport electricity all across Sweden. The transmission capacity is however limited, and sometimes this means that all power that is needed in one area cannot be transferred from the adjacent area. This situation is known as congestion of the power grid. A place where the power flow is limited due to lack of transfer capacity is called a bottleneck. These bottlenecks are defining the bidding zone borders and are one of the reasons why the spot price of electricity varies between different bidding zones. Having bottlenecks and grid congestion is a problem, seeing as electricity cannot flow where it is needed. This may result in a power shortage in a part of the grid if the demand is high, but the available electricity is low. In a worst-case scenario, it may also lead to power outages and rolling blackouts, and in general act as a hindrance to the transition to a more sustainable society which uses electricity as a main energy carrier. In order to prevent these things from happening and make way for the wide-spread electrification there is thus a need for increasing the transmission capacity and extending the transmission network in Sweden. Building new transmission lines is a time-consuming process often lasting around 10-12 years on average. Thus, there is a problem where the electrification needs to take place as fast as possible to avoid climate change, new transmission lines are already needed and more will be needed if the electricity consumption doubles, but building new transmission lines takes a lot of time. A solution to this problem could be using *virtual power lines*, hereafter referred to as VPLs.

VPLs are energy storage systems connected to the electrical power grid at two locations. They may for example be used as reinforcements of the grid and in some places even instead of an extension of the transmission network. It is common for one side to be a “supply-side storage”, where power is available, and for the other to be a “demand-side storage”, where power is needed. The VPL mimics the behaviour of a power line by charging the supply side when the transmission lines connecting the two storages are full and simultaneously discharging the demand side to provide more power at peak demand. When there is available transfer capacity, the supply side storage instead discharges so that the demand side storage can charge. This technique can generally help avoid congestion without having to change the balance between electricity generation and usage. Since the VPL does not move power in time it can be considered to be energy and power neutral. This is important due to the legal framework in Sweden which states that it is not allowed for a network company to sell and buy electricity from a energy storage system in order to profit from it, since that affects the competition on the market. Implementing a VPL is estimated to take approximately 1-2 years. These aspects motivate studying whether VPLs can be a part of a solution to the problem with bottlenecks in the Swedish transmission system.

## 1.1 Aim

The main aim of this thesis work is to investigate if virtual power lines can eliminate bottlenecks at the Swedish bidding zone borders. Part of the aim is also to determine which factors play a role in deciding size and location of a VPL. In order to do this, the second aim is to update the Nordic44 network model, which represents the Nordic synchronous area. Another aim is to develop a script that can be used to distribute data for electricity consumption and generation in the model. This data originates in time series with hourly resolution from Svenska kraftnäts *Long term market analysis* from 2021.

## 1.2 Research questions

- Can virtual power lines contribute to increasing the transfer capacity across the Swedish bidding zone borders in 2045 in a scenario where there is a lack of transfer capacity?
- Which factors are important to consider when determining the size of the energy storage in a virtual power line?
- How can virtual power lines be modelled in a power system?

## 1.3 Delimitations

- Only some selected scenarios are studied, specifically *Elektrifiering förnybart* and *Elektrifiering planerbart* for year 2045 from Svenska kraftnät.
- The focus in the simulations is Sweden. Consequently, the modifications of the network model are truer to reality for Sweden compared to Norway and Finland. Since it has no relevance for the results for Sweden if the power lines in Norway are overloaded, as long as the transmission capacities between Sweden and the other two countries are accurate, the transfer capacities within Norway and Finland are not updated.
- The Nordic44 model and the updated version of it called the Nordic46 model are used, which are approximate models of the Nordic power system and does not capture all of its properties. However, the overall outline and characteristics of the system are fairly well represented in the models. It can thus be expected that large scale behaviours in the models can be seen in reality too.

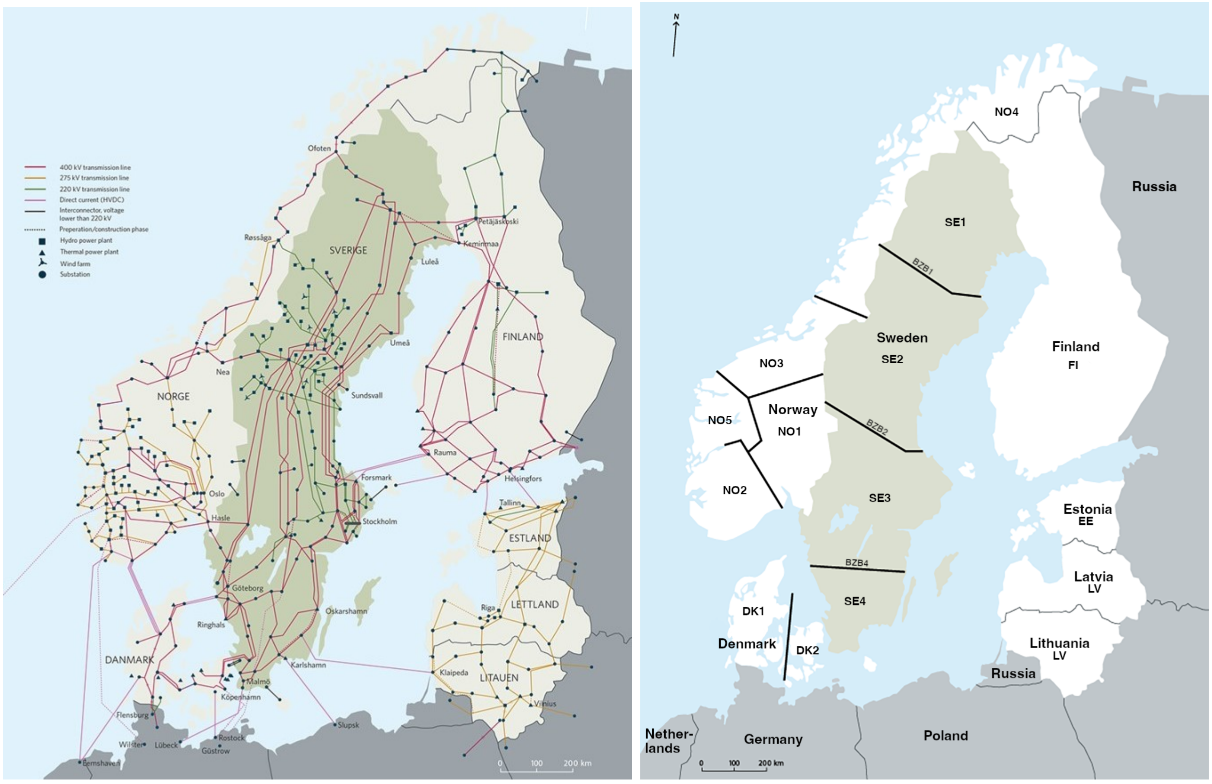
- Simulations only concern load flows and no system dynamics are modelled.
- The simulations done in the Nordic44 and Nordic46 models does not take economic aspects, such as spot price variations, into consideration.
- Only active power is considered. It is assumed that the need for reactive power is met and does not constitute a problem.
- Only unidirectional VPLs are used.
- The dynamics of an energy storage system are out of scope, so is the reactive and apparent power of the storage.
- No losses are included in the modelling of the VPLs.
- All economic aspects concerning real world applications of VPLs are out of scope.

# 2 Background

In this section, firstly the Swedish power grid will be introduced followed by an introduction to scenario analysis, together with a description of the two scenarios that the rest of this thesis work will be based upon. Thereafter the simulation tools will be introduced. This will be followed by a description of what a virtual power line is, and how it can be used. Lastly the technology for lithium-ion batteries is introduced, together with their environmental and climate impact.

## 2.1 The Swedish power grid

The Swedish power grid consists of the transmission grid and multiple smaller distribution grids. In addition to this there are also connections to other countries. When the connection is to another country in the same synchronous area as Sweden, for example Finland, Norway or eastern Denmark, the connection is usually an AC link. If instead the connection is to a country outside this Nordic synchronous area a HVDC link is always used. This work only considers the Swedish transmission system along with connections to other countries. The voltage level in the Swedish transmission grid is either 400 kV or 220 kV [3]. A graphic representation of the transmission system in Sweden and the rest of the Nordic synchronous area can be seen in figure 1a.



(a) *The transmission system in the Nordic area and its surroundings [4].*

(b) *The four Swedish bidding zones, BZB1, 2 and 4 from north to south, and bidding zones in the surrounding countries. Translated version of figure from Svk [5].*

Figure 1: *The Nordic transmission systems and bidding areas.*

Since 2011 Sweden is divided into four bidding zones. From North to South these are SE1 (Luleå), SE2 (Sundsvall), SE3 (Stockholm) and SE4 (Malmö) [6]. The bidding zones can be seen in figure 1b. The need for the Swedish bidding zones arose when EU ruled it unacceptable that Svk limited the transfer capacity to other countries in order to keep the Swedish power system stable. The reason for EU's decision was that Svk's actions kept other countries from accessing the Swedish electricity market. By introducing bidding zones other tools were provided for Svk to ensure reliability of the Swedish power system [5].

### 2.1.1 Electricity generation in Sweden

Ever since the year 2011 Sweden has had a net export of electricity [7]. During 2022 Sweden had a net export of 33.3 TWh, which is a record high. The gross export of electricity in 2022 was 39.4 TWh and the import was 6.2 TWh. Most of the exported energy went to Finland and most of the import came from Norway. In total the electricity production in 2022 was 170 TWh, the division of which can be seen in figure 2. As can be seen, hydro power contributes the most to the Swedish electricity production, with 70 TWh. Nuclear power is the second largest power source with 50 TWh, followed by 33 TWh wind power. Other thermal power production than nuclear power generated 15 TWh of electricity. Lastly about 2 TWh was generated by solar power. Compared to previous years the electricity generation from both hydro power, nuclear power and other thermal power decreased slightly. Both wind- and solar power however increased their power production. Compared to 2021 the electricity generation from wind power increased with 20 % and for solar power the corresponding increase was 75 %. The electricity consumption in 2022 was 137 TWh [6].

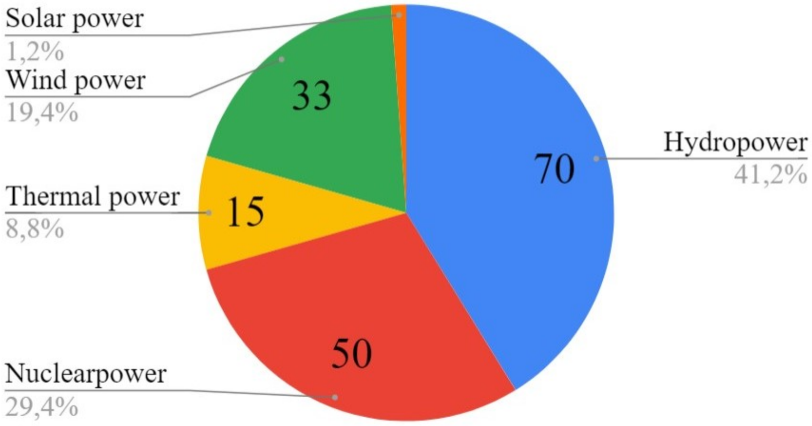


Figure 2: *Electricity production in TWh by type in Sweden 2022 [6].*

When it comes to internal electricity flows in Sweden, there is a general flow from north to south. This is a direct consequence of the fact that the electricity generation is higher than the consumption in SE1 and SE2, whilst the opposite is true for SE3 and SE4. This is partly because of the high amount of hydro generation in the north and because of the high population density in the south. Thus there is a surplus of electricity in the northern parts of Sweden and a shortage of electricity in the southern parts. [8]

### 2.1.2 Transfer capacities

The transfer capacity across a BZB describes how much electricity can be transferred over that border. In order for the transmission to be safe and reliable some constraints are placed on the magnitude of flow allowed in the power lines. There are several different types of transfer capacities in the power grid. The "total transfer capacity", TTC, refer to the physical transfer capacity of the line [9]. This takes thermal constraints, voltage limits and stability limits into account. Thermal constraints are imposed on the power lines both to ensure that there is no damage to the equipment, but also to avoid thermal expansion, which could cause the power line to sag. The voltage limit exists because all equipment connected to the transmission system is designed for a certain voltage and thus works best in close range to that voltage. Lastly, the stability limits are required to avoid large oscillations in for example frequency, since that could otherwise result in blackouts. There is also a risk for a phenomenon called voltage collapse if the voltage level drops too much. The TTC is thus the largest power transfer that the lines can be relied upon to deliver and that can be permitted without endangering the system stability. [9]

Another important term is the 'transmission reliability margin", TRM. This is a margin which is imposed in order to account for uncertainties in the TTC. The uncertainties can originate in both approximations, inaccurate measurements and in the need for spare transmission capacity in case of unforeseen events. The power flow might also take other routes during operation than expected, which can create a need for more transmission capacity [10]. The safety margin can vary depending on the direction of the transmission across a border [9].

By subtracting the TRM from the TTC, see equation (1), a new transfer capacity is acquired, the "net transfer capacity", NTC.

$$NTC = TTC - TRM \tag{1}$$

Figure 3: *NTC transmission capacities within, to and from Sweden in 2022. Translated version of figure from Svk [11].*

The NTC represents the maximum transfer capacity across a bidding zone border that is possible when safety margins are taken into account [9]. Since the safety margin can vary depending on the direction of the power transfer across a border, the NTC can can vary too [9]. This is the reason why for example the transmission capacity from SE3 to SE4 is not equal to the transfer capacity from SE4 to SE3 across bidding zone border 4, BZB4 for short. This is partly because the power production is lower in SE4 compared to SE3 [11]. The transmission capacities, NTC, between the four Swedish bidding areas and their surroundings are depicted in figure 3. From here on, whenever transmission capacities or transfer capacities are mentioned, these refer to the NTC.

### 2.1.3 Bottlenecks

Bottlenecks are locations in the power grid where the demand for transfer capacity frequently is larger than the available transfer capacity. In Sweden these bottlenecks have determined where the BZBs are located [5]. Since there are four bidding zones, there are three BZBs in Sweden, see figure 3. From north to south they are called BZB1, BZB2 and BZB4. For example it is common that the bottlenecks limit the transfer capacity from north to south, especially across BZB2 in Sweden [12]. This is due to the surplus of electricity in the northern parts in combination with the electricity shortage in SE3 and SE4 [5]. There is also a bottleneck for large power flows from east to west on a larger scale, mainly from Finland to Norway via Sweden [13]. This bottleneck has not yet resulted in a new BZB. As the power system grows and evolves over time old bottlenecks might disappear and new ones might be created [5].

Having bottlenecks and congestion in the power grid is a problem, seeing as electricity cannot flow where it is needed. This may result in a power shortage in a part of the grid if the demand is high but the available electricity is low [14]. In a worst-case scenario this could lead to a power outage or rolling blackouts. Grid congestion can also lead to curtailment of power, especially renewable power, if there is no need for it where it is produced, and there is not enough transfer capacity to transport it elsewhere [15]. Bottlenecks also effect the spot price of electricity, usually causing a higher price in the south of Sweden compared to in the north. However, since economy is out of scope in this report this will not be discussed further.

### 2.1.4 Power grid development

In order to handle future challenges, such as electrification of heavy industry and transportation and a higher share of intermittent power production, the power grid most likely will have to adapt. This adaptation might come both as an expansion of the transmission system, but also as a reinforcement of existing infrastructure. Current plans for changes in the transmission system in Sweden are presented in the *System Development Plan* issued by Svk [13]. The latest version of this plan consists of undertakings for the time period 2021 to 2031. In figure 4 the current and future transfer capacities are visualized, based on projects undertaken by Svk which increases the transmission capacity across the BZBs [12]. A positive capacity means capacity in the southward direction and negative in the northward direction. The blue bars represent the current transfer capacities, the red ones the transmission capacities added until 2035, and the yellow ones represent the transmission capacity added until 2045. The reinforcement of BZB2 takes place preliminary in 2040 and the reinforcement of BZB4 in 2026. For a more detailed description of the transfer capacities in and around Sweden, see table 15 in appendix A.

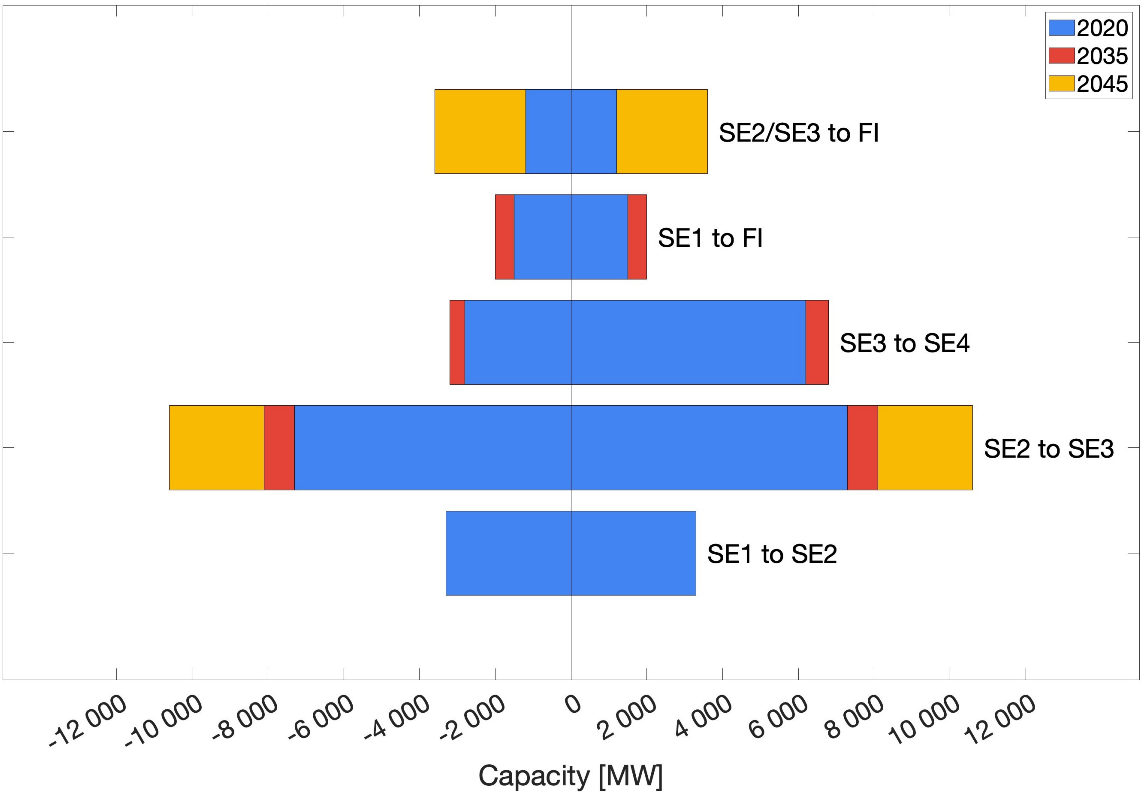


Figure 4: *Current and future transmission capacities across BZBs based on planned changes according to Svk [12].*

The *System Development Plan* also describes large general changes which the system has to undergo. One project that is of great importance for this work is the *North-south package*. The North-south package is the biggest investment package ever to be planned by Svk. Its purpose is to reinforce the transmission capacity from the north of Sweden to the south, particularly over BZB2. This is important since this section of the grid currently is a bottleneck. The package includes 2 000 km of new power lines. Another important development package is the *Electrification of industry* package, which aims at expanding the transmission system north of Luleälven in order to make way for new green industry, for example the HYBRIT project. Currently there is no transmission system in that area, and the regional distribution system is not dimensioned to handle the electricity demand from the new industry. There is also a project with the purpose to handle the bottlenecks in the power system for flows from east to west, and thus solving or decreasing the bottleneck problem that exists today. [13]

Offshore wind power is also treated in the *System Development Plan* from Svk. Up until September 2021 Svk had received requests for building new offshore wind power with a total installed power of 116 GW, with 9 GW in SE1, 14.5 GW in SE2, 34.4 GW in SE3 and 58.4 GW in SE4. Some of these projects consider the same geographic area, so even if all locations would be approved, the total sum of the installed capacity would not be 116 GW. However, considering that there was 11 GW wind power installed in 2021, the volume of requests for new offshore wind power, and thus the potential for new off shore wind power, is still large. [13]

Time is an important aspect when expanding the transmission system. From the point when a decision to build a new transmission line has been taken, it takes 10-12 years until it can be commissioned [12]. This is because the process includes consultations with local land-owners, the general public and authorities, seeking permits, which might include for example an environmental impact statement [16], and also agreeing on compensation for those who are affected by the new transmission line. Additionally, there is a need for detailed studies of for example geological conditions at the locations where the power line is to be built. It is not until after all of this that the power line can be built [17]. See figure 5 for a visual representation of the steps included in the process of building a new transmission line.

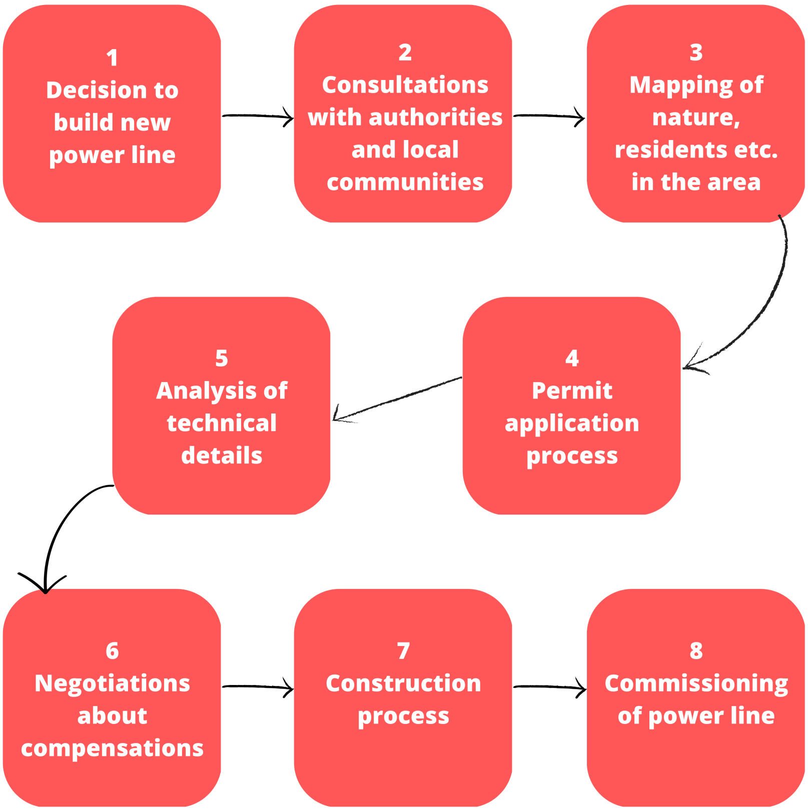


Figure 5: *Steps included in the process of building a new transmission line. Figure inspired by [17].*

## 2.2 Climate impact of power grid expansion

Building new transmission lines comes with both a carbon footprint and environmental impacts. However, to assess the climate impact of a new power line without considering the eventual positive impact from connecting renewable energy will make the carbon footprint for the power line seem larger than it is in a wider context. This is because the power line in itself does not contribute with any carbon saving aspects, but it is rather an essential part in an energy system where renewable energy can be connected [18].

When it comes to transmission grid expansion it is generally the extracting and processing of the materials which cause most of the carbon emissions. The construction phase, which includes transports, adaption of the site, for example felling of forest, and construction also causes a significant carbon footprint and environmental impact [19]. The life cycle climate impact for a 50 km long 400 kV overhead line with a lifetime of 40 years in the north of Sweden can be seen in figure 6 [20].

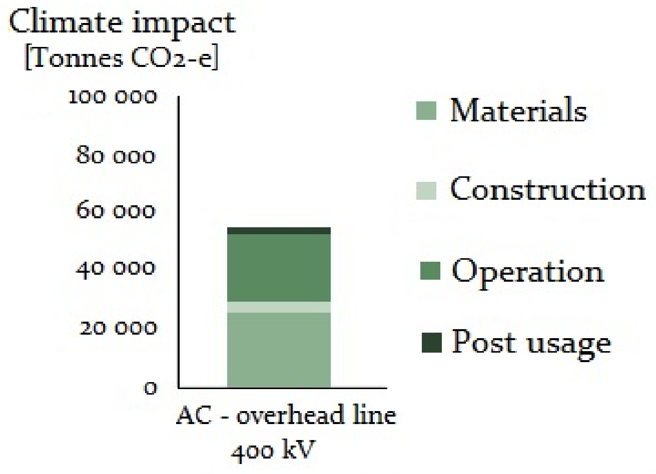


Figure 6: *Climate impact from a 50 km long AC overhead line from a life cycle perspective [20].*

It is evident in figure 6 that the materials and the operation phase contribute with the majority of the environmental impact for the 400 kV AC overhead line. The construction and decommissioning of the power line only have a minor impact compared to that. In total the carbon footprint is approximately 55 000 tonnes $CO_2$e for the 50 km overhead line. This gives a carbon footprint of 1 200 tonnes per km overhead line.

The level of recycling for components in overhead lines is in general high and most of the steel, copper, aluminium and lead in the line are recycled [20].

## 2.3 Scenarios

This section starts by explaining what a scenario is and what it is used for. Thereafter Svk is introduced together with two of the scenarios that they developed in their *Long term market analysis* from 2021.

### 2.3.1 The basics about scenarios

Scenarios are made-up versions of the future that can be either probable, possible or desirable. They can be used both as a way of making predictions of the future, but also as a tool to broaden the possibilities which are considered [21]. Scenarios based on the same information, but with different goals in regard to what questions they are meant to answer, can thus give very different outcomes. It is therefore important to know which type of scenario you are dealing with in order to interpret the results correctly. Also worth noting is that some scenarios might not be desirable at all, but rather show a direction of developments that should be hindered in order to avoid the problems attached to that particular path.

Developing scenarios of the future as a strategic planning tool has been a practice for a long time. The first known use of structured scenario-planning was used in the US military in the 1950s by Herman Kahn [22]. After this the use of scenarios to navigate the future spread to companies like Royal Dutch Shell, which started to use scenarios in 1965 through the initiative ‘Long-Term Studies” [21]. At Shell scenarios are not used to predict the future, but rather to make plausible scenarios that help the company to think outside the box and prepare for more than one version of the future [21]. The Swedish TSO, Svk, use scenarios in a similar fashion, to identify future problems and needs in the power grid [12]. Their scenarios pose as different possible development paths for the grid, where each path comes with its own challenges and opportunities. Thus, the scenarios presented in Svk:s Long term market analysis from 2021, LMA2021, are not forecasts of the future. They are tools which are used to take measures to counter future challenges that may occur in the grid [12]. Therefore, none of the scenarios presented by Svk will be a perfect description of the future.

### 2.3.2 Svenska kraftnät

Svenska Kraftnät is the Swedish TSO and is therefore responsible for the transmission system in Sweden [23]. This includes power lines with voltages of 400 kV and 220 kV, substations and connections to other countries [12]. To ensure that the transmission system is safe, reliable and cost effective are also responsibilities for Svk. In order to reliably provide electrical power, Svk makes sure that the balance between production and consumption of electricity is upheld at all times [23]. In addition to this Svk is also responsible for reaching targets set for energy and climate. To extend the transmission network and trading electricity with other countries are also some of their responsibilities [23]. The work towards reaching targets for climate and energy includes adapting and strengthening the grid so that it is possible to connect a large portion of renewable energy [23]. How the Swedish national electricity grid and the electricity mix will look in the long-term future is not clear. Because of this, Svk works with scenarios in order to prepare for different developments of the grid. The latest scenario work, published in 2021, includes four different scenarios for the future of the Swedish transmission system. Two of these four scenarios will be included in this work: *Elektrifiering förnybart*, translated to *Electrification renewable* and *Elektrifiering planerbart*, roughly translated to *Electrification dispatchable.* The starting point for these scenarios is the current state of power production in Sweden, which is presented in section 2.1.1.

#### Electrification renewable

Electrification renewable, EF for short, is a scenario developed by Svk that includes a steep increase in the amount of renewable electricity and a large expansion of green industry, especially in the north of Sweden. The large expansion of the industry is a consequence of the focus on producing and exporting products with a low carbon footprint. One example of this new industry is HYBRIT, which will produce fossil free steel by replacing coal and coke with hydrogen [24]. Thus, the integration between electricity, which is the primary energy carrier in this scenario, and the use of hydrogen will be extensive [12].

The electricity-intensive industry is assumed to follow roughly the same load profile as today. However, it is also assumed that some level of flexibility exists. This flexibility occurs due to a price-sensitivity where a part of the industry reduces its production, switches to another energy carrier than electricity or shuts down at electricity prices between 100-500 Euros/MWh. Flexibility is also added by the hydrogen storage that the fossil-free steel industry is assumed to keep, which has a capacity corresponding to seven days' needs. [12]

The electricity consumption per sector for the years 2020, 2035 and 2045 can be seen in figure 7. The year 2035 is included in all figures in this section to illustrate the gradual change in the power system, even if it is not included in the research question. It is evident that there is a substantial increase in the need for electricity in the industry from 2020 to 2045. Data centres and electric vehicles will also use more electricity in 2045 compared to 2020. The residential/service/transport area will however still have approximately the same electricity consumption in 2045 compared to 2020. When studying the losses in the system it is also clear that they increase. [12]

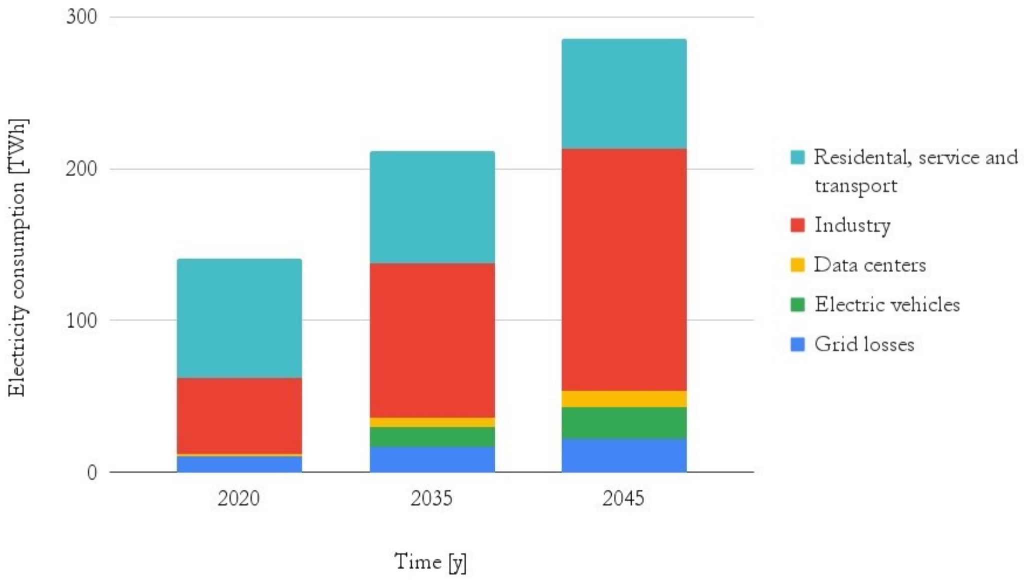


Figure 7: *Electricity consumption per sector for the years 2020, 2035 and 2045 for the Electrification Renewable scenario [12].*

In this scenario the Swedish nuclear power plants are taken out of service after a lifetime of 60 years, which means that the Swedish goal of a completely renewable electricity system year 2045 is reached. Off-shore wind power expands around all of Sweden, and land-based wind power is built mostly in the northern parts of the country, see figure 8 for installed production capacity. Solar power is built mostly in cities together with batteries. The large portion of wind and solar power in the power system however means that only 22% of the electricity production is dispatchable. Thermal power production will still be used, but decrease somewhat, due to reinvestments not being profitable. To compensate for this more residual heat will be used. [12]

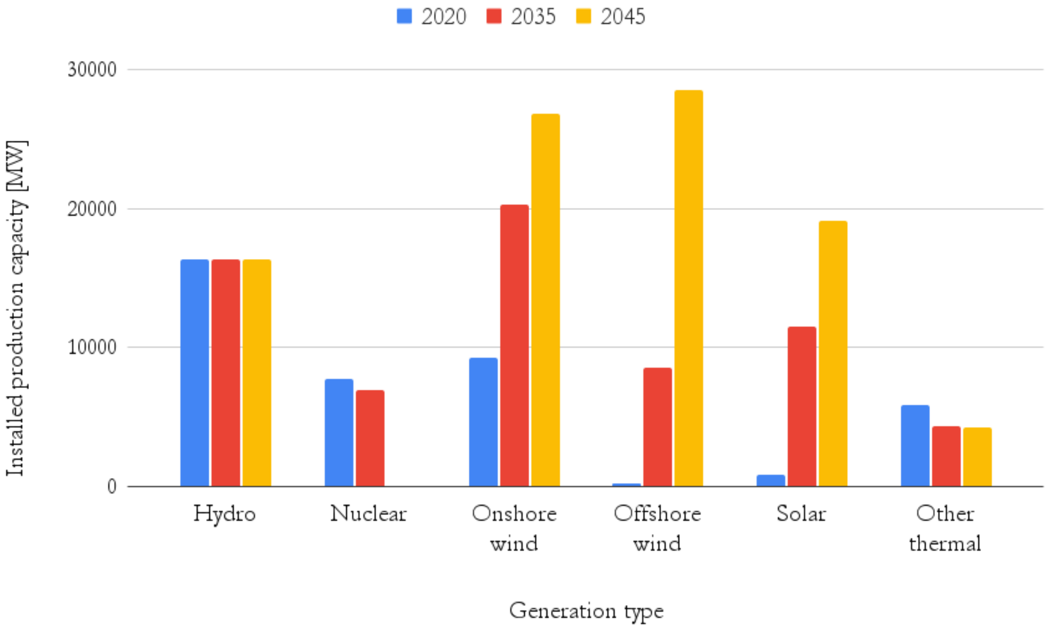


Figure 8: *Electricity generation from different power sources for the years 2020, 2035 and 2045 for the Electrification renewable scenario [12].*

The large share of wind and solar power production in this scenario in combination with an extensive electrification results in challenges for the power grid that to some extent do not exist today. For example, there will be hours where the electricity generation fails to meet the electricity demand and hours when the electricity generation is too high to handle without curtailment. The problem with a too high electricity generation will require new technology so that renewable power is not wasted. When the Swedish nuclear power plants are taken out of service to be replaced by solar and wind power, the number of synchronous generators connected to the grid decreases. A direct consequence of this is a lower system inertia, which poses a threat to the grid frequency stability. [12] This is a challenge with top priority at Svk and a lot of work is done to create a larger portfolio of frequency-related ancillary services[1] on the market. With a lower share of dispatchable electricity production, providing reactive power for voltage stability becomes another challenge. This calls for alternative providers of reactive power, such as HVDC lines and wind turbines [13]. The low share of dispatchable power production is assumed to put greater emphasis on the balancing abilities of hydro power, which will be utilized to a greater extent compared to today [12].

Today there is in general a flow of electricity from the north of Sweden to the south. This will partly change in scenario electrification renewable. Due to the large expansion of the industry in SE1, this area will switch from being a net exporter to a net importer of electricity already in 2035. SE2 will thus export electricity to the north. However, SE2 will continue exporting to the south to SE3. The flow between SE4 and SE3 will also change. There is a net import of electricity from SE3 to SE4 today, but in 2045 the situation is the reverse. [12]

**Electrification dispatchable**

Electrification dispatchable, EP for short, is a scenario with a steep increase in the use of electricity, where carbon neutrality is in focus rather than that the system is completely renewable. This means that nuclear power continues to be a part of the Swedish electricity mix. The lifetime of the current reactors is extended and new nuclear power is built. Small modular reactors are also introduced, since they gain political support. The continued operation of nuclear power means that Sweden does not reach its goal of a 100% renewable power system in 2045. The system will however be 100 % fossil free. [12]

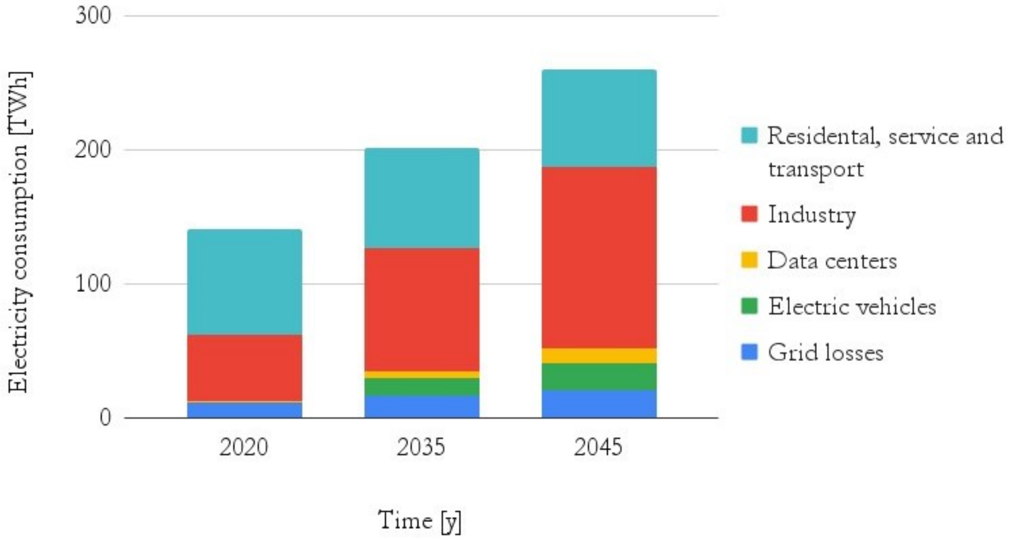


Figure 9: *Electricity consumption per sector for the years 2020, 2035 and 2045 for the Electrification dispatchable scenario [12].*

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[1] Ancillary services refer to operations, other than generation, which help to keep grid stability, for example frequency control.

Similarly to electrification renewable, this scenario includes a widespread electrification of the industry, though not as large as in electrification renewable. The focus on producing and exporting low-carbon products like green steel and cement is present in this scenario too. Electricity is the primary energy carrier, and there is an extensive integration between hydrogen and electricity. The transport and chemistry sectors are to a large extent electrified. This increase in the need for electricity in the industry can be seen in figure 9. It is also evident that the electricity consumption for the residential/service/transport area remains approximately the same as today in 2045. The electricity needed for electric vehicles and data centres increases. [12]

The expansion of solar power and wind power is large in this scenario, however not as extensive as in electrification renewable. This has to do with the fact that this scenario also utilizes nuclear power. The thermal power production will vary somewhat until 2045 but remain approximately the same as it is today. All together the renewable electricity production makes up 88% of the electricity production in 2035 and 89% in 2045. See figure 10 for installed production capacities for different power sources for years 2020, 2035 and 2045. [12]

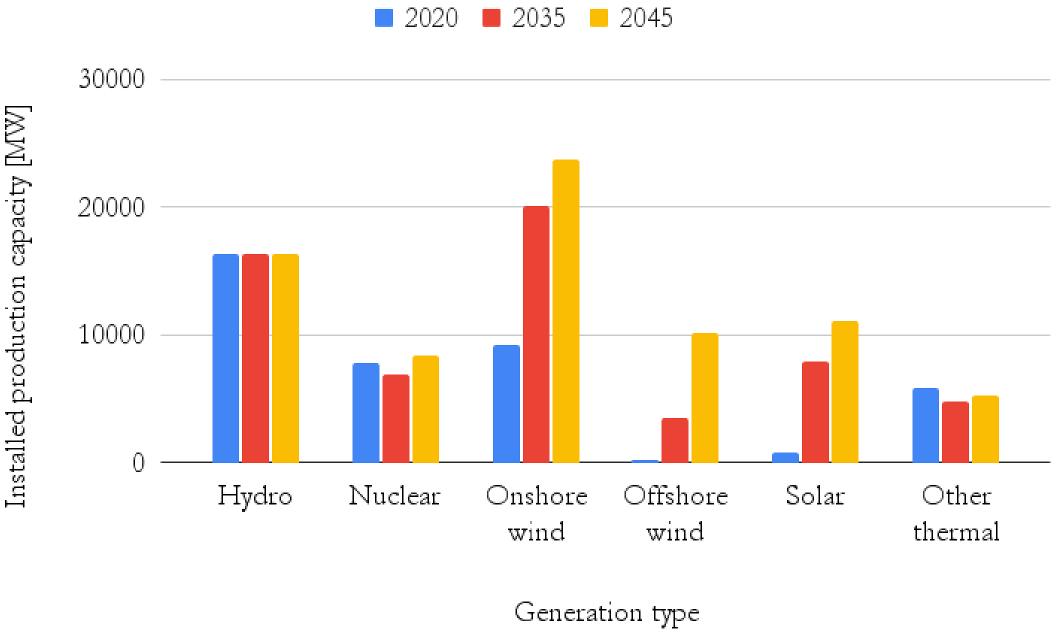


Figure 10: *Electricity generation from different power sources for the years 2020, 2035 and 2045 for the Electrification dispatchable scenario [12].*

The inclusion of nuclear power in this scenario entails that the share of dispatchable electricity production is 47% in 2035 and 40% in 2045. This higher share of dispatchable power production results in few hours per year with issues concerning the power balance. Local dispatchable power production in cities also contribute to this. A higher share of dispatchable power production also results in very little power being wasted due to a too high power generation. The availability of inertia is good, since both the hydro power and the nuclear power are contributing. [12]

The overall balance of where power is produced and consumed in the system is improved in this scenario compared to today, due to the increased electricity consumption in the north and the increased power production in the south. This especially improves the balance between the northern and the southern parts of Sweden. There is also a better balance between cities and rural areas, since dispatchable power production is installed in the cities. However, the steep increase in electricity use in SE1, largely due to the electrification of the industry, will cause a shortage of electricity there and therefore also higher prices compared to the rest of Sweden, which is unseen hitherto. [12]

### 2.3.3 Comparison to other scenarios

In the scenarios from Svk, the assumptions made regarding development in continental Europe and Great Britain are based on the scenarios in the *Ten year network development plan* from 2020, developed by ENTSO-E. Assumptions on the Swedish development presented in the LMA from 2021 is then used as input for the next Ten year network development plan for 2022. The results from the scenario electrification renewable in the LMA from 2021 are used as input to the *Nordic Grid Development Perspective*, which is a joint project by the Nordic TSOs consisting of a climate neutral future scenario for the Nordic countries [25]. Svk also base the analyses made in their national grid development plan on the work done in the LMA [12]. The scenarios produced by Svk are thus closely linked to the work done by TSOs in all of Europe. Scenarios for the future electricity grid in Sweden are also created by the industry and it can be of interest to compare assumptions, inputs and results from these. In Sweden, the most extensive work beyond Svk is published by the *Confederation of Swedish Enterprise*, *Svenskt Näringsliv* in Swedish, and in the section below follows a brief comparison to this.

**The Confederation of Swedish Enterprise**

The main difference between the analysis performed by the Confederation of Swedish Enterprise, CSE, and the one by Svk is the type of optimization method used. The purpose of the scenarios created by Svk was to gain information about how the system is best operated in each scenario and which challenges there are. The CSE on the other hand has performed a system cost optimization, which result in a suggestion on how to design the system to the lowest possible cost.

The two main scenarios presented by CSE are called *Teknikneutralt*, translated to *Technology neutral* and *100 % förnybart*, translated to *100 % renewable.* In both cases, the yearly electricity demand is set to 290 TWh for 2050. This is in the same order of magnitude as Svk assume for both the EF and EP scenarios, 298 TWh for EF and 282 TWh for EP. The scenario Technology neutral with lowest cost results in an energy mix of nuclear, hydro and onshore wind power. The scenario 100 % renewable with lowest cost results in an energy mix of hydro, onshore and offshore wind power, solar power, bio-based power and relies on hydrogen storages. The total installed generation capacity for Technology neutral is 58 GW and for 100 % renewable it is around 94 GW [26]. In comparison, Svk's EP and EF scenarios assume an installed capacity of 74 GW and 102 GW respectively in year 2050 [12]. In CSE's analysis the Technology neutral scenario is preferable cost wise to the 100 % renewable. One reason Technology neutral is the optimal solution is the huge grid investments needed to handle the power produced by renewables. The system also relies on import from neighbouring countries to account for the large variability. Thus, in the 100 % renewable scenario Sweden does not produce as much electricity as it consumes. This is because it is considered to be cheaper to import electricity from neighbouring countries than extending the renewable power production further than what is done. [26]

The respective scenarios from CSE and Svk are in many aspects comparable. Identified trends are mainly the same, with an increased demand from transport and industry, in particular the steel industry.

## 2.4 Simulation tools

Power systems are in general large and complex to model and analyse. The immense number of nodes and components in a detailed network model means that limitations in computational power must be considered when doing simulations. Simplified network models that still are detailed enough to capture the properties of the full actual network are needed. Nordic44 is one of these models, depicting the transmission network in the Scandinavian synchronous area, consisting of Norway, Finland and Sweden [27].

### 2.4.1 Nordic44

The precursor to the Nordic44 model was developed at The Norwegian University of Science and Technology, NTNU. The purpose of constructing the model was to study a new proposition regarding automatic generation control, which advocated for more HVDC connections between Norway and other Nordic countries. It started out as a 15 node model with 11 nodes in Norway and four in Sweden. The model then grew in steps, first to 18 then 23, until it consisted of 44 nodes with representation in Norway, Sweden and Finland. The first version of the Nordic44 model originated in the Nordic23 model and was developed by the company STRI and NTNU in the iTesla project for Statnett, however after this, the model has branched. After the iTesla Nordic44 model, there are six different versions of the Nordic44 model. This project originated in the NTNU branch of the Nordic44 model version. [27]

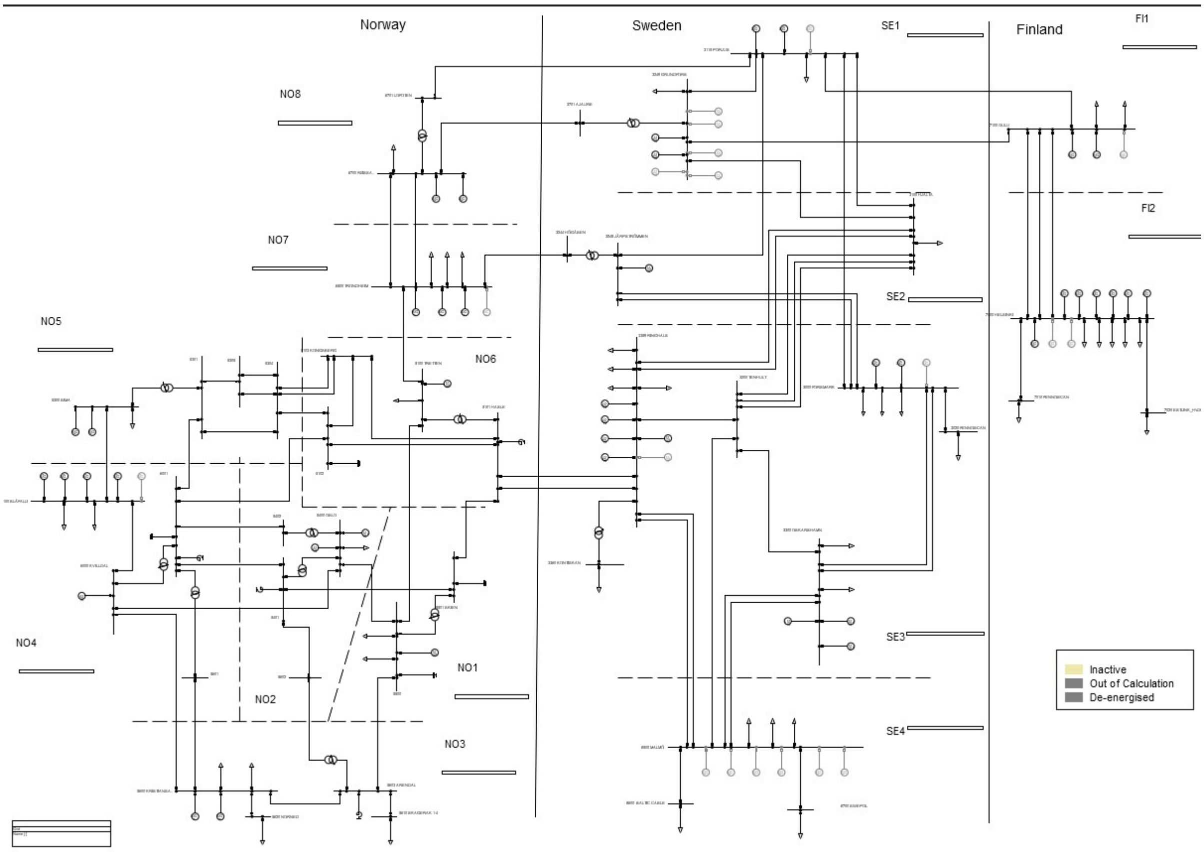
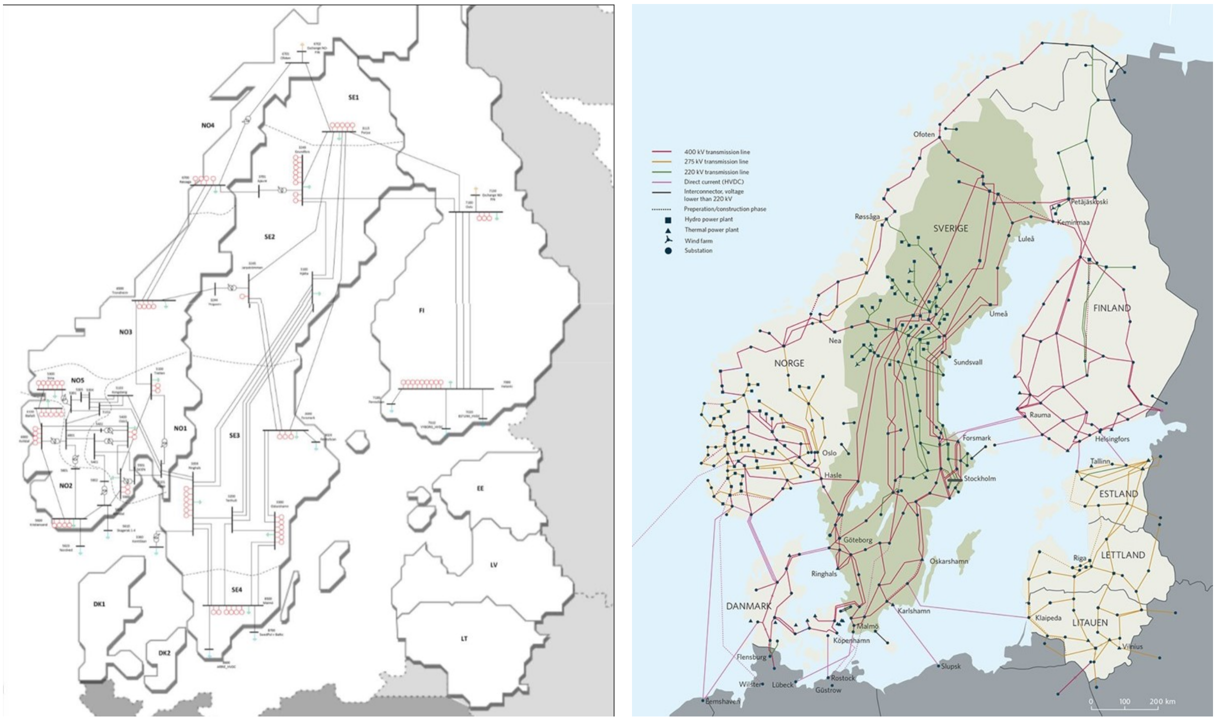


Figure 11: *The Nordic44 network model drawn as a single line diagram. Circles represent generators and triangles represent loads. A single load on a small node indicate a HVDC link. Bidding zone borders are indicated by dashed lines.*

The Nordic44 model as a single line diagram can be seen in figure 11 and as a geographically spread-out single line diagram in figure 12a. In figure 12 the Nordic44 model can be compared to the actual power grid in the Nordics. It is evident that the Nordic44 model is heavily simplified. It does however capture the most important properties of the actual system. In Sweden, the big nuclear power sites are represented as well as the hydro power generation in the northern parts. Distribution networks are modelled as loads. Connecting everything, there are power lines stretching from north to south. The voltage levels that are used are 420 kV and 300 kV.



(a) *The Nordic44 network model [28].*

(b) *The Swedish power grid [4].*

Figure 12: *Shows how the transmission grid is modelled in the Nordic44 model and what the real transmission system looks like in the Scandinavian area.*

The Norwegian part of the grid is modelled in more detail because the model is created at NTNU [27]. The Finnish part of the grid is only modelled by two buses in one bidding zone each, and the Danish bidding area DK2 isn't modelled at all. Since the Swedish bidding area SE4 was only modelled using one single bus, the DK2 area was probably not large enough to merit its own bus. Western Denmark is not modelled either, but this is due to it not being part of the same synchronous area as the rest of the countries. In the model, the Oskarshamn node serves as a swing bus. The HVDC links modelled in Nordic44 can be seen in table 13 in appendix A. They are modelled as a busbar with a load that can either produce or consume power to simulate import or export.

It should also be noted that the bidding areas in Nordic44 differ from the actual bidding areas for Norway and Finland. For example, in Nordic44 Finland is divided into two bidding zones, whilst in reality there is only one zone. How to convert between real bidding zones and bidding zones in Nordic44 can be seen in table 1.

Table 1: *Conversion table between real bidding zones and bidding zones in Nordic44.*

| **Real bidding zones** | **Bidding zones in Nordic44** |
|---|---|
| NO1 | NO1 + NO2 + NO6 |
| NO2 + NO5 | NO3 + NO4 + NO5 |
| NO3 | NO7 |
| NO4 | NO8 |
| FI | FI1 + FI2 |

### 2.4.2 PowerFactory

PowerFactory is one of the industry-leading software application used for analysing and simulating power systems. Some of the tools in PowerFactory are real-time simulations, load flow analysis and modal analysis. The load flow calculations determine how power flows in the electrical grid and tells the users for example which components are overloaded as well as the voltage at different buses. The active and reactive power flows through lines can also be acquired. It is also possible to run PowerFactory using Python scripts which can speed up and simplify iterative calculations [29]. PowerFactory is used to run simulations in the Nordic44 model.

## 2.5 Virtual power lines

In this section a technical description of a virtual power line is given, together with illustrations of how it works. Advantages of the technology are also mentioned, followed by the legal frameworks for using energy storage systems, ESSs for short, in the Swedish electricity grid.

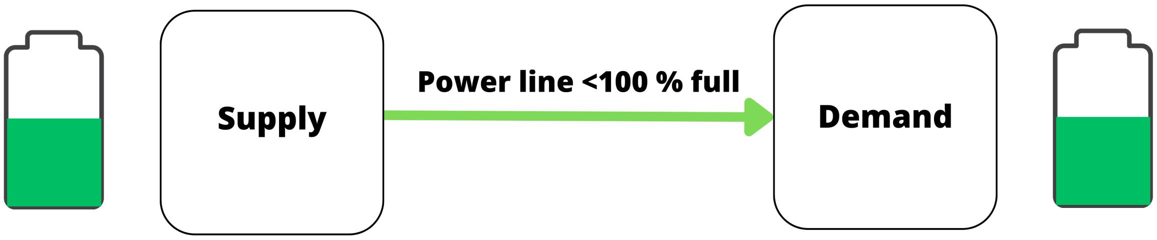
### 2.5.1 Technical description

*Virtual power lines*, or VPLs, are ESSs connected to the electrical power grid at two locations. They may for example be used as reinforcements of the grid or instead of an extension of the transmission network. They may be used as a temporary solution, for example during longer maintenance work or while waiting for a new power line to be built. It is common for one side to be a "supply-side storage" and for the other to be a "demand-side storage". Both ESSs are of the same size. The VPL mimics the behaviour of a power line by charging the supply side when the transmission lines connecting the two ESSs are congested and discharging when there is available transfer capacity. The ESS at the demand side then charges when there is available transfer capacity, and discharges during demand peaks. This technique can be used for enabling the integration of renewable energy into the grid without causing congestion. It is also a tool which can generally help to avoid congestion without having to change the balance between electricity generation and usage [30]. Since the supply and demand ESSs work inversely in sync, which means that the VPL does not move power in time. It can be seen as if X amount of power is added in one place and X amount of power is subtracted in another place, which means that +X-X=0, so there is no change in the power balance. Since the VPL does not move power in time it can be considered to be energy and power neutral. This also means that it does not affect the electricity market [31]. Sizes of current VPLs range from slightly over 10 MW to a couple of 100 MW [30].

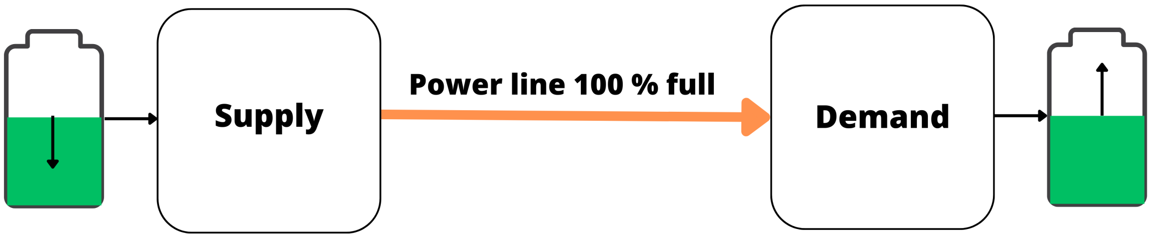
A study on how ESSs might increase the transmission capacity in the grid has been done by the company DNV on behalf of Svk. The overall conclusion from this work was that electrochemical ESSs are best suited for the task, especially lithium-ion batteries, also called Battery energy storage systems, BESS for short. It was also concluded that in some operating cases, especially during thermal overloading after an

N-1 case, ESSs increased the transmission capacity in the grid. [31]

A situation where the VPL can charge is illustrated in figure 13, both the way the system looks like without using the VPL, see figure 13a, and when the VPL is used, see figure 13b.



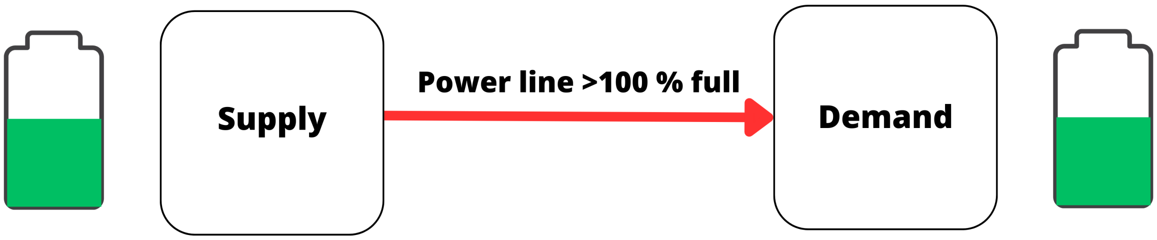
(a) *Power line is less than 100% loaded, and can be used to recharge the demand side BESS. Shows the transmission line as it would look if the VPL did not exist.*



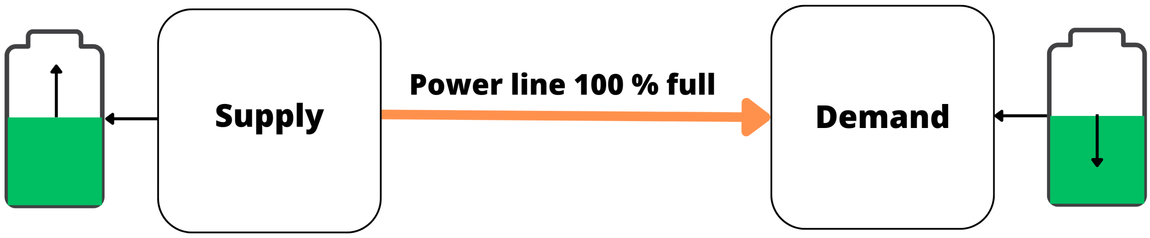
(b) *The demand side BESS is charging through the power line, using all available transfer capacity. The supply side BESS is discharging.*

Figure 13: *Shows the underlying grid conditions in a charging situation and the charging situation for a VPL.*

The situation when the VPL can discharge is shown in figure 14, both the way the system looks like without using the VPL, see figure 14a, and when the VPL is used, see figure 14b.



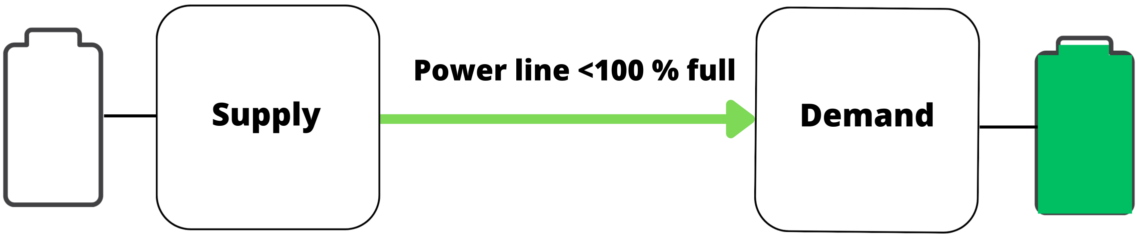
(a) *The power line is congested and needs to be relieved. Shows the transmission line as it would look if the VPL did not exist.*



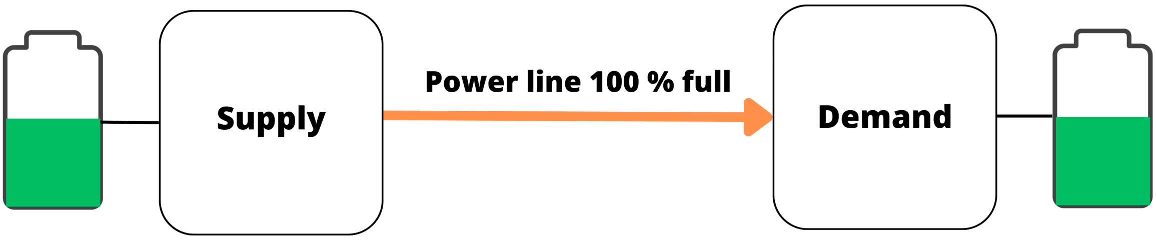
(b) *The demand side BESS is connected and discharges to the grid. The supply side BESS is charging. The VPL relieves the underlying grid, lowering the load on the line.*

Figure 14: *Shows the underlying grid conditions in a discharging situation and the discharging situation for a VPL.*

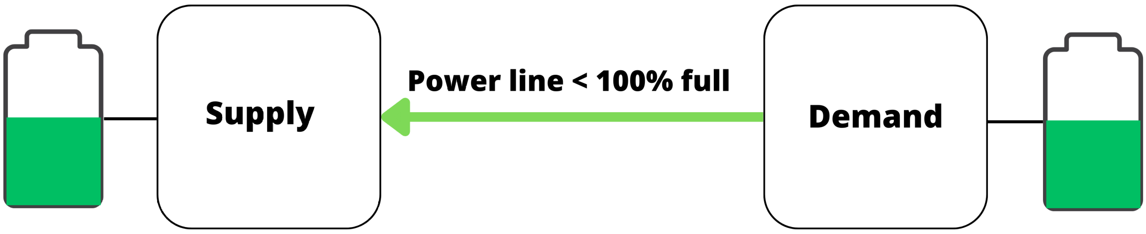
There are three situations in which the VPL does nothing, see figure 15. One is when the power line is not full, but the demand side BESS is already full, so there is no need for additional charging, see figure 15a. The second situation occurs in the event that the power line is precisely 100 % full, see figure 15b. In that case it is not possible to charge the demand side BESS, and there is no need for discharging the demand side. The last situation occurs when power flows in the opposite direction, thus towards the supply side, see figure 15c. Since it is desirable for the demand side to keep its state of charge until needed, the BESS will remain in standby.



(a) *VPL in the standby situation when the demand side BESS is already full and cannot charge anymore.*



(b) *VPL in the standby situation when the power line is full to exactly 100 %.*



(c) *VPL in the standby situation when the active power flow in the power line goes in the opposite direction compared to the VPL.*

Figure 15: *Shows the three standby situations which may occur for the VPL.*

The BESSs that are used in a VPL connected to the transmission system require a very fast response time, only parts of a second. Lithium-ion batteries have a response time of milliseconds and are therefore well suited for the task. In order to increase the transmission capacity in the grid the BESS also has to be of at least several 100 MWh size, which is possible with lithium-ion batteries [31]. One example of large BESSs used in both the ancillary services and energy markets is operated by ERCOT, the *Electric Reliability Council Of Texas*, which in February 2023 had installed BESSs with a total power rating of 3 014 MW. They're also planning to install a further 4 028 MW of BESSs by the end of 2023 [32].

A VPL can in theory be connected either directly over a transmission line or between two nodes between which there is no direct transmission line.

### 2.5.2 Advantages

There are several reasons why using VPLs as components in the transmission network is a good idea. Firstly, by using VPLs new capacity for electricity transmission can be made available faster compared to expanding or reinforcing the existing grid. It takes approximately 10 to 12 years for a new transmission line to be put into service in Sweden from the time when the decision to build it has been made [12]. Comparatively it takes approximately one to two years to implement a BESS based on lithium-ion batteries, if the permit process is not included [31]. Since large scale BESSs are not yet widely used, the permit process has not yet been extensively tried. However, as the BESSs are relatively non intrusive, the permit process should not be too complicated or time consuming [33]. The reason for the slow implementation process for transmission lines is the extensive permit processes that a new transmission line has to undergo [34]. That the permit process for transmission lines is demanding is partly because the line stretches over a lot of land, with different landowners and different types of nature or buildings, which require different levels of deference. There might also be issues with crossing waters. A BESS of 200-300 MW on the other hand could fit into the same space as a 600 m 220 kV power line [34] and does consequently not face many of the challenges posed to a transmission line. It is also common for the BESSs to be installed at substations, which in that case means that no new locations are needed [30].

The fact that BESSs are much smaller compared to many transmission line installations makes them more flexible in regard to scale and usage. It is possible to adapt the BESS to the conditions on site and even move to another location if there is no longer a need for the VPL. [34]

Another advantage of VPLs over ordinary transmission lines is that VPLs can provide ancillary services. These may include frequency control and system protection schemes. Since the VPL can provide reactive power it can also provide voltage control. Since the supply-side BESS can absorb power during hours when the electricity production on the supply side is higher than the available transmission capacity, the electricity can be accessed later, instead of being wasted. The need to redispatch[2] generation will thus decrease.

### 2.5.3 Legal framework

According to the *Swedish Energy Markets Inspectorate*, EI, it is stated that system operators are not allowed to own or operate ESSs unless they are fully integrated into the electricity grid or if the market has failed to provide the service in question. All exceptions are to be approved by the supervisory authority or fulfil a large number of conditions. It is not allowed for a network company to sell and buy electricity from a BESS in order to profit from it, since that affects the competition on the market. [35]

These legal frameworks may be interpreted to focus on moving electricity consumption in time, and thus affecting the electricity price. However, the framework is not specifically against moving electricity consumption in space, like what is done with VPLs. A VPL can be called “power neutral”, since it does not change the amount of power on the market at any given time and should therefore be possible to exempt from the rules against utility-owned ESSs. [31]

## 2.6 Batteries

In this subsection the technology used in lithium-ion batteries is briefly described. This is included in order to illustrate how the technology affects the lifetime and degradation of the batteries and hence also

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[2] Managing congestion by redispatch means to ramp down generators on the side of the congestion where the production is too large compared to the transfer capacity and simultaneously increasing the generation downstream the congestion.

the advantages and limitations of them. The climate impact is also presented, followed by an overview of the environmental impact of the batteries. Lastly, current recycling alternatives are presented.

### 2.6.1 Technology

Batteries are one of many possible ways of storing energy. The energy is stored as chemical energy within the battery. Since the conversion from chemical to electrical energy happens within the battery, a battery appears from the outside as storing electrical energy [36]. The most widely used battery technology today is lithium-ion [37].

Lithium-ion batteries work by creating an electrochemical potential between two sides separated by an electrolyte in a battery cell. By completing the circuit, this electrochemical energy can be released and used. To recharge the battery a voltage source is connected to force the electrons against the potential created by the battery's internal chemistry [38]. During the charging process, there is a risk of chemical compounds being created inside the battery cell. Compounds can also be created when the battery is completely discharged. These two processes are irreversible and help explain why the performance of a lithium-ion battery deteriorates with the number of charges cycles. [39]

The round trip efficiency of a BESS using lithium-ion batteries is typically around 85-95% [40]. Lithium-ion batteries have an energy to power ratio of between 1 to 2 MWh per MW and a space to power ratio of 4 to 20 $m^2$ per MW [31]. There are examples of BESSs of 100 MW that requires a space of 400-2000 $m^2$. As a comparison, a handball field is approximately 800 $m^2$. For further comparative context, lithium ion batteries used in many electric cars have a capacity of around 70-100 kWh [41], and the largest nuclear reactor in Sweden, *Oskarshamn 3*, has an output power of 1 400 MW [42].

The lifetime for a BESS is about 15 years, however after 8-15 years the storage capacity has decreased on average to 60-70 % of its original capacity. How fast this decline in capacity goes depends on the depth of the battery discharges, how many cycles that are used per day and how often the system is maintained. Increased depth in the discharges and many cycles per day will wear out the battery faster compared to few cycles with little depth due to the battery's chemistry mentioned earlier. Mechanical wear from wind and rain can affect the lifetime of a BESS as they are usually placed outside. Due to the decline in storage capacity there might be a need to either over dimension the system or replace some of the batteries if the storage is going to be in operation for many years. [31]

Lithium-ion batteries have a high technology readiness level, TRL for short, of level 9. The TRL describes the degree of maturity for a technology. The scale ranges from one, which is the lowest level and represents basic research, to nine, which means that the system is proven to work in an operational environment and that the system is competitive. The aim of the scale is to be able to compare the readiness of different technologies [43]. Lithium ion batteries also have a fast response time and the high energy capacity per square meter [31]. They are also suitable for a storage period of minutes to days, which is what is needed in a VPL. A more detailed comparison to other types of energy storage can be found in a report by DNV [31].

The market for lithium-ion batteries has boomed during the past decade, and prices plummeted with 85 % between 2009 and 2019 [44]. The installed grid connected energy storage capacity globally is expected to continue to grow from approximately 3 GW in 2020 to over 500 GW in 2045 [45].

### 2.6.2 Environmental impact

The majority of the lithium-ion battery production takes place in China, South Korea and Japan [46]. In all of these three countries, the electricity used for manufacturing lithium-ion batteries is to a large extent fossil based, which gives the electricity, and therefore also the batteries, a high carbon footprint. The carbon footprint in $CO_2$e/kWh for each of the countries electricity-mix is 555 g for China, 506 g for Japan and 500 g for South Korea [47]. As a comparison the carbon footprint for Swedish electricity is 12 g [47].

According to a Swedish literature study the carbon footprint of a lithium-ion battery lies somewhere in between 61 - 106 kg $CO_2$e per kWh battery capacity [48]. The large uncertainty is due both to the fact that the electricity mix in manufacturing varies in different countries and to the fact that little data from manufacturing is available for analysis. Approximately 50 % of the $CO_2$ emissions from the life cycle of the battery occurs in the manufacturing process [49]. In its new facility, the Swedish company Northvolt aims to produce lithium-ion batteries with a carbon footprint of 10 kg $CO_2$e/kWh in 2030, using 50% recycled materials and 100 % renewable energy [50]. Their ambition is to be able to recycle their own batteries in the factory in order to be used again in new batteries, but at the moment that is not the case.

It should also be noted that in order to produce lithium-ion batteries many different metals are needed, some which have an extraction process which is intrusive and harmful for the local environment. Lithium is one such example. The extraction process mainly takes place in Australia, Chile, China and Argentina [51]. Approximately a third of the global extraction takes place on salt flats in Chile and Argentina [52]. The process, also used in China, involves pumping salty water from brine reservoirs into ponds, where it remains for months until all the liquid has evaporated [53, 54]. What remains will be salt, containing among others, lithium [53, 54]. The extraction process requires large volumes of water, around 1 900 000 liter per ton lithium [53], which is a lot considering the dry climate of the salt flats of South America [52]. In Chile this process can consume 65% of the regions entire water resources, affecting surrounding nature in a negative way [53].

There are several examples of incidents with chemical leaching from lithium mines, contaminating the surrounding area and river water as far as 1 500 km down stream from the mine [53]. The increasing demand for lithium, due to a large extent to the increasing demand for lithium-ion batteries, also increases the drive for deep sea mining [46]. This type of mining is very harmful for biodiversity since the low level of nutrition in the deep seas leads to long recovery times, decades to centuries, for the species living there. The risk for biodiversity not only located in the direct area where the metals are extracted, but also in the surrounding area due to contaminated water. Restoring damaged areas is difficult, and it has not been established that it can be done satisfactorily [55]. There is little knowledge about the life in the deep seas, owing to the fact that they to a large extent are unexplored [56], however research suggests that the biodiversity is high [57].

There are of course many more examples of the environmental impacts of lithium-ion batteries, especially considering the extraction processes of other elements. These will however not be mentioned here, since most are of the same character as the issues mentioned above.

### 2.6.3 Recycling

When it comes to the recycling of worn-out lithium-ion batteries a common method is to melt the batteries in a furnace at high temperatures. The plastic, which is 40 - 50 % of the mass of the battery, is incinerated. The metals left after this process can be recycled through another process where solvents are used to leach metals from the original material after which they are recovered through precipitation reactions. Metals like lithium can be recovered through the last of these recycling processes, but usually not by the first. [58]

Mechanical recycling is also common. This includes all processes in which the battery is disintegrated and materials are sorted by physical properties, such as size, magnetism and water solubility. In most cases the material from the cathode can be removed and used directly, but the anode needs new lithium before it can be used in a new battery, since lithium degrades as the battery ages. Theoretically, all materials should be able to be recycled through this process. However the efficiency of this method is inversely proportional to the battery health, which means that the worse the battery health becomes, the worse the efficiency of the recycling process becomes. The same is true for the amount of lithium that can be recovered. For the method to reach a high efficiency it also needs to be specifically adapted to the combination of materials found in the cathode, which means that it will not work well on all batteries. [58]

Different recycling methods can be combined in order to recycle a higher percentage of the battery. For example, 80 % of a battery can be recycled by combining the mechanical and leaching recycling processes [59]. In general however, recycling lithium-ion batteries is hard, and no method provides pure and separated materials, which can easily be used to manufacture new batteries [58].

# 3 Method

The method is described in chronological order as to how it was implemented, starting in data description and pre-processing and moving onward to describe the changes made to the model and how the simulations were carried out.

## 3.1 Description of data

The data that is the backbone of this work originates in Svk's Long term Market Analysis from 2021, the LMA, where Svk through the use of scenarios, have constructed versions of the future electrical system and its utilization in Sweden. Svk provided data for electricity consumption and generation with hourly resolution for all scenarios. Since the majority of the electricity produced in the future is expected to come from weather-dependent sources, Svk has produced data series with hourly values for 35 different so called weather years, resulting in 305 760 individual values for consumption and generation for each scenario. The different weather years are created by looking at historical weather measurements spanning from 1986 to 2021 and scaling weather dependent production accordingly.

In the results section of this thesis work the simulation results will be compared to the LMA data. The purpose of this work is not to perfectly replicate the results from the LMA, hence the purpose of this comparison is merely to make sure that the PowerFactory model gives reasonable outputs.

## 3.2 Data pre-processing

The data from Svk is represented in the categories seen in table 2 in rows 1 to 9 for each bidding area in the Nordic power system.

Table 2: *The categories into which the data from Svk is divided are presented in rows 1 to 9. Columns 10 to 12 are the results of the data pre-processing.*

| Column index | Category | Explanation |
|---|---|---|
| 1 | Consumption | Electricity consumption + flexibility |
| 2 | Hydro | Hydro power production |
| 3 | LoadCurtail | Demand flexibility at certain price levels |
| 4 | Nuclear | Nuclear power production |
| 5 | othThermal | Thermal power production (not nuclear) |
| 6 | Price | Electricity prices |
| 7 | RES | Solar and wind power production |
| 8 | RESCurtail | Curtailed wind and solar production |
| 9 | Residual | Electricity production minus solar and wind power production |
| 10 | Offshore wind power | Offshore wind power production |
| 11 | Onshore wind power | Onshore wind power production |
| 12 | Solar power | Solar power production |

The category named RES (renewable energy sources) includes both wind and solar power. In order to properly see the effect of different renewable energy sources these need to be handled separately. A script for dividing the aggregated RES data has been developed by Henrik Nordström [60] and is used to gain the desired resolution. The script utilizes data on installed capacity and load factors for the different renewables to split the RES data in a proportional way according to equation (2). Capacity factors, $\mathrm{CF}_{\mathrm{type}}$, are obtained from the Pan-European Climate Database [61]. The share of total installed capacity, $\mathrm{share}_{\mathrm{type}}$, is calculated from capacities for the year of interest obtained from the LMA and Nordic grid development perspective [25]. The script results in an addition in table 2, see rows 10 to 12, which corresponds to offshore wind power, onshore wind power and solar power.

$$\text{Energy share}_{\text{type}} = \text{RES} \cdot \frac{\text{CF}_{\text{type}} \cdot \text{share}_{\text{type}}}{\text{CF}_{\text{PV}} \cdot \text{share}_{\text{PV}} + \text{CF}_{\text{offshore}} \cdot \text{share}_{\text{offshore}} + \text{CF}_{\text{onshore}} \cdot \text{share}_{\text{onshore}}} \tag{2}$$

To limit execution time since many simulations had to be run, only three of the previously mentioned 35 weather years are chosen to be the basis for all the simulations. Choosing three weather years is done by examining the total number of overloaded hours over all bidding zone borders. One year with the maximum number of overloaded hours is chosen along with one with the minimum number of overloaded hours and one with an average number of overloaded hours.

## 3.3 The Nordic46 model

The Nordic44 model need some modifications to better represent the current and future transmission system presented in the scenarios from Svk. Several changes are made to more accurately accomplish this, and these are described below. Firstly, new loads are introduced to represent HVDC links. All these loads end with number 5, see table 12 in appendix A. They are placed on separate buses in order to be more visible in the system. In the cases where two different HVDC-buses are connected to the same parent bus, the two loads are placed on one of the HVDC-buses. The empty bus is then removed. Some new HVDC links are added to the model to gain resemblance with reality. A list of the HVDC links present in the updated Nordic44 model can be found in table 3. For a more detailed description of the changes made to the HVDC links see table 14 in Appendix A. Since the model now contains 46 nodes it will from here on be referred to as the Nordic46 model.

Table 3: *List of all the HVDC-links in the updated Nordic46 model.*

| **Parent node** | **HVDC-node** | **Represents** |
|---|---|---|
| 7000 | 7010 Fennoskan + Estlink | Fennoskan and Estlink |
| 8500 | 8600 South | Baltic cable, Swepol and Nordbalt |
| 5600 | 5620 NO2South | NorNed and Nord.Link |
| 5300 | 5310 NO5GB | HVDC link between Norway and Great Britain |
| 6000 | 6010 North Sea link | North sea link |
| 3100 | 3110 Fennoskan 3 | Fennoskan 3 Swedish side |
| 7100 | 7110 Fennoskan 3 | Fennoskan 3 Finnish side |

The second change is that one of the nodes is redefined as to where it is geographically located. Grundfors is marked to belong to SE1 in the Nordic44 model in which this work originated, though in reality Grundfors lies in SE2. SE2 is also the area in Sweden which has the highest generation of hydro power, but in the unchanged Nordic44 model there is only one generator in SE2. SE1, in comparison, has 10. Another reason supporting the relocation of Grundfors to SE2 is the fact that there should be power lines connecting SE2 and NO8, which is not the case unless Grundfors is moved. Placing Grundfors in SE2 is thus truer to reality, both in terms of geography and in terms of the hydro power production, compared to letting it remain in SE1.

In order to be able to include renewable power production in the simulations, wind generators and PV-systems were added to every node in the system that originally had either loads or generation. Onshore and offshore wind generation are represented by wind generators in the Nordic46 model. Solar generation is represented by PV-systems. A list of the nomenclature of loads and renewable generation in Nordic46 can be found in table 12 in appendix A.

When it comes to the loads, two loads were added to all buses to which renewable generation was previously added. Consumption is assigned to one single load named "lod_*busnumber*_1" representing all consumption occurring at that node. One load named 'lod_*busnumber*_6" is also added to be able to handle curtailment of renewable production.

To update the transmission capacity in the model to better resemble the future Swedish power system, see figure 4, additional 400 kV lines are added over some of the BZBs. This is done by increasing the number of parallel lines from 1 to 2 or 3 on some of the power lines. Parallel lines are added to the power lines listed in table 16 in appendix A for the year 2045 in order to best match the transmission capacities listed in table 15 also in appendix A. The number of power lines across each BZB in and from Sweden before and after the changes to the Nordic46 model are listed in table 4. These are the full capacities and will not be used for all simulations, see section 3.4.4.

Table 4: *Number of power lines across BZB in the Nordic46 model compared to the Nordic44 model.*

| **Bidding zone border** | **# power lines in Nordic44** | **# power lines in Nordic46** |
|---|---|---|
| BZB1 | 4 | 7 |
| BZB2 | 8 | 16 |
| BZB4 | 5 | 10 |
| SE1 → FI | 2 | 3 |
| SE1 → NO4 | 1 | 2 |
| SE2 → NO4 | 1 | 2 |
| SE2 → NO3 | 1 | 1 |
| SE3 → NO1 | 2 | 2 |

When it comes to the electricity production all generators that were present in the model from the start are kept. Synchronous compensators are also added to help keep up the voltage at some buses, for example in Tenhult and Hjälta where they are only adding reactive power. A complete list of added synchronous compensators can be found in table 5.

Table 5: *Synchronous compensators added to Nordic46.*

| **Name** | **Bidding zone** | **Location** |
|---|---|---|
| sym_3100_12 | SE2 | Hjälta |
| sym_3200_12 | SE3 | Tenhult |
| sym_3603_12 | NO2 | Arendal |
| sym_5101_12 | NO1 | Hasle |
| sym_5304_12 | NO5 | Bus 5304 |

Virtual Power Lines were added to the Nordic46 model by utilising a pair of PowerFactory load-objects, for locations see section 3.4.4. One load was placed at the demand side of the VPL and one at the supply side. These could then be run in sync through a Python script so that if one load consumed power, the sign would be flipped on the other, making it in practice produce power. Keeping track of charge levels, battery capacity and charge- and discharge-schedules was done exclusively through a Python script.

The ESS chosen for the VPLs is lithium-ion batteries. The reasons for choosing lithium-ion batteries for the electricity storages in the VPLs are above all the high TRL level (level 9), but their energy rating, fast response time and suitable optimal storage period were also considered. After some initial trial and error simulation experiments, the default energy rating of the BESS has been chosen to be 5 000 MWh and a power rating of 5 000 MW.

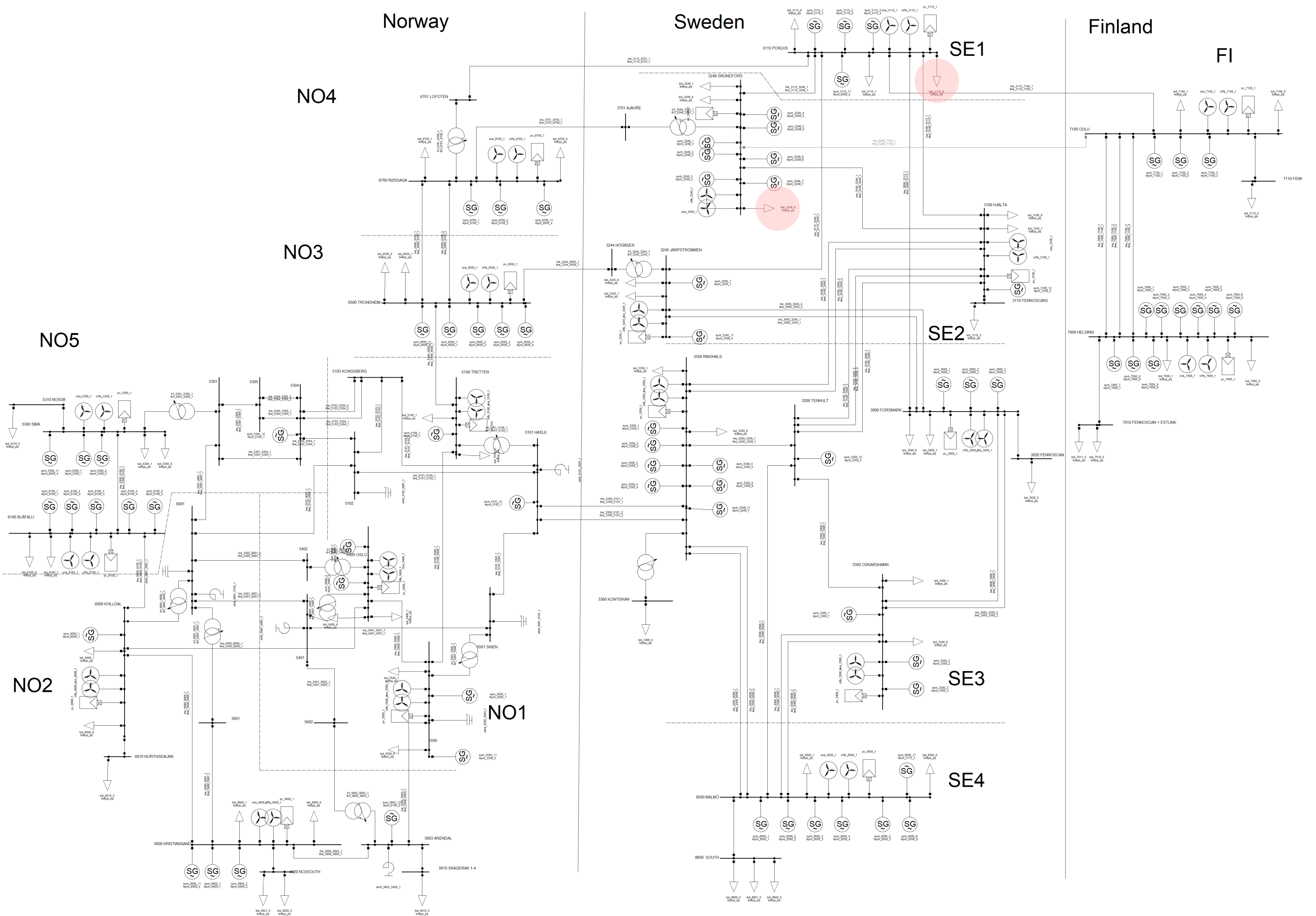

Figure 16: *The Nordic46 model. Wind power, solar power and new synchronous generators are added. HVDC links are updated. The number of loads on each bus is adjusted to 2. An extra load can be found on Porjus and Grundfors representing VPL1, marked with red circle. The bidding zones are updated to match the real ones.*

A picture of the updated Nordic46 model can be seen in figure 16. In the picture VPL1 is included across BZB1, between Porjus and Grundfors, the two upper nodes in Sweden. The bidding zones have been changed to match the real ones.

## 3.4 Simulation process

Instead of running PowerFactory through the graphical user interface, some tasks can be automated and sped up using Python scripts[3]. The amount of consecutive load flows executed to obtain results in this work was made possible by using the Python interface. A Python script was written to assign values to generation and consumption, execute a load flow calculation and then save the results. In the script this was done by iterating through all the hourly values that came out of the pre-processing. Highlights from the Python code for the main script can be found in appendix B, and the complete code can be made available upon request. The Python code exports the data to csv-files. These files are then analysed in Matlab.

### 3.4.1 The main Python script

The structure of the main Python script can be seen in figure 17.

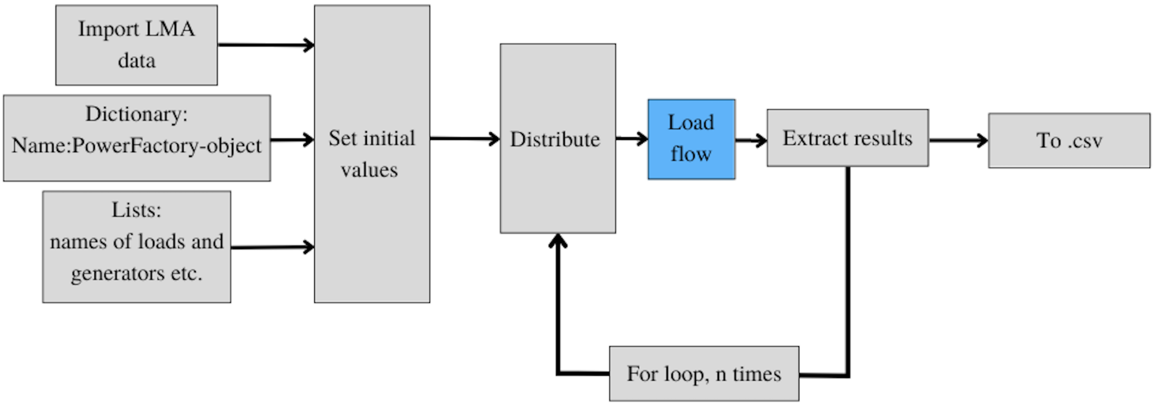

Figure 17: *The structure of the main Python script.*

Reading from left to right, top to bottom in figure 17, the first box is the one called “Import LMA data”. First the program imports data from csv-files that store the different amounts of consumption and generation in the different bidding areas, with an hourly resolution. The next box is the one called “Dictionary: Name:PowerFactory-object”. The object that is subject to change in PowerFactory has to have a connection with its name, which is done by arranging a dictionary of name:PowerFactory-object-pairs. Lastly, the box named “Lists: name of loads and generation etc” is the part of the program where lists of every consumption load and generation object in the Nordic44 model are listed.

These three parts are combined to first set the initial values for a load flow. After that, the first set of values are loaded into PowerFactory where they are distributed in the Nordic46 model to their corresponding objects. The distribution is done by going through the list of generation and consumption objects and assigning them the correct value from the imported set of pre-processed scenario data through the use of the dictionary. A more detailed description of the distribution can be found in 3.4.2. Once loaded in the model, a load flow calculation is carried out in PowerFactory, indicated with a blue box in figure 17 and the relevant parameters are saved and stored within the program. The loading of values and load flow calculations are repeated as many times as needed (in the magnitude of thousands of times) before the program terminates by writing the relevant values for every load flow calculation to a csv file that can later be processed.

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[3] PowerFactory version 2022 SP1 is used together with Python version 3.9.

### 3.4.2 The distribute function

Since the LMA data are already divided into separate bidding zones, there is only a need to distribute the generation within each bidding zone. This is done by dividing the total electricity generation for the specific type of power with the number of generators for that type of power, see equation (3). Thus equation (3) is used once for hydro power and once for nuclear power plus thermal power for each bidding area. Since the majority of the bidding zones only has one busbar with generation, this method is deemed sufficient. In addition to this, in areas with more than one busbar with generation, there is a difference in the number of generators connected to each of the busbars. This difference will thus make sure that more generation is allocated to a busbar with more generators. In for example SE3 this means that Ringhals will produce more electricity than Oskarshamn.

$$Electricity_{production} = \frac{Tot\ generation\ in\ bidding\ zone}{Number\ of\ generators} \tag{3}$$

The same approach is used when distributing the remaining data, for example renewable generation, consumption etc. However, since there is only one of each component on each busbar this means that the data will be distributed equally between all the busbars in a bidding zone. This rough division means that for example the offshore wind generation in SE2 is divided equally on buses Hjälta, Grundfors and Järpströmmen, even though some of them are not located by the coast. Since it is only the total power flow across each BZB that is studied, this simplification is not deemed to affect the results significantly.

### 3.4.3 VPL

In order for the VPL to know whether to charge or discharge, simulations were carried out first without VPLs, so that these results could be used as a perfect forecast of the electricity consumption and production for the studied time period. The aim is to remove all overloads, and not to reduce the maximum power of the overloads. In the Python script a loop goes through a list of VPLs, which contains information about which side is the demand side and which is the supply side, if the VPL is north-going or south-going, and which BZB it crosses. The VPL is then controlled through a series of logical if and else statements, see figure 18. The first condition separates north-going VPLs from south-going VPLs. After that the direction of the flow the current hour is identified and flows going northward are separated from those going southward. If the flow of active power goes in the same direction as the defined direction of the VPL, more conditions are used to determine what happens. If instead the active power flow and the defined direction for the VPL are opposite, nothing happens.

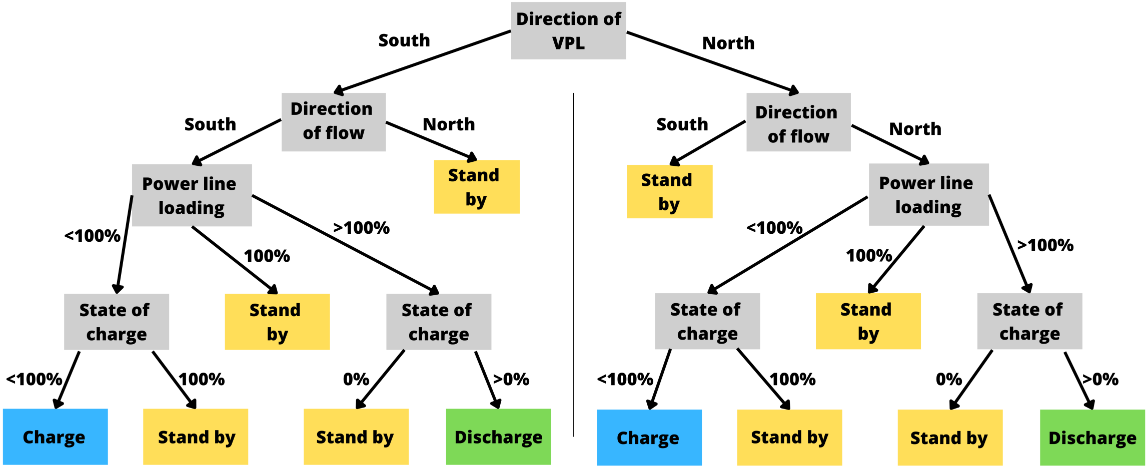


Figure 18: *Flowchart showing the control of a VPL based on the demand side BESS.*

When the active power flow across the BZB and the defined direction of the VPL are the same there are three situations which must be taken into account. The first is when the active power flow is lower than the maximum transfer capacity. In this case two things can happen. If the demand side BESS in the VPL is less than 100 % charged, the available transfer capacity over the BZB can be used to charge the demand side battery. The amount of charging that can be done is limited both by the available transfer capacity and by the empty capacity of the demand side battery. If instead the BESS is completely charged nothing happens.

The second situation occurs when the active power flow across the BZB is exactly equivalent to the maximum transfer capacity. In that case, nothing happens. The third and final situation occurs when the active power flow across the BZB is larger than the maximum transfer capacity. In that case two things can happen. If the demand side BESS is uncharged, nothing happens. If instead the BESS on the demand side of the VPL is charged, it will discharge to relieve the power lines across the BZB. Whether it is discharged fully or partly is determined by comparing the size of the overload with the available energy in the battery. The opposite will happen to the supply side battery.

### 3.4.4 Chosen simulations

In order to cover both geographical and size differences of the VPLs, 27 different simulations are carried out for each scenario. One extra simulation is also done for scenario EP, which is explained at the end of this section. All simulations carried out are summarized in table 7. The base simulation is a VPL with one demand and one supply side BESS of 5 000 MWh and 5 000 MW each. This case is used over every power line in the Nordic46 model which connects two adjacent Swedish bidding zones. In total there are nine of these, three across each BZB, see table 6. Unless specifics are stated, there is a 1:1 ratio between the energy and power ratings of the BESSs, meaning 1 MWh correspond to 1 MW.

Table 6: *The nine different VPLs that are used throughout the simulations.*

| **VPL number** | **BZB** | **Demand side** | **Supply side** | **Direction** |
|---|---|---|---|---|
| 1 | 1 | Porjus | Grundfors | North |
| 2 | 1 | Porjus | Järpströmmen | North |
| 3 | 1 | Porjus | Hjälta | North |
| 4 | 2 | Forsmark | Järpströmmen | South |
| 5 | 2 | Ringhals | Hjälta | South |
| 6 | 2 | Tenhult | Hjälta | South |
| 7 | 4 | Oskarshamn | Malmö | North* |
| 8 | 4 | Ringhals | Malmö | North* |
| 9 | 4 | Tenhult | Malmö | North* |

* The direction of this VPL is reversed for the scenario *Electrification dispatchable*.

A graphical representation of the VPLs all at once in a single line diagram can be seen in figure 19. The direction of flow in the Nordic46 model is always defined as positive in the southbound direction.

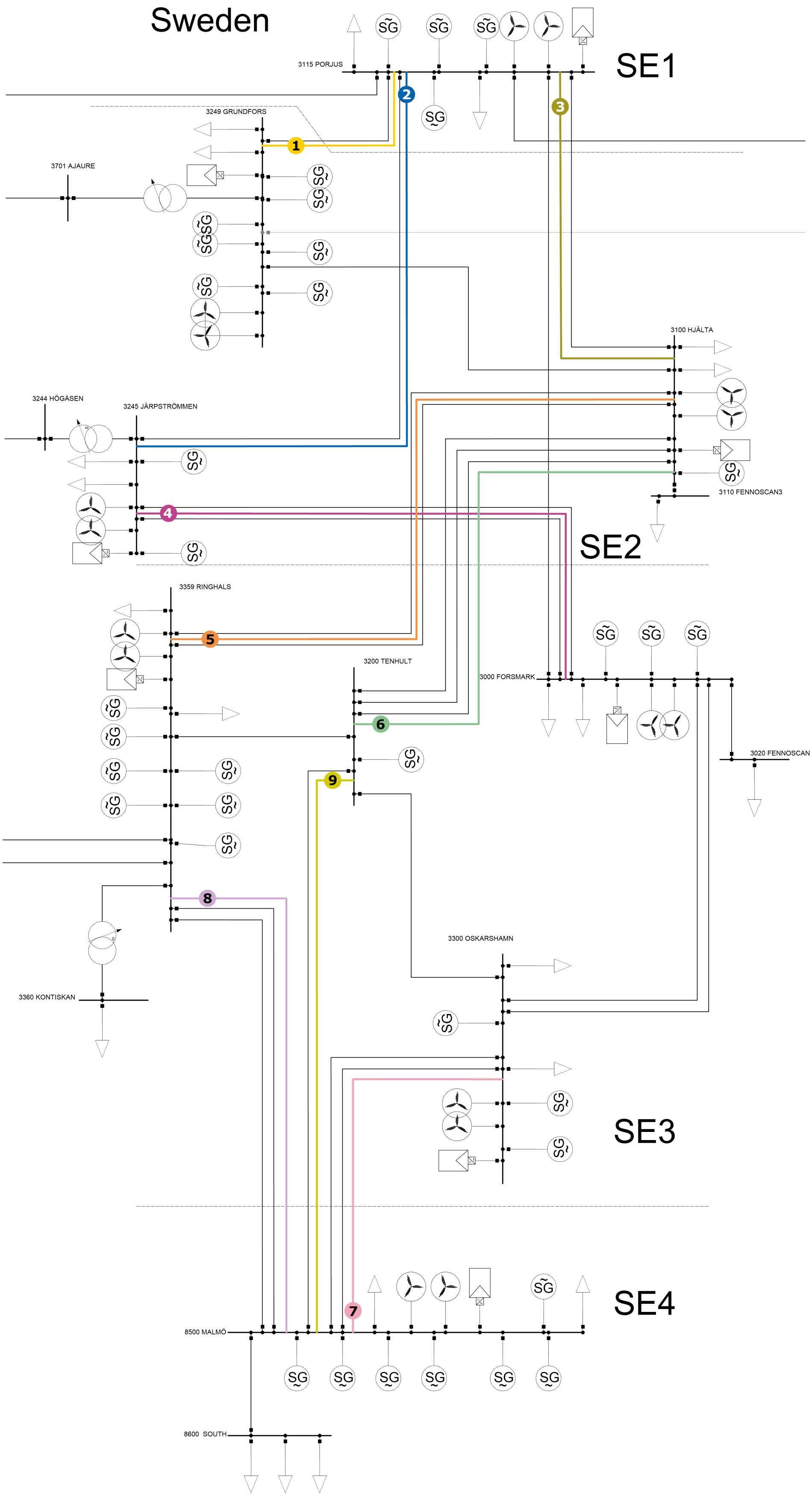


Figure 19: *The nine different colours shows the nine different locations of the nine VPLs in the Nordic46 model. The numbers indicate the number of the VPL. There is one BESS at the end of each coloured line.*

In order to create situations in which VPLs are needed over BZB2 and BZB4, two cases are created: Case2 and Case4. Case2 represents a situation where the reinforcement of BZB2, which is to take place preliminary in 2040, is delayed, and thus not in place in 2045. The transfer capacity across BZB2 is thus in Case2 8 100 MW instead of 10 500 MW. Case2 is applied to all simulations with an active VPL across BZB2. Case4 represents a situation where the reinforcement of BZB4, which is to take place in 2026 is cancelled. The transfer capacities will then be 6 200 and 2 800 MW instead of 6 800 and 3 200 MW north-going/south-going. See figure 4 for reference. Case4 is applied to all simulations with an active VPL across BZB4.

Table 7: *A list of all simulations for both the EF and the EP scenario.*

| **VPL** | **BZB** | **Energy rating [MWh]** | **Power rating [MW]** | **Simulated for scenario** |
|---|---|---|---|---|
| 1 | 1 | 5 000 | 5 000 | EF, EP |
| 2 | 1 | 5 000 | 5 000 | EF, EP |
| 3 | 1 | 5 000 | 5 000 | EF, EP |
| 1, 2, 3 | 1 | 1 667 | 1 667 | EF, EP |
| 1 | 1 | 5 000 | 500 | EF, EP |
| 1 | 1 | 5 000 | 250 | EF, EP |
| 1 | 1 | 10 000 | 10 000 | EF, EP |
| 2 | 1 | 10 000 | 10 000 | EF, EP |
| 3 | 1 | 10 000 | 10 000 | EF, EP |
| 4 | 2 | 5 000 | 5 000 | EF, EP |
| 5 | 2 | 5 000 | 5 000 | EF, EP |
| 6 | 2 | 5 000 | 5 000 | EF, EP |
| 4, 5, 6 | 2 | 1 667 | 1 667 | EF, EP |
| 4 | 2 | 10 000 | 10 000 | EF, EP |
| 5 | 2 | 10 000 | 10 000 | EF, EP |
| 6 | 2 | 10 000 | 10 000 | EF, EP |
| 7 | 4 | 5 000 | 5 000 | EF, EP |
| 8 | 4 | 5 000 | 5 000 | EF, EP |
| 9 | 4 | 5 000 | 5 000 | EF, EP |
| 7, 8, 9 | 4 | 1 667 | 1 667 | EF, EP |
| 7* | 4 | 1 000 | 1 000 | EP |
| 7 | 4 | 1 000 | 1 000 | EF, EP |
| 8 | 4 | 1 000 | 1 000 | EF, EP |
| 9 | 4 | 1 000 | 1 000 | EF, EP |
| 1, 6 | 1<br>2 | 5 000<br>5 000 | 5 000 | EF, EP |
| 1, 9 | 1<br>4 | 5 000<br>5 000 | 5 000 | EF, EP |
| 6, 7 | 2<br>4 | 5 000<br>5 000 | 5 000 | EF, EP |
| 1, 6, 7 | 1<br>2<br>4 | 5 000<br>5 000<br>5 000 | 5 000 | EF, EP |

* This simulation is done with full transmission capacities over BZB4, thus without Case4.

In addition to the simulations with BESSs with an energy rating of 5 000 MWh, simulations with BESSs with an energy rating of 10 000 MWh are carried out for VPLs 1 to 6, and simulations with BESSs with an energy rating of 1 000 MWh for VPLs 7 to 9, see table 7. Simulations where all three VPLs crossing the same BZB were used at once, are also carried out, but with BESSs with energy ratings of 1 667 MWh each, so that the total energy rating on the supply and demand sides were still approximately 5 000 MWh each, just geographically dispersed.

In order to see how different VPLs affect each other simulations with combinations of VPLs are also carried out. These are VPL1 and VPL6, VPL1 and VPL9, VPL6 and VPL7 and lastly, representing all three bidding zones VPLs 1, 6 and 7 together.

Lastly four different simulations with VPL1 are done, two for each scenario, with power and energy ratings that do not have a 1:1 ratio. One simulation with a power rating of 500 MW and an energy rating of 5 000 MWh and another simulation with a power rating of 250 MW and an energy rating of 5 000 MWh. This is done by restricting the power output of the batteries in the Python script.

In order to determine whether Case4 is actually needed at BZB4 in scenario EP, one additional simulation without Case4, but with a VPL with an energy rating of 1 000 MWh is executed. This is not done for scenario EF, since there are no overloaded hours at BZB4 without Case4, see the result section 4.2.

## 3.5 Post processing

The processing of the result files which are extracted from PowerFactory via the Python script is done in Matlab. By dividing the active power transfer across each BZB with the maximum capacity limits for each BZB it is possible to calculate the percentual loading of an entire BZB. Time series both for the active power transfer across each BZB and time series for the VPL are also plotted. To be able to compare the performance of the VPLs, a limit of 101% of the maximum transfer capacity of the BZB is used. The reason for this choice is to avoid treating residual errors as overloads. The active power transfer time series are then compared to this limit in order to count both how many hours there are with BZB overloading and how many MWh overload there are in total. To determine how much of the time the VPL is active the number of hours which have an active battery power other than 0 W are counted and then divided by the total number of hours in the simulation.

## 3.6 Accumulated overload energy

The size of energy peaks that need compensating using VPLs is an important part in deciding the energy rating of the BESSs used in the VPLs. The basic principle of VPLs is that they will be able to recharge using existing power lines during hours of low demand. However, if the demand is especially high for a sufficiently long time the VPL will at some point discharge completely. To be able to choose battery sizing, the term *Accumulated overload energy* [MWh] is defined. The Accumulated overload energy is the energy needed to be stored in a BESS to be able to handle periods of use when the VPL does not have time to fully recharge.

In figure 20 the purple line, with its corresponding axis to the right, describes the accumulated overload energy. The blue line is the flow across BZB1 and the red line indicates the BZB1 max transmission capacity. The hours during which the blue line is above the red line are defined as overloaded hours. In the left part of the figure the purple line can be seen rising as the overloaded hours are counted and resulting in accumulated overload energy. When the blue line dips below the red line, the spare capacity, thus the difference between the blue and red line, is subtracted from the accumulated overload energy to symbolise the possibility of charging a VPL. In the left part of the figure, there are a lot of overloaded hours and few hours with loading less than 100% giving the VPL a chance to recharge, and the purple line can be seen staying far above 0 until about day 20. The yellow markers on the red line are indicators for when an event of accumulated overload energy ends.

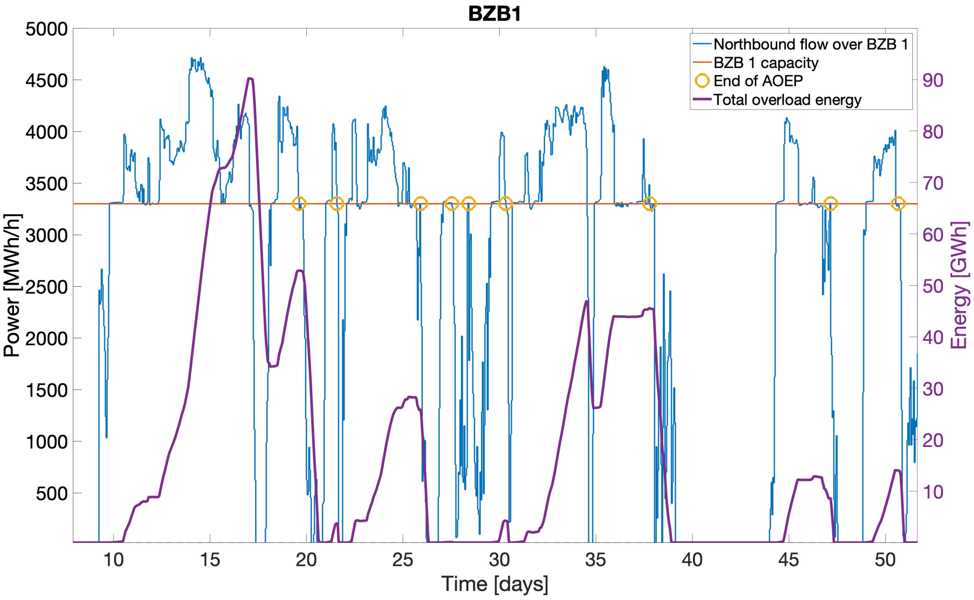


Figure 20: *Example of Accumulated overload energy peaks together with active power transfer at BZB1 for a selected period of time.*

To the right in the figure, an easier task for the VPL can be studied. The energy needed in the VPLs BESSs can instantly be recharged in the following valley after the peak. The need for large BESSs arises when a lot of overloads occur directly after one another for a long time without hours of low load in between where the batteries can be recharged. An accumulated overload energy peak, AOEP for short, corresponds to the theoretical maximum BESS energy rating needed to be able to handle that event of accumulated overload. One AOEP is counted from when the total overload energy first exceeds zero until it then gets all the way back to zero. This refers to a cycle that starts with a fully charged BESS and ends when the BESS is once again fully charged. An example of an AOEP can be seen between days 45 and 47 in figure 20. The number of AOEPs and their size is an important variable when choosing the energy rating of the BESSs in VPLs.

# 4 Results

In this section the results from the scenario work are first presented, followed by the results from the simulations based on data from the EF scenario. Lastly, results from the simulations based on data from the EP scenario are presented.

## 4.1 Scenarios

The results from the scenario work are presented as a comparison between the simulation results from the Nordic46 model and the LMA data from Svk. This is presented firstly for the EF scenario and secondly for the EP scenario.

### 4.1.1 Electrification renewable

In figure 21 the active power transfer across the three Swedish BZBs can be seen. The yellow bars represent the LMA data from Svk, while the blue bars represent the simulation results from PowerFactory with the Nordic46 model without any VPLs. It is clear that the two data series are almost identical for BZB4, very similar for BZB2 and quite similar for BZB1. At BZB1 it can be seen that there are overloads, mostly in the northward direction, in the data from the simulation, where there are none in the LMA data. It is also clear that the LMA data has sharp transmission capacity limits and do not allow for higher transfer than the maximum transfer capacity. There is also a peak at zero transmission in the LMA-data both for BZB1 and BZB4. In the simulation results for BZB1, this peak is near zero, but not precisely zero. The rightmost blue bar for BZB2 represents a BZB loading of 100 %. It is thus not an overload. Svk placed their limit for maximum transfer capacity slightly below 10 500 MW, which is the NTC for BZB2.

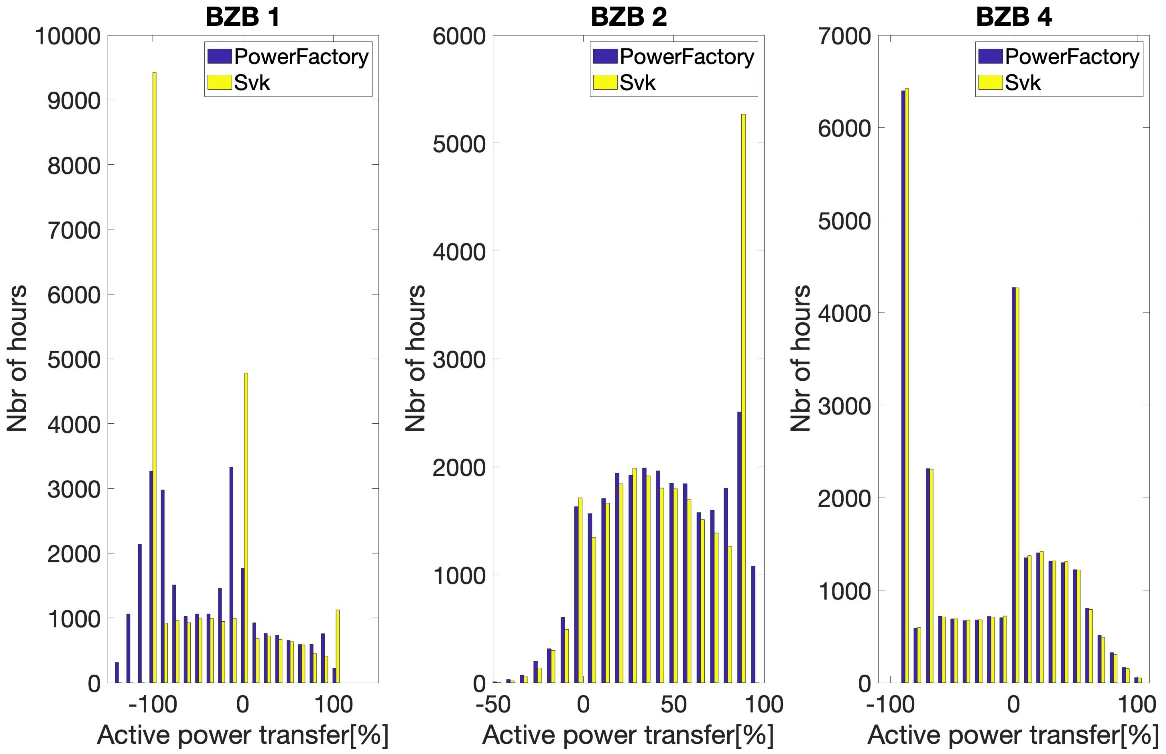


Figure 21: *Active power transfer as a percentage of the maximum transfer capacity for all three Swedish bidding zones in the Electrification renewable scenario. Total number of hours is 26 208 for both Svk and PowerFactory.*

### 4.1.2 Electrification dispatchable

In figure 22, the active power flow over the three Swedish BZBs for the EP scenario can be seen. The two data series are almost identical at BZB4. At BZB2, there seems to be some kind of offset between the two data series. At BZB1, the two data series are almost identical except for at the leftmost part of the graph. The strict transmission capacity limit in the LMA-data can be seen by a tall bar at -100%, but the simulation results from PowerFactory, where there are no strict transfer capacity limits, shows some overloaded hours. It is evident that there are no overloaded hours at BZB2. At BZB4 there are some overloads, especially in the south going direction. These are included in the bar at 100 % loading, since they are small.

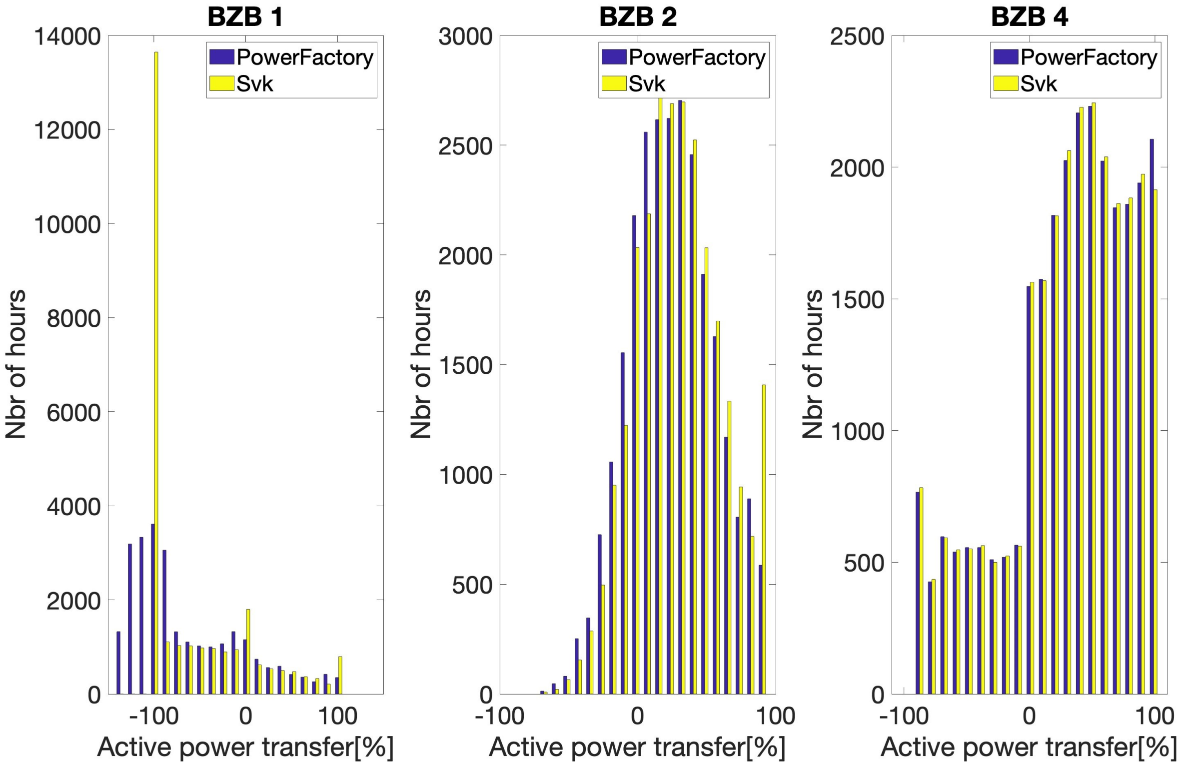


Figure 22: *Active power transfer as a percentage of the maximum transfer capacity for all three Swedish bidding zones in the Electrification dispatchable scenario. Total number of hours is 26 208 for both Svk and PowerFactory.*

## 4.2 Electrification renewable

In this section all results from simulations based on the EF scenario are presented. Graphs plotting results from an example simulation, VPL1, are presented first. After this, results concerning all simulations are presented. This includes accumulated overload energy peaks, average line loads and how the overloads change when adding VPLs to the system.

### 4.2.1 VPL1 Porjus - Grundfors

In this section graphs from the simulations for VPL1, which is connected over BZB1 between Porjus and Grundfors, are presented. In figure 23 the active power transfer across BZB1 is shown together with the active power for the two BESSs in VPL1 as well as their state of charge for a chosen period of time. In the upper graph the blue curve shows the simulation results without the VPL and the red curve shows the simulation results with the VPL. In the upper graph negative flow means that power flows northward. It is clear that the red curve avoids some of the overload peaks in the northward direction, since it does not dip as low as the blue curve. It is important to note that the two BESSs in the VPL are active during those peaks. By looking at the middle graph it is also evident that the two BESSs work in symmetry. When the red curve is positive in the lower graph it means that the VPL discharges on the demand side. Alternatively, when it is blue on the positive side it means that the demand side is charging. Looking at the bottom graph, the state of charge of BESS 1 i.e. the demand side BESS can be seen. The state of charge for the supply side BESS is the inverted version of this one. The rapid changes in the state of charge are a result of the high power rating together with the low resolution in time.

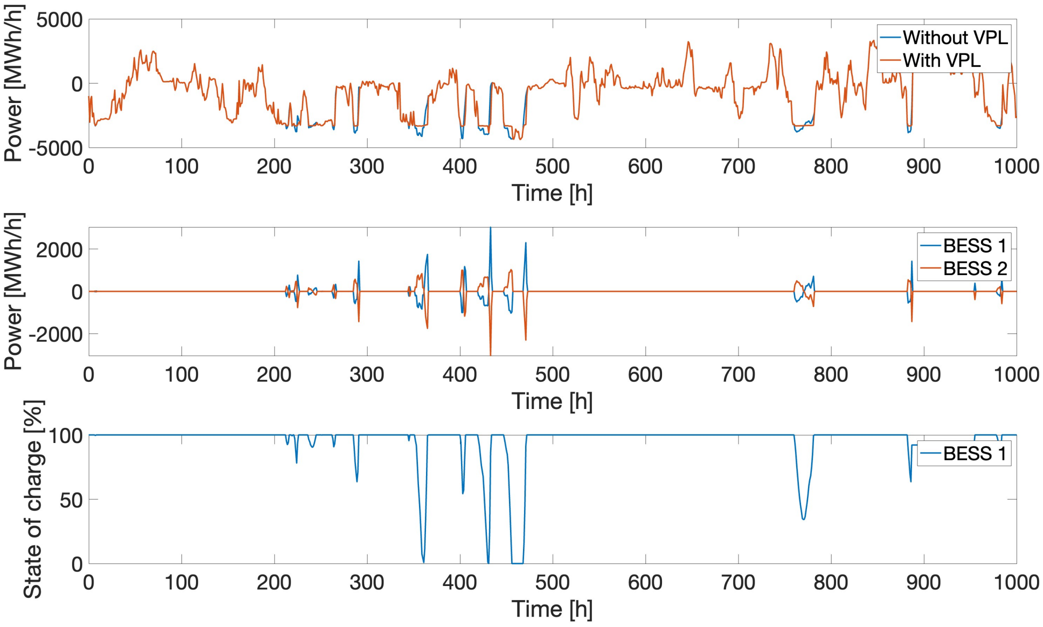


Figure 23: *The upper graph shows active power transfer across BZB1 both with and without VPL1 for a chosen period of time for scenario Electrification renewable. The middle graph shows active power for the BESSs in VPL1 for the same chosen period of time. The bottom graph shows the state of charge of BESS 1.*

By studying the negative peak at approximately 460 h in figure 24 it can be seen that the BESS capacity is not enough to cover the entire peak. This can be seen because the red curve starts off by not dipping as low as the blue curve, but after approximately half of the peak it joins the blue curve. When they join it means that the demand side BESS is empty. The straight yellow line in figure 24 represents the maximum transfer capacity in the southbound direction over BZB1. It can be noted that the red line representing the flow with the VPL active does not end up at exactly the yellow line, but rather a few MW over the yellow line. Similar behaviour has been observed in all other simulations. This is further discussed in section 5.

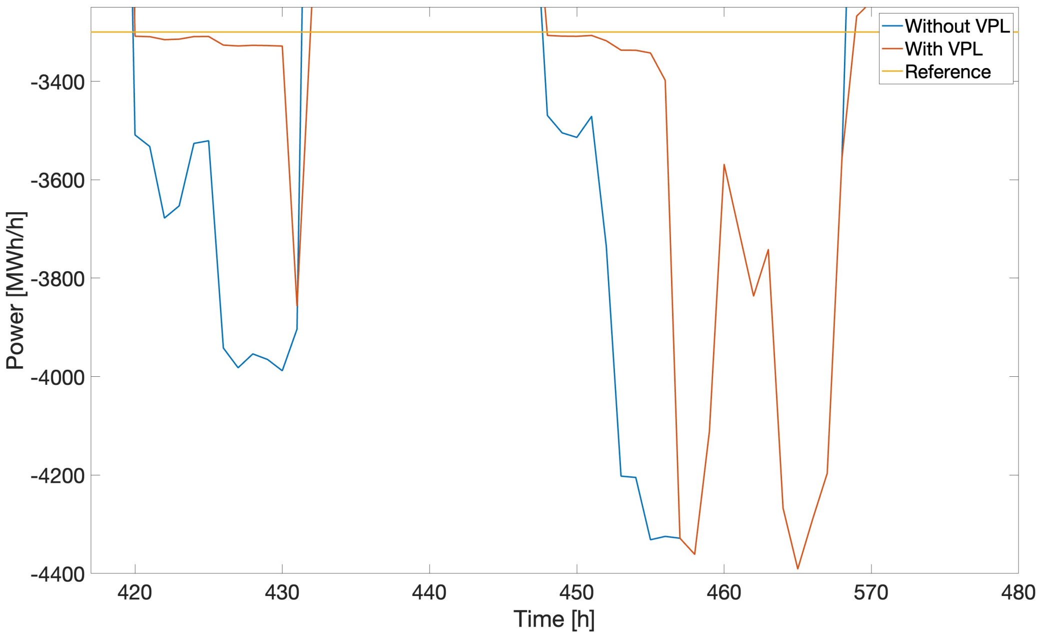


Figure 24: *Zoomed in version of figure 23 where the activity of the VPL can be studied in greater detail.*

The active power transfer, in % of the maximum transfer capacity, across BZB1 both with and without VPL1 can be seen in figure 25. The blue bars indicate the simulation results without VPL1 and the yellow ones represent the simulation with VPL1. Active power flow going northward is negative. When studying the left part of the graph between -150 % and -100 %, i.e. the number of hours with overloads across BZB1 from SE2 to SE1, it is clear that the yellow bars are lower than the blue bars for each bin. This means that the number of overloaded hours has decreased, which is done when the VPL discharges on the demand side. Consequently, it can also be seen that in bin -100 % and in the adjacent bin to the right, the yellow bars are larger compared to the blue bars. This is because the VPL use the hours when the BZB is less then 100 % loaded to charge, which increases the loading and fills the BZB capacity to a 100 % or close to it in situations when it before had spare capacity. The active power flow in the southward direction does not change between the two simulations, which is expected since the VPL is unidirectional.

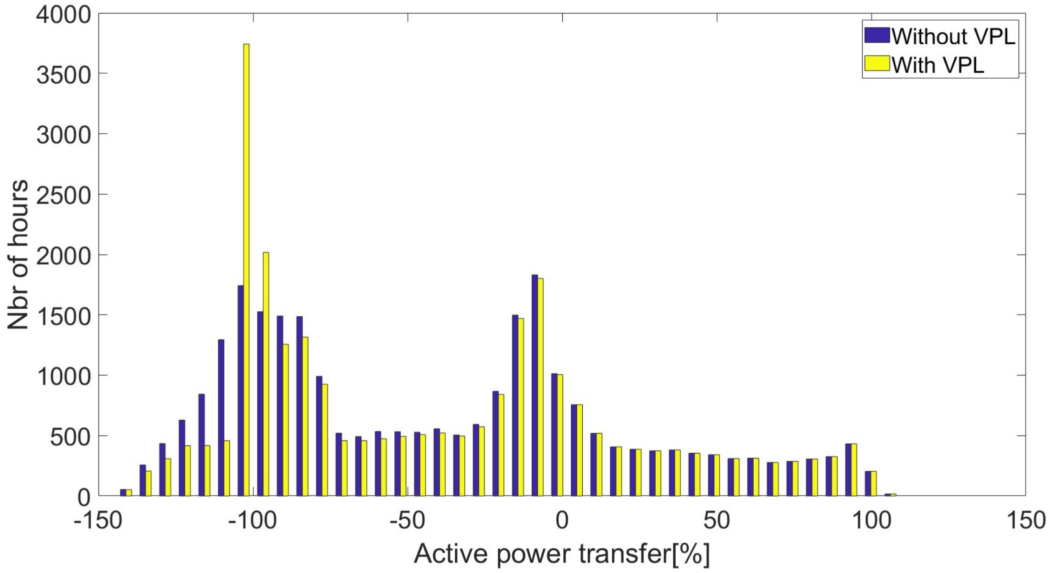
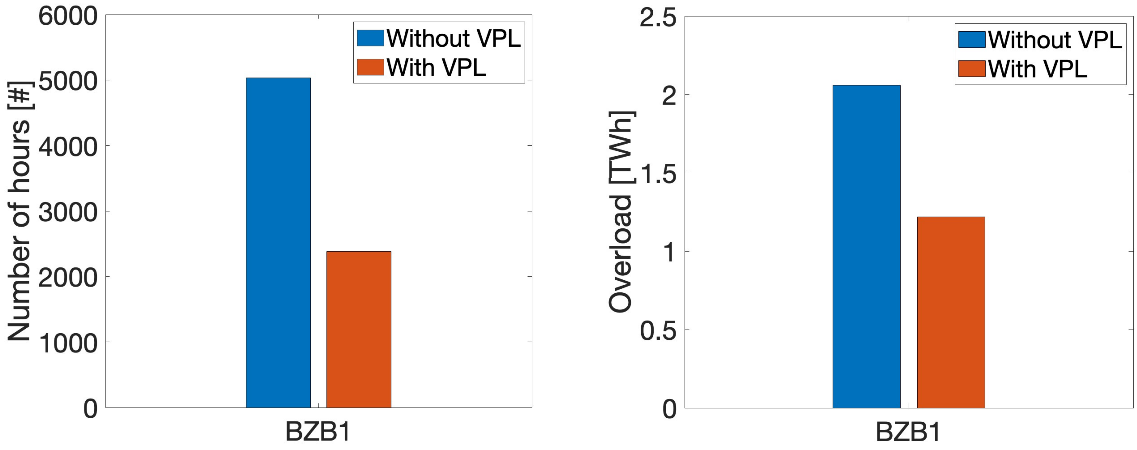


Figure 25: *The loadings on BZB1 both with and without VPL1 connected from Porjus to Grundfors for scenario Electrification renewable.*

The number of hours when BZB1 is overloaded is shown in figure 26a. The blue bar represent the simulation without using the VPL and the red bar represent the simulation using VPL1. In figure 26b the amount of MWh overload at BZB1 can be seen both with ad without VPL1. A reduction in the amount of MWh overload of approximately 40 % can be seen when using the VPL.



(a) *Number of overloaded hours for BZB1 both with and without VPL1 for scenario Electrification renewable.*

(b) *Number of MWh overload for BZB1 both with and without VPL1 for scenario Electrification renewable.*

Figure 26: *The reduction in the number of overloaded hours and MWh overload with VPL1 at BZB1 in the Electrification renewable scenario.*

### 4.2.2 Accumulated overload energy - no VPL in operation

In figure 27 the number and size of AOEPs can be seen for BZB1 in Sweden. It is clear that the majority of AOEPs are small, and a selected few are very large. The corresponding numbers for all Swedish BZB can be found in table 8. By comparing column three and six it is evident that the energy rating of the BESS changes rapidly if one wants to transition from removing 80 % of the AOEPs to removing 100 %. The energy rating required for each BESS to remove 80 % of the AOEPs is only 8.1 % of the energy rating required to remove 100 % for BZB1. The corresponding numbers for BZB2 and BZB4 are 3.5 % and 13 % respectively. Removing the very last AOEP thus requires lots of energy storage capacity.

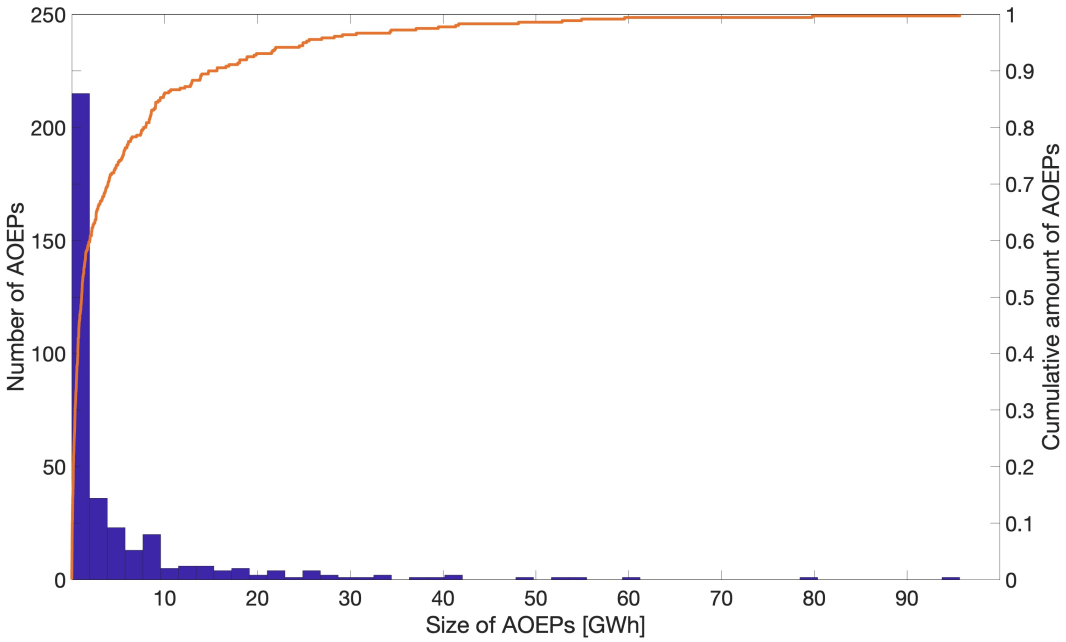


Figure 27: *The number and size of AOEPs at BZB1 for three selected weather years for the Electrification renewable scenario.*

Another interesting observation that can be made from table 8 is that the energy rating needed for the BESS is considerably much smaller for BZB4 compared to BZB1 and BZB2, regardless of the aim of removal between 80 and 100 %. It can also be noted that the energy rating needed to remove the largest AEOP from BZB2 requires an enormous energy rating.

Table 8: *Number of AOEPs at each BZB and their size depending on coverage in the Electrification renewable scenario. The numbers include Case2 and Case4.*

| **BZB** | **Total # of AOEPs** | **80 % of AOEPs smaller than [GWh]** | **90 % of AOEPs smaller than [GWh]** | **95 % of AOEPs smaller than [GWh]** | **Max AOEP [GWh]** |
|---|---|---|---|---|---|
| 1 | 360 | 7.74 | 14.7 | 24.9 | 95.7 |
| 2 | 381 | 13.4 | 24.8 | 42.7 | 383 |
| 4 | 515 | 2.28 | 3.78 | 6.25 | 17.5 |

### 4.2.3 Average line loadings - no VPL in operation

In figure 28 the maximum, mean and median line loadings can be seen for the lines over which the VPLs are connected. It is evident that the line across which VPL1 is connected is loaded to a much higher degree compared to the rest of BZB1, i.e. line 2 and 3. The differences between lines crossing the other two BZB are not as large. In the group crossing BZB2 VPL4 is connected over the highest loaded line. at BZB4 VPL7 is connected over the highest loaded line.

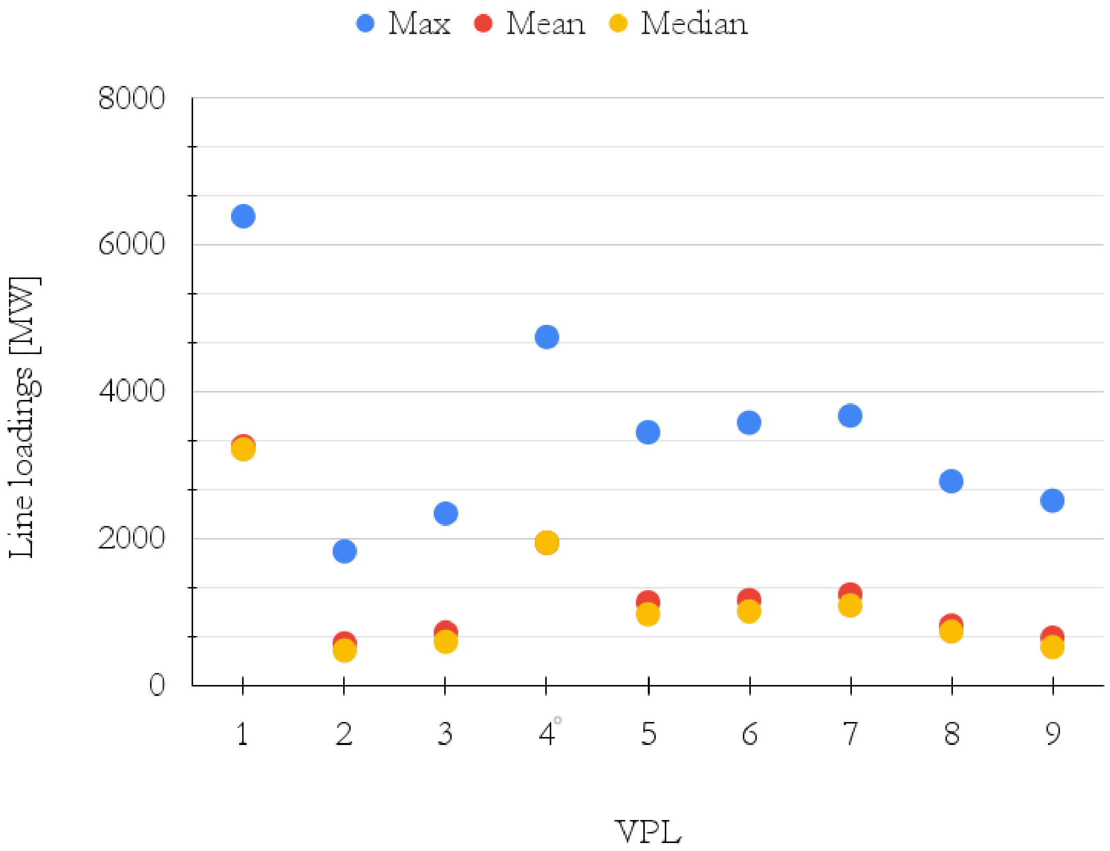


Figure 28: *Shows the maximum, mean and median line loadings for the transmission lines over which VPLs 1 to 9 are connected for the Electrification renewable scenario.*

### 4.2.4 Percentual changes in overloaded hours and MWh overload

In table 9 the percentual changes in the number of overloaded hours and MWh overload with VPLs compared to without VPLs are shown for all simulations for scenario EF. Actual simulation values in MWh and hours can be found in appendix D.1. As can be seen there are seven simulations for each BZB except for BZB1, three for each of two different sizes and one which contains all VPLs from that BZB. For BZB1 there are two additional simulations which include a limit on the power of the VPL. Lastly there are four simulations with combinations of VPLs belonging to different BZBs.

By studying the results from all VPLs across one BZB with size 5 000 MWh together with the simulation of all three together it can be seen that in almost all of the cases, the location of the VPL affects the result with only a few percent. The exception is VPL1 which is considerably better at limiting the number of overloaded hours. This is still the case when the energy rating is scaled up to 10 000 MWh.

Table 9: *Percentual changes in the number of overloaded hours and MWh overload with VPLs compared to without VPLs for scenario Electrification renewable.*

| **VPL** | **BZB** | **Energy rating [MWh]** | **Power rating [MW]** | **Change in # of overloaded hours [%]** | **Change in amount of overload [%]*** | **VPL usage [% of time] **** |
|---|---|---|---|---|---|---|
| 1 | 1 | 5 000 | 5 000 | -52.7 | -40.8 | 19.1 |
| 2 | 1 | 5 000 | 5 000 | -30.7 | -38.6 | 19.1 |
| 3 | 1 | 5 000 | 5 000 | -37.5 | -39.6 | 19.1 |
| 1, 2, 3 | 1 | 1 667 | 1 667 | -39.2 | -39.8 | 19.1 |
| 1 | 1 | 5000 | 500 | -45.7 | -38.0 | 22.7 |
| 1 | 1 | 5000 | 250 | -33.3 | -31.2 | 27.8 |
| 1 | 1 | 10 000 | 10 000 | -64.7 | -59.6 | 22.9 |
| 2 | 1 | 10 000 | 10 000 | -34.4 | -56.0 | 22.9 |
| 3 | 1 | 10 000 | 10 000 | -43.0 | -57.7 | 22.9 |
| 4 | 2 | 5 000 | 5 000 | -37.5 | -27.7 | 14.5 |
| 5 | 2 | 5 000 | 5 000 | -37.6 | -27.7 | 14.5 |
| 6 | 2 | 5 000 | 5 000 | -37.8 | -27.8 | 14.5 |
| 4, 5, 6 | 2 | 1 667 | 1 667 | -37.7 | -27.7 | 14.5 |
| 4 | 2 | 10 000 | 10 000 | -53.4 | -44.1 | 18.2 |
| 5 | 2 | 10 000 | 10 000 | -53.5 | -44.1 | 18.2 |
| 6 | 2 | 10 000 | 10 000 | -53.7 | -44.2 | 18.2 |
| 7 | 4 | 5 000 | 5 000 | -85.2 | -86.7 | 25.5 |
| 8 | 4 | 5 000 | 5 000 | -85.2 | -86.7 | 25.5 |
| 9 | 4 | 5 000 | 5 000 | -85.2 | -86.7 | 25.5 |
| 7, 8, 9 | 4 | 1 667 | 1 667 | -85.2 | -86.7 | 25.5 |
| 7 | 4 | 1 000 | 1 000 | -43.3 | -45.8 | 15.2 |
| 8 | 4 | 1 000 | 1 000 | -43.3 | -45.8 | 15.2 |
| 9 | 4 | 1 000 | 1 000 | -43.3 | -45.8 | 15.2 |
| 1, 6 | 1 | 5 000 | 5 000 | -52.9 | -41.1 | 19.0 |
|  | 2 | 5 000 | 5 000 | -37.8 | -27.8 | 14.5 |
| 1, 9 | 1 | 5 000 | 5 000 | -52.7 | -40.8 | 19.1 |
|  | 4 | 5 000 | 5 000 | -85.2 | -86.7 | 25.5 |
| 6, 7 | 2 | 5 000 | 5 000 | -37.7 | -27.7 | 14.5 |
|  | 4 | 5 000 | 5 000 | -85.2 | -86.7 | 25.5 |
| 1, 6, 7 | 1 | 5 000 | 5 000 | -52.9 | -41.1 | 19.0 |
|  | 2 | 5 000 | 5 000 | -37.8 | -27.8 | 14.5 |
|  | 4 | 5 000 | 5 000 | -85.3 | -86.8 | 25.5 |

* The amount of MWh overload w.o. VPL are for BZB1: 2 057 930 MWh, for BZB2: 4 610 520 MWh and for BZB4: 667 456 MWh.

** The total time for each simulation is three years, which equals 26 208 hours.

When studying the nine base case VPLs with BESSs with an energy rating of 5 000 MWh it can be seen that the VPLs removes the most MWh overload and overloaded hours at BZB4, second best at BZB1 and least at BZB2. This corresponds well with table 8, since it states that the BESS with the lowest energy rating is needed to remove between 80 and 100 % of MWh overload at BZB4, followed by BZB1 and thereafter BZB2. For BZB1 and BZB2 simulations with BESSs with an energy rating of 10 000 MWh were carried out too, and these results show a larger decrease in the amount of MWh overload and overloaded hours compared to BESSs with an energy rating of 5 000 MWh. The VPLs with BESSs with an energy rating of 1 000 MWh on each side across BZB4 removes a larger part of both the overloaded hours and the MWh overload compared to the simulations with an energy rating of 5 000 MWh at BZB1 and BZB2. The percentual change is however not as large as compared to simulations with an energy rating of 5 000 MWh VPLs across BZB4.

The two simulations with limited power rating from VPL1 are indicated with the parentheses. It can be seen that these perform slightly worse compared to the unrestricted simulation. However, the difference is not large. The difference in MWh overload removed is only 2.8 percentage points when the power rating is limited to 500 MW. It is worth noting that even with the limited power rating, this VPL performs on par with the unrestricted VPL2 and VPL3. When decreasing the power rating further to 250 MW the performance also decreases further, and the VPL can no longer be said to perform in range with the unlimited ones. When studying the results from the four combination simulations it is interesting to see that the results for the separate VPLs in those combinations remain approximately the same as when they're run separately.

If counting the number of hours with overloads at BZB2 and BZB4 without Case2 and Case4, there are zero overloaded hours at BZB2 and 33 at BZB4.

In the last column in table 9 the time in percent the VPL is used can be seen. It is clear by studying the VPLs crossing the same BZB that the percentual usage of the VPL does not differ between BESSs of the same power rating. Increasing the energy rating of the BESSs increases the percentual usage, though if this would be true if the energy rating would be increased even further is uncertain. With so few data points it is not possible to say whether it increases further. The highest percentual usage of the unlimited simulations can be found for BESSs with an energy rating of 5 000 MWh at BZB4, followed by BESSs with an energy rating of 10 000 MWh at BZB1. The lowest level of usage can be found at BZB2 with BESSs with an energy rating of 5 000 MWh, followed by BZB4 with BESSs with an energy rating of 1 000 MWh. It can be seen that limiting the power rating for the BESSs increases the usage time for the VPLs. Thus, the simulation with the lowest power rating is the simulation with the highest usage time. The reason for this is that both charging and discharging takes longer time when the power rating is lower.

Comparing the combination simulations at the bottom of table 9 to the separate simulations it is clear that the percentual usage only varies slightly for each BZB with BESSs with an energy rating of 5 000 MWh as in the separate simulations. There is a small reduction in all categories for VPL1 when run together with VPL6, compared to when it is working on its own. There is no difference in performance for VPL1 and VPL9 when run together compared to running individually. A slight decrease in performance can be seen in VPLs 6 and 7 when working together as well as when VPLs 1, 6 and 7 are working together.

Graphs showing the results in more details for VPL1 are presented in sections 4.2.1, and in appendix D, C.3.1 and C.3.2 for VPL4 and VPL8 to show examples from all BZB.

## 4.3 Electrification dispatchable

In this section all results connected to simulations based on the EP scenario are presented. The results include accumulated overload energy peaks, average line loadings and how the overloads change when adding VPLs to the system.

### 4.3.1 Accumulated overload energy - no VPL in operation

The number of accumulated overload energy peaks displayed in figure 29 are mostly gathered in the left part of the figure. The majority of the AOEPs are smaller than 20 GWh. As can be seen in table 10 that the majority of AOEPs over the different BZBs can be covered by BESSs with an energy rating of around 10 000 MWh. In the rightmost column in table 10 the maximum size of an AOEP during the three selected weather years is displayed. The corresponding BESSs needed to handle these AOEPs are orders of magnitude larger than the BESSs needed to cover the majority of AOEPs. This is also visually demonstrated in figure 29 where only single digit amounts of AOEPs are larger than 100 GWh. The number of AOEPs for BZB2 and BZB4 follow very closely the same pattern as the number of AOEPs for BZB1 visualised in figure 29.

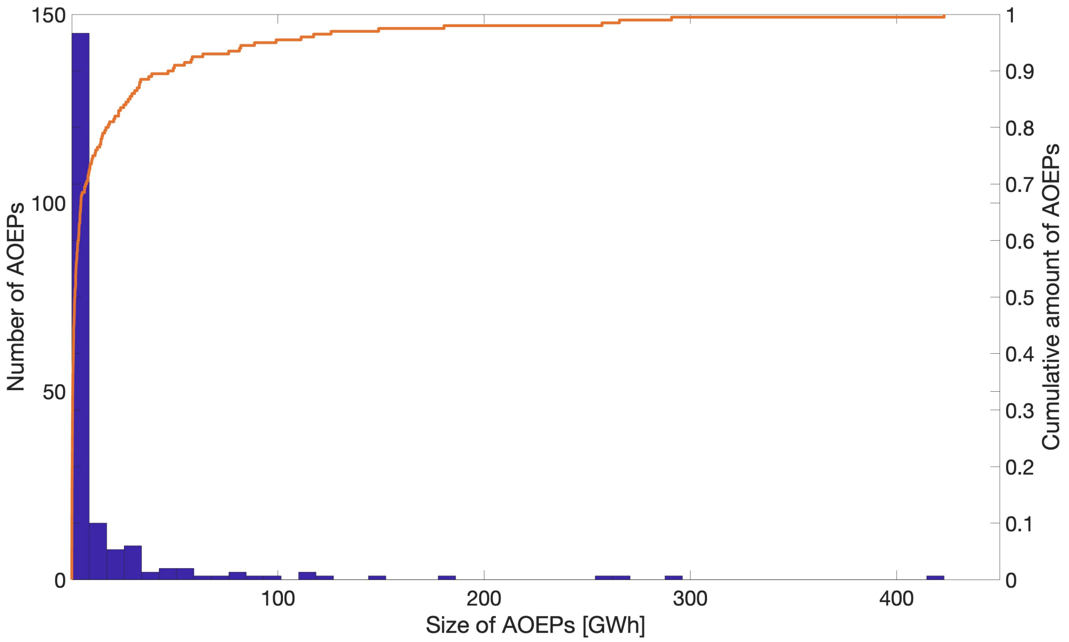


Figure 29: *The number and size of AOEPs at BZB1 for three selected weather years for scenario Electrification dispatchable.*

Table 10: *Number of AOEPs at each BZB and their size depending on coverage during the three chosen weather years for scenario Electrification dispatchable. The numbers include Case2 and Case4.*

| **BZB** | **Total # of AOEPs** | **80 % of AOEPs smaller than [GWh]** | **90 % of AOEPs smaller than [GWh]** | **95 % of AOEPs areas less than [GWh]** | **Max AOEP [GWh]** |
|---|---|---|---|---|---|
| 1 | 200 | 16.6 | 46.6 | 88.6 | 423 |
| 2 | 125 | 11.3 | 24.1 | 37.8 | 112 |
| 4 | 276 | 6.00 | 10.8 | 16.3 | 51.4 |

### 4.3.2 Average line loadings - no VPL in operation

The average line loads presented in figure 30 are the line loadings in the Nordic46 model before the VPLs are connected, but over the same line or lines that are then reinforced with VPLs. The line which is reinforced with VPL1 has a very large maximum loading as well as high mean and median loadings. The on average least loaded lines are the ones reinforced by VPL2 and VPL3.

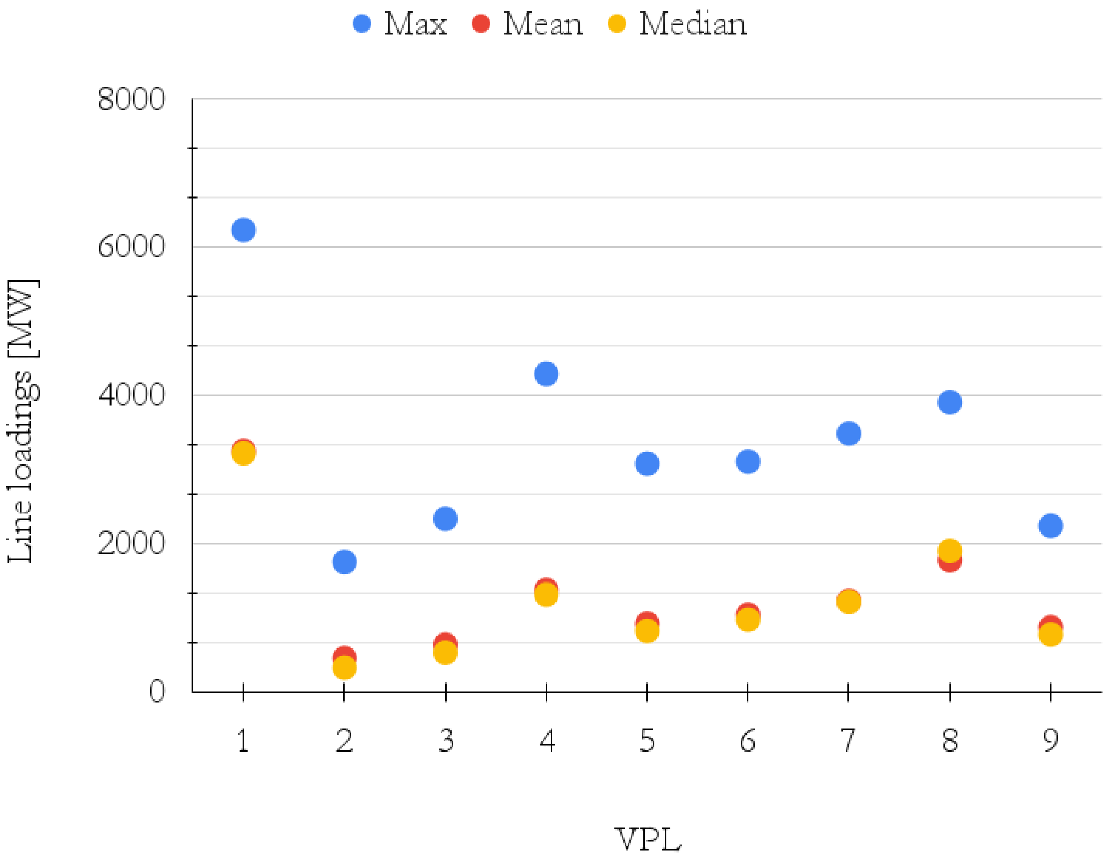


Figure 30: *The maximum, mean and median line loadings for the transmission lines over which VPLs 1 to 9 are connected for the Electrification dispatchable scenario.*

### 4.3.3 Percentual changes in overloaded hours and MWh overload

When looking at the change in the number of overloaded hours at BZB1, thus VPLs 1, 2 and 3, it is evident that it is only slightly higher when using a BESS with an energy rating of 10 000 MWh. The larger change comes in the number of MWh overload that is reduced further with the larger BESS energy rating. Running the three VPLs belonging to the same BZB at the same time does not seem to give rise to large changes in terms of change in number of overloaded hours or MWh overload. The result is rather an average of the three separate simulations.

When studying the two simulations with restricted power rating on VPL1, it can be seen that it performs worse compared to the unrestricted VPL1. However even with the limited power rating, this VPL performs on par with the unrestricted VPL2 and VPL3.

Table 11: *Percentual changes in the number of overloaded hours and MWh overload with VPLs compared to without VPLs for scenario Electrification dispatchable.*

| **VPL** | **BZB** | **Energy rating [MWh]** | **Power rating [MW]** | **Change in # of overloaded hours [%]** | **Change in amount of overload [%]*** | **VPL usage [% of time] **** |
|---|---|---|---|---|---|---|
| 1 | 1 | 5 000 | 5 000 | -28.2 | -18.7 | 21.1 |
| 2 | 1 | 5 000 | 5 000 | -14.4 | -17.6 | 21.1 |
| 3 | 1 | 5 000 | 5 000 | -18.4 | -18.1 | 21.1 |
| 1, 2, 3 | 1 | 1 667 | 1 667 | -19.3 | -18.2 | 21.1 |
| 1 | 1 | 5 000 | 500 | -23.1 | -17.3 | 24.8 |
| 1 | 1 | 5 000 | 250 | -15.6 | -14.1 | 30.7 |
| 1 | 1 | 10 000 | 10 000 | -35.3 | -28.7 | 26.2 |
| 2 | 1 | 10 000 | 10 000 | -16.0 | -26.8 | 26.2 |
| 3 | 1 | 10 000 | 10 000 | -20.8 | -27.7 | 26.2 |
| 4 | 2 | 5 000 | 5 000 | -43.5 | -35.7 | 4.9 |
| 5 | 2 | 5 000 | 5 000 | -43.6 | -35.7 | 4.9 |
| 6 | 2 | 5 000 | 5 000 | -43.6 | -35.8 | 4.9 |
| 4, 5, 6 | 2 | 1 667 | 1 667 | -43.6 | -35.7 | 4.9 |
| 4 | 2 | 10 000 | 10 000 | -62.0 | -54.0 | 6.1 |
| 5 | 2 | 10 000 | 10 000 | -62.0 | -54.0 | 6.1 |
| 6 | 2 | 10 000 | 10 000 | -62.0 | -54.0 | 6.1 |
| 7 | 4 | 5 000 | 5 000 | -50.7 | -57.8 | 11.1 |
| 8 | 4 | 5 000 | 5 000 | -50.3 | -57.8 | 11.1 |
| 9 | 4 | 5 000 | 5 000 | -50.7 | -57.8 | 11.1 |
| 7, 8, 9 | 4 | 1 667 | 1 667 | -50.7 | -57.8 | 11.1 |
| 7*** | 4 | 1 000 | 1 000 | -80.3 | -80.9 | 5.1 |
| 7 | 4 | 1 000 | 1 000 | -20.8 | -19.6 | 6.7 |
| 8 | 4 | 1 000 | 1 000 | -20.8 | -19.6 | 6.7 |
| 9 | 4 | 1 000 | 1 000 | -20.8 | -19.6 | 6.7 |
| 1, 6 | 1 | 5 000 | 5 000 | -28.2 | -18.7 | 21.1 |
|  | 2 | 5 000 | 5 000 | -43.7 | -35.8 | 4.9 |
| 1, 9 | 1 | 5 000 | 5 000 | -28.2 | -18.8 | 21.1 |
|  | 4 | 5 000 | 5 000 | -50.5 | -57.6 | 11.2 |
| 6, 7 | 2 | 5 000 | 5 000 | -42.7 | -34.5 | 4.9 |
|  | 4 | 5 000 | 5 000 | -50.6 | -57.9 | 11.2 |
| 1, 6, 7 | 1 | 5 000 | 5 000 | -28.2 | -18.8 | 21.1 |
|  | 2 | 5 000 | 5 000 | -43.0 | -34.9 | 4.9 |
|  | 4 | 5 000 | 5 000 | -50.6 | -57.6 | 11.2 |

* The amount of MWh overload w.o. VPL are for BZB1: 5 129 150 MWh, for BZB2: 1 023 470 MWh and for BZB4: 1 051 530 MWh.

** The total time for each simulation is three years, which equals 26 208 hours.

*** This simulation is done without Case4, thus with full transmission capacities over BZB4.

Over BZB2, the VPLs 4, 5 and 6 are used. A quite substantial jump both in reduction of number of overloaded hours and MWh overload can be seen for all VPLs when using a BESS with a higher energy rating. Over BZB4 the VPLs 7, 8 and 9 are used. Here the chosen energy ratings of the BESSs are 5 000 and 1 000 MWh. Compared to the EF scenario the flow over BZB4 is reversed and is in this case from SE3 to SE4. The numbers for all 3 VPLs seems to be quite similar in all columns with the same BESS energy rating. The results from running all tree VPLs in parallel does not differ much from the result of running them individually. One simulation without Case4 applied was also run with VPL7, marked with three asterisks in table 11. It is evident that a VPL with BESSs with energy ratings of 1 000 MWh can remove the majority of all overloads from BZB4.

The VPLs have also been run in pairs over multiple BZBs. The first pair was VPLs 1 and 6, ie BZB1 and BZB2. The number of overloaded hours and MWh overload are almost identical to the separate simulations of VPLs 1 and 6. The pair of VPLs 1 and 9 corresponds to VPLs over BZB1 and BZB4. The number of overloaded hours and MWh overload reduced are almost identical for VPL1 comparing to running on its own. VPL9 performs slightly worse when run in combination compared to on its own. The pair of VPLs 6 and 7 corresponds to VPLs over BZB2 and BZB4. The results are approximately the same as the separate simulations, but with a slight decrease in performance for VPL6 and a slight increase in performance for VPL7.

The last combination simulation is a triplet consisting of VPLs 1, 6 and 7 which corresponds to VPLs across all three BZBs. The reductions in overloaded hours and MWh overload for each BZB seems to be only barely impacted by running the three VPLs at once. VPL1 performs identically to when it is run on its own and both VPL6 and VPL7 have a slight reduction in performance.

If counting the number of hours with overloads at BZB2 and BZB4 without Case2 and Case4, there are zero overloaded hours at BZB2 and 1 130 at BZB4.

The amount of time a VPL is used is calculated as a percentage of all hours the simulation is run for. The most used of the unlimited VPLs are the ones over BZB1, namely VPLs 1, 2 and 3. The least used VPLs can be found over BZB2 where VPLs 4, 5 and 6 are used a lot less. In general, the bigger the energy rating of the BESS is, the more the VPLs get used. The VPL usage when running multiple VPLs over different BZBs at the same time does not seem to change the amount of time when the VPL is running compared to running them on their own. It can also be seen that limiting the power rating for a VPL increases the usage time. The most limited simulation of VPL1 is the simulation with the highest usage time. Again, this is because charging and discharging takes longer time when the power rating is lower.

# 5 Discussion

The discussion will commence with a discussion of the methods used in this thesis work. Following this, a comparison and discussion about the results from the simulations for scenario EF and EP are made. A comparison is also made between the simulation results and the LMA data from Svk. Thereafter the climate and environmental impact of primarily the lithium-ion batteries are considered. After that the factors contributing to deciding the location and size of a VPL are discussed. Lastly the legal framework for VPLs crossing BZBs is discussed.

## 5.1 Method discussion

In this section explanations and motivations of decisions made in this work can be found. Firstly this is done for the data used, then for the pre-processing of the data. This is followed by a discussion on the development process of Nordic46. Lastly the modelling of the VPLs is discussed.

### 5.1.1 Data

The data used in this thesis work originate in the scenario work done by Svk in their LMA from 2021, which studies several scenarios for the future power system in Sweden. Since the data was published in 2021 it is very new and thus constitutes some of the newest ideas and speculations of the future power system. The exact numbers for electricity generation or consumption given by the two scenarios used in this work are not truly important. The purpose is not to predict the future, but rather to illustrate under what conditions a VPL might be a contributing part of the Swedish power system. If a VPL is to be constructed in the future, the placement and size should be based on real data from the power system in place then.

The LMA data already contains some flexibility, see column 3 in table 2. This means that the amount of MWh overload will be smaller compared to what it would have been without this flexibility. It might also mean that peaks in the electricity consumption are smaller than they would have otherwise been. However, in a real power system a VPL would never be the only flexibility application used, but rather work together with other types of flexibility solutions. Therefore, it is deemed alright that there is flexibility included in the data from start.

### 5.1.2 Preprocessing of data

The preprocessing happening in the Python script created by Henrik Nordström is an early step in this work. The data provided by Svk in their LMA is not divided in different categories for renewable production, ie wind onshore, wind offshore and solar power. Since renewable power is of high interest in a future energy system, the division of the RES category in the LMA data is important and has in a previous work been done by Henrik Nordström. Weather data from ENTSO-E's Pan-European Climatic Database was used to divide the RES category. There might be minor improvements possible as Nordström mentions in his own work, but the division of the RES categories are deemed more than good enough to be able to gain interesting result in this work. This separation is not strictly necessary in order to use it as input for the PowerFactory simulations. By separating the data it was however possible to distinguish between different types of renewable power production in the model.

Another preprocessing task was to select three out of the 35 available weather years. The reason for limiting the number of simulated years was due to time constraints, and the reason for choosing three weather years was to be able to do a maximum value, a minimum and an average value. A lot of parameters were taken into account, such as the variability of renewable production, as well as amount of renewable production. The deciding factor at the end was however the number of overloaded hours combined over all BZBs since this would most accurately help answer the research questions posed in this work.

### 5.1.3 The Nordic46 model

The following section will discuss changes made to the Nordic44 model, and the usage of Nordic46 model.

In order to increase the transmission capacity in the Nordic44 model it was decided to add parallel lines to those already present in the model. The reason for increasing the capacity was to better match the future Swedish transmission system. It would have been possible to increase the transmission capacity by modifying the parameters of the power lines, which would have given more freedom in the levels of transmission possible. However, by adding parallel lines the lines could still be of the same size and properties, which is considered to be favourable, specifically in terms of being able to easily test various transfer capacities.

The Nordic46 model network is a great tool for exploring and investigating the Nordic power system. One of the strengths of Nordic46 -its simplicity- is also one of its greatest weaknesses. Since the entire Nordic synchronous area is modelled using only 46 nodes, the model is by definition quite crude. Keeping in theme with this crudeness, the distribution of generation and consumption in the model is equal to every node. This means that for example the inland nodes in Sweden are assigned equally much offshore wind power as the nodes located near the coast. This is obviously a simplification and a more thought through distribution would be interesting in a future work. The main reasoning behind the simple distribution was that since the model is approximate the information gained from a more elegant distribution would be lost in the decimals. Also, this work is performed in a scenario environment. Some abnormalities, like offshore wind connected in Järpströmmen which is located far from the coast, can be excused as the goal is not to make a prediction, but rather to investigate.

The coarseness of the model also raises some question when it comes to VPLs. The resolution of the Nordic46 model does not permit gathering results of single power lines with the needed accuracy which is problematic since VPLs are meant to reinforce smaller areas. It is worth noting that they affect the surrounding transmission system too. The smallest unit of resolution where general conclusions can be drawn has been judged to be at the level of bidding zone borders where the transmission capacity in total in the model can be verified against real world values. Practically, this means that VPLs reinforcing single lines in the model are controlled using the total loading of the BZB. This may not be ideal, but while working well with the model at hand it still manages to produce interesting results worth analysing.

### 5.1.4 Modelling of VPLs

In this thesis work a decision was made to use unidirectional VPLs. The reason for this choice was that the majority of the overloads for BZB1, for BZB2 in Case2 and for BZB4 in Case4 was caused by flows in one direction. Thus, not that many overloaded hours were disregarded by using unidirectional VPLs. Modelling VPLs which work in both directions is not that much more complicated, however it would probably require BESSs with large energy capacity, since the VPL must have enough stored energy on both sides to discharge and remove overloads in both directions. The issue of higher capacity BESSs for two way VPLs might be solved by using good forecasts and intelligent control, but since logic loops are used as control method in this thesis work this would not be the case. Since there were few hours with overloads caused by flow in the other direction using larger energy capacity BESSs for two way VPLs was considered unnecessary.

When it comes to the locations of the nine different VPLs in this work, it was decided to place VPLs on all possible lines crossing each BZB. This way no possible location was disregarded in an early selection process. It is of course also possible to place the BESSs in the VPL even further apart, for example one in SE1 and one in SE3, however since the purpose of this thesis primarily was to study overloads across the three Swedish BZBs one at a time, this was not done. Neither have they been placed on nodes which are not connected via a direct power line.

The two cases with reduced transmission capacity that were used in this work, Case2 and Case4, were both based on assumptions that certain grid reinforcement projects were either delayed or cancelled. This was done in order to create situations in which a VPL could be useful. Without using Case2 and Case4 there were almost no overloaded hours for the EF scenario, and only few for BZB4 in the EP scenario, which would make the need for solutions like a VPL small. That the reinforcement package for BZB2 could be delayed is not unlikely. It is set only preliminary to be done in 2040, which is 17 years from now, and only five years from 2045, which is the studied year. A lot can happen in 17 years, especially when political strategies vary. Even if the reinforcement project does start on time, there is of course always the risk of delays in the construction phase.

That the reinforcement of BZB4, which is to take place three years from now, in 2026 would not be in place before 2045 is more unlikely. The most likely reason is if it is cancelled. Given that the limited capacities in this BZB contributes to the current high electricity prices in the south of Sweden, there would have to be strong arguments for the reinforcement to be cancelled. Case4 is however still very interesting to study since it is not uncommon for malfunctions to occur or maintenance needing to be done in transmission lines. Case4 could thus also represent a case where not all of the transmission capacity across BZB4 is available, and thus additional help from for example a VPL could be helpful. Since BESSs are relocatable, it could be possible to move them to create a VPL across BZB4 if larger maintenance work is scheduled. This could also be an application for BZB2. The reason no Case1 is used is that there are already enough hours with overloads during which a VPL can be studied.

The round-trip efficiency of an ESS based on lithium-ion batteries is around 85-95 %. In spite of this, losses were disregarded in this thesis work. The reason for this is that the LMA-data provided by Svk was from the start perfectly balanced, in other words the electricity generation exactly matched the electricity consumption. Including losses in the BESSs would disturb this balance and risk not reaching convergence in the load flow simulations. Because of this, losses were not included. Had they been included it would be expected that more electricity would have to be generated in order to cover the electricity consumption, since the losses in the system increases. This could mean that fewer MWh overload can be removed, since the VPL needs to spend more time charging. It could also mean that the VPL fills the transmission line in order to charge during more hours.

The effect of the VPLs has been measured against a limit that is 101% of the transfer capacity of the current BZB. This was done due to the VPLs not bringing overloads below the limits being put on the transmission lines. This can clearly be studied in figure 24 where a yellow reference line is drawn at -3300 MW, which is the northbound transmission capacity over BZB1. When the VPL is active, the overloads are reduced a lot, but there are still a few MW too much transmitted. This is probably a residual error stemming from the values being set for the VPL based on load flow values obtained without a VPL connected to the grid. When the VPL is connected, some flows might be changed, compared to the previous simulation used as reference values, resulting in the VPL being a few MW off. In appendix C.2 the effect of measuring against a limit that is exactly equal to the BZB transfer capacity can be seen.

A possible explanation why the VPL always is a couple of MW over the specified limit has to do with the VPL being modelled as completely lossless compared to the line which is relieved. The few MW seen above the limit is probably around the same number of MW that would have been lost if the power had flowed on a regular transmission line instead of a virtual one. The easiest way to make this more accurate would be to model some losses in the VPL or maybe iteratively do load flows where the VPL has a chance to adapt and minimize the overflow.

The choice to use a 1:1 relationship between energy and power in the majority of the simulations is a simplification, which affects the results. How large this effect is depends both on how large a limit would be reasonable to put on the power, and on how large the hourly overloads are for the BZB in question. In order to estimate how large the error of this simplification is, two simulations with limits on power rating were run for VPL1 in each scenario. By comparing the results from the simulation with a power limit of 500 MW with the unlimited simulation for VPL1 it can be seen that the difference is 2.7 percentage points for EF and 1.4 percentage points for the EP scenario. The change here is thus small. If instead imposing a power limit of 250 MW the difference is 9.4 percentage points for EF and 4.6 for the EP scenario. The difference between the two scenarios is most likely due to the larger share of intermittent power in the EF scenario, which results in larger fluctuations in power flow, and thus also larger required inputs from the VPL. However, it is clear that the difference between the unlimited and the limited simulations increases when the power rating is further limited for the BESSs. Though, if it is assumed that a limited power rating of 500 MW for a BESS with an energy rating of 5 000 MWh is reasonable, the difference in the results is not very large. Since assuming a 1:1 ratio between energy and power does not significantly alter the results, it seems like a reasonable simplification to make in order to simplify the simulation process. Further studies are however needed in order to gain clear results when it comes to dimensioning a VPL.

This work was carried out focusing on reducing the number of overloaded hours as well as the overloaded energy measured in MWh. This was done instead of for example trying to minimize the power of the overloads, measured in MW. Looking at figure 24, it can be seen that (in this case) about a third of the overloaded energy (MWh) is removed. The overload power is however not reduced at all, in this case peaking at 1 000 MW above the rating for the BZB. The same phenomena can be seen in figure 25 where there are still overloads at around -150% of the BZB border even after the VPL is connected. These high overload powers could in a real world application damage equipment. For example, the goal could be to reduce overloads to a maximum of 200 MW above a BZB power rating instead of trying to remove the overload in its entirety.

## 5.2 Common features of the two scenarios

First the different sets of VPLs over the 3 BZBs will be discussed. Many results are almost identical between the EF and EP scenarios and whenever a scenario is not mentioned, the statement is true for both scenarios. Differences will be discussed in section 5.5.

Starting with BZB1, VPL1 stands out compared to VPLs 2 and 3 both with a BESS energy rating of 5 000 and 10 000 MWh. The reduction in the number of overloaded hours is significantly larger compared to the other VPLs over the same BZB. In figure 28 and 30 the line loads are presented for the lines across which the VPLs are connected, and here the line which is reinforced by VPL1 also stands out as having considerably higher load compared to the others. The line corresponding to VPL1 is simply a lot more loaded than the lines corresponding to VPLs 2 and 3, and thus a VPL reinforcing that line has the possibility to reduce the number of overloaded hours more compared to one of the other lines, since there are simply more power being transferred and more opportunity for the VPL to work. This reasoning is further strengthened by the fact that VPL2, which has the least improvement in number of overloaded hours also has the lowest mean and median loading out of the three lines reinforced by VPLs.

The difference in change in the amount of MWh overload is not as large between the VPLs as the change in number of overloaded hours. The amount of MWh overload is simply the product of overloaded hours and how much each overloaded hour is overloaded. In VPL1 the reduction in the number of overloaded hours is greater compared to VPLs 2 and 3, but the reduction in MWh overload is similar. This is probably due to many small overloads being removed to a larger extent in the case of VPL1 whereas for VPLs 2 and 3 smaller overloads are not as common or are not removed to the same extent.

The combination simulation, with VPLs 1, 2 and 3 spread out across BZB1 with BESSs with smaller energy ratings, does not change the result significantly. The result is some kind of average of how the VPLs would have operated on their own with a higher value in both reduction in overloaded hours and MWh overload compared to VPLs 2 and 3, but lower values compared to VPL1. Using a spread out VPL over the entire BZB could be argued is more accurate since all VPLs are controlled using the entire BZB loading and maximum transfer capacity.

When the simulations are run with a larger VPL power rating, the greater reduction in the number of hours with overloads as well as reduction in the amount of MWh overload is clear. Since the BESSs have a possible power rating of 10 000 MW, all this power could in practice never be expended all in one hour, considering it would correspond to more than 7 nuclear reactors the size of Oskarshamn 3. Since the BESSs have a 1:1 ratio of energy to power, this means that a BESS with a power rating of 10 000 MW also has a energy storage capacity of 10 000 MWh. This increased capacity will result in stored energy lasting longer and being able to cover bigger AOEPs. This is what can be seen as a larger reduction in overloaded hours and MWh overload.

When comparing the results from the simulations with power rating limits with the ordinary simulation for VPL1 for both scenarios, it performs slightly worse. However, with the limitations on VPL1 it still performs in the same range as VPLs 2 and 3. Especially since the difference in performance is small, it can be said that limiting the hourly power rating for the BESSs in a VPL to 500 MW does not significantly alter its performance. Hence the same conclusions can still be drawn while using the simplification of an unlimited hourly power rating from the BESSs. However, if the realistic limit of the hourly power rating is instead 250 MW, the performance of the VPL decreases further, and while still showing the same trend as the unlimited simulations, the magnitudes will differ more.

The VPLs connected across BZB4 seem to be quite indifferent to which geographical location they are placed at. The simulation of VPLs 7, 8 and 9 combined shows almost identical results compared to all three VPLs run individually. A possible explanation for this is that BZB4 is only connected to SE3 in the model. All other connections are symbolized by loads. This limits the number of routes power can take. The transmission capacity is also relatively evenly distributed between the power lines which connect Malmö with Ringhals, Tenhult and Oskarshamn, with a little more transfer capacity to Oskarshamn, which then goes on to Forsmark. The lowest transfer capacity is to Tenhult, where there is no load.

The BESSs in the VPLs at BZB4 was chosen with an energy rating of 5 000 MWh, the default value, and 1 000 MWh. This choice was made because of the identified lesser need for VPL capacity over BZB4. In table 10 it can be noted that 80 % of AOEPs are below 2 283 MWh for the EF scenario, significantly lower compared to the other BZBs. The overall need for a VPL is not as large at BZB4 as at BZB1. Consulting table 10, 80 % of AOEPs for the EP scenario are below 6 000 MWh, also indicating a smaller capacity need in the VPL.

The four last rows in tables 9 and 11 presents the results from multiple VPLs connected at the same time over different BZBs for the two scenarios. The conclusion that can be drawn from these simulations is that the VPLs do affect each other when run together, but the changes in performance are slight. VPLs situated geographically far from each other seems to be affecting each other less than closer neighbors. For example, there are no noticeable changes in performance when running VPLs 1 and 9 together in the EF scenario but running VPLs 6 and 7 at the same time seems to induce the largest mutual changes in both scenarios.

The magnitude of the changes in running multiple VPLs at the same time compared to on their own is small. It cannot be ruled out that some of the changes are magnified due to rounding errors since the changes generally occur in the last significant digit of the results. A general trend that can be noticed is that the changes are a little bit larger for the EP scenario compared to the EF scenario. This change can be attributed to the inherent differences in the two scenarios and can probably be explained by the lower variability in electricity production and smaller average power flows across BZBs in the EP scenario.

When introducing the power rating limit for VPL1 in two simulations the usage time increases. The more limited the power rating, the higher percentual usage time. This relates to the fact that it takes more hours for the VPL both to charge and discharge. Even if the usage time increases with increasing the limit on power rating, it is in general not desirable to limit the power rating, since it decreases the performance of the VPL in terms of how many overloaded hours and MWh overload it removes. Despite this, it is more realistic with a limited power rating for the BESSs.

For all VPLs it is true that an increase in energy rating of the BESSs does not result in a correspondingly large increase in the percentual usage time. There is an increase, but it is rather small. From the perspective of usage time, increasing the BESS's energy rating or power rating seems to have a diminishing return.

## 5.3 Electrification renewable - EF

To draw general conclusions in the EF scenario tables 8, 9 and 19 are studied together. In table 8 it can be seen that to remove 100 % of the MWh overload at BZB2 a VPL with BESSs with around 400 000 MWh capacity would be needed, which is not reasonable considering existing technology. Neither is it desirable since most of the MWh overload would be removed by a VPL with BESSs with much lower energy ratings. For example, a BESS with a capacity of 13 400 MWh would remove 80 % of MWh overload. Even if this is a very large BESS too, it is only 3,5 % as large as the BESS which removes all overloads.

This means that to go from removing 80 % of MWh overload to 100 %, the BESSs would have to increase with 2 860 %. This easily illustrates that the relationship between the size of the BESSs and the removed overloads is not linear. The same trend can be seen for BZB2 and BZB4 too, but not in as extreme terms.

Studying the values in % in table 9 makes the results more comprehensible, however the magnitudes of the overloads are lost. By studying either the note underneath table 9 or table 19 it can be seen that for BZB2, there are over 4 600 000 MWh overload from start, which can be compared to slightly over 2 000 000 MWh for BZB1 and approximately 670 000 for BZB4. This means that even though VPLs at BZB2 remove just under 30 % of MWh overload and VPLs at BZB1 remove around 40 %, the VPLs at BZB2 still remove around 454 000 MWh more overload compared to those at BZB1. It also means that even though the VPLs at BZB4 remove over 85 % of the overloaded hours, this still constitutes over 200 000 fewer removed MWh compared to the VPLs at BZB1, which only remove around 40 % of the overloaded hours. Thus, the VPL which removes the highest percentage of MWh overload across its BZB is not the same as the one which removes the largest amount of MWh overload.

When the size of the BESSs in the VPLs are increased, the average number of MWh that are removed increase from 40 to 58 % at BZB1, from 27 to 43 % at BZB2 and from 46 to 87 % at BZB4. The difference in BESS size is a factor two for BZB1 and BZB2 and a factor five for BZB4. The change in percentage points is approximately the same for BZB1 and BZB2, however it is over twice as large for BZB4, which is fitting, since the size of the BESSs increased the most for BZB4.

By closely comparing tables 8 and 9 for BZB4 in EF some differences can be observed. According to table 8, a VPL with BESSs of 5 000 MWh should cause a reduction in the amount of MWh overload somewhere between 90 and 95 %. This is though not the case when studying the results from the simulations in table 9, where the reduction is around 86 % with a BESS with a capacity of 5 000 MWh. This difference could be due to the residual errors that occur in the simulation.

For the EF scenario, the last column in table 9 shows the usage time for the different VPLs. In this case, out of the unlimited simulations, the VPLs over BZB4 are the most used, which corresponds well to them being the VPLs where the largest reduction in MWh overload happens. The large usage time also indicates that the BESS energy rating of 5 000 MWh is a good choice. Another reason for the high level of usage for VPLs connected over BZB4 can be found in table 8 where it can be seen that somewhere between 90% and 95% of AOEPs can be covered by a VPL energy rating of 5000 MWh.

## 5.4 Electrification dispatchable - EP

To be able to draw conclusions from the simulations in the EP scenario, the results from table 11 where the percentual changes comparing VPL and no VPL have to be regarded. The results from table 10 where the AOEPs are listed should also be taken into account. According to that table, a battery storage of around 420 000 MWh would be needed to cover all AOEPs over BZB1 during the three chosen years. This is hardly reasonable since it would correspond to more than 4 million electric vehicle batteries. Since the distribution of AOEPs over all BZBs are similar to the one displayed in figure 29 it is easy to see that a majority of AOEPs can be covered with a lot smaller energy storages compared to the size needed to cover the maximum values. This is also shown in table 10. If 80% of all AOEPs should be covered by the VPLs, battery storage sizes in the VPLs over BZB1 should be 16 550 MWh, over BZB2 they should be 11 318 MWh and over BZB4 they should be 5 998 MWh.

The amount of change in number of overloaded hours and MWh overload presented in table 11 does not show the entire picture. The note underneath table 11 or table 21 shows the actual values in absolute terms, and even though around 20% of MWh overload are removed with a VPL over BZB1, they are by far the most impactful VPLs in terms of the amount of reduced MWh overload. At BZB2, around 35% of overloads are removed, but in actual number of MWhs, it's only around 400 000 MWh compared to the around 1 000 000 MWh at BZB1.

When the battery storage size is increased at BZB1, the average percent of MWh overload that are removed increases from 18 to 27 %. The same number for BZB2 is 35 to 53 % and for BZB4 20 to 58 %. The difference in storage size is a factor two for BZB1 and BZB2 and a factor five for BZB4. The benefit of doubling the size of the storage at BZB1 in terms of percentual reduction in overloaded hours is not that impressive compared to BZB2, but keeping in mind the amount of MWh overload, the change is more substantial. At BZB4, the storage size of 1 000 MWh removes 20% of MWh overload, while a five times larger battery of 5 000 MWh only removes around 50 %. There is clearly a diminishing return in increasing the battery storage size at all BZB, even though it is the most prominent at BZB4.

It can be discussed if Case4 is needed for scenario EP, as there are 1 130 overloaded hours to work with from start. When using a 1 000 MWh storage for VPL7, the VPL manages to remove the majority of the MWh overload. This illustrates that there are overloads to work with. However, the number of overloaded hours at BZB4 without Case4 is low, which makes it interesting to study Case4. A conclusion from this is that even if the reinforcement package for BZB4 is completed, a VPL might still be useful, but it would be smaller compared to what is needed if the transfer capacity equals that in Case4. It is interesting to compare this simulation to the simulation of VPL7 with Case4, since the removal of overloads is much larger for VPL7 without Case4 compared to with Case4, but the usage time is almost the same. This means that a VPL with the same size and approximately the same usage time could give very different results in terms of how many MWh overload it removes depending on the capacity in the surrounding grid. Constructing a VPL with an energy ratio of 1 000 MWh could thus be beneficial at BZB4 both with and without Case4, but the efficiency of the VPL will differ depending on the transmission capacity across BZB4.

For the EP scenario, the last column in table 11 shows the amount of time the VPLs are used. The highest usage can be seen at BZB1 where the VPLs are used well over 20 % of the time during the simulated years. This can be explained since the actual number of overloaded hours and MWh overload at BZB1 is by far the largest. Over BZB2, the VPL is used only around 5% of the time, where it is around 10% over BZB4 for approximately the same reduction in MWh overload. Since battery lifetime is affected by the number of cycles they experience, a lower amount of usage is on one hand positive. On the other hand, low usage should also be put into contrast to the need for the VPL. A low percentual usage time but a large reduction in overloaded hours and MWh overload at the same time would be ideal.

## 5.5 Differences between the EF and EP scenarios

There are several differences between the simulation results from the two scenarios EF and EP. Most notable is perhaps the fact that the highest performing VPLs are not the same in the two scenarios. In scenario EP, the VPLs across BZB2 perform the best in terms of percent MWh overload removed, followed by VPLs at BZB4 and lastly VPLs at BZB1. In scenario EF VPLs at BZB4 are instead the highest performing VPLs, followed by VPLs at BZB1 and then at BZB2. This difference is owing to the fact that the location and characteristics of overloads vary between the scenarios. In the EP scenario, over 5 000 000 MWh overload occur at BZB1, followed by just over 1 000 000 MWh overload at BZB2 and BZB4, see table 11. In the EF scenario the same numbers are 2 000 000 MWh overload for BZB1, 4 600 000 for BZB2 and 670 000 for BZB4, see table 9. Thus, the total number of overloaded hours is approximately the same for the two scenarios, but they are distributed differently. This can be explained by the difference in both production type and location of the generation between the two scenarios.

It can also be seen that a higher percentage of MWh overload are removed in scenario EF at all BZBs. This can probably be explained by the different characteristics of the scenarios. The EF scenario has more intermittent power production compared to the EP scenario. A VPLs is put to best use in a power system where the loading of the reinforced lines varies a lot. This is due to the fact that the VPL needs recharging between its active phases, and this is more easily managed with variations of higher occurrence. If the variations instead occur with lower occurrence, the BESSs in the VPL need to hold their charge for longer, as well as provide power during longer periods of time, resulting in a larger need for capacity. The intermittent nature of the EF scenario can thus explain the larger amounts of reductions across the board in MWh overload compared to the EP scenario.

Another difference between the scenarios is the direction of flow over BZB4 where the EF scenario has a northbound flow compared to the southbound flow for the EP scenario. This difference of flow is due to the large implementation of offshore wind power in SE4, which generates excess electricity which is transported northward in the EF scenario. The different directions of flow cannot be seen in tables 9 and 11. Even though the direction of flow is different, it is still of approximately the same magnitude. The difference in flow direction can be seen in figures 21 and 22. The reduction in the amount of MWh overload in the EF scenario is larger than the reduction in the EP scenario which once again can be explained by the nature of the scenarios. In the EF scenario intermittent wind power generation is exported from SE4 to the rest of Sweden whereas SE4 is importing non intermittent power in the EP scenario.

## 5.6 Comparison to LMA data

In figures 21 and 22 it is evident that the Nordic46 model does not give the exact same results as the LMA-data from Svk, even if the input generation and consumption is the same for every bidding zone. These differences occur because the model used in this thesis work is not the same as the one used by Svk, which means that power can take different routes in the system. SE4 in the Nordic46 model is only connected to SE3 via transmission lines, which means that it is not possible for power to take a route through a different bidding zone to get from SE4 to SE3. This is the reason why the simulation results and the LMA data are almost identical for BZB4. When it comes to SE1, the situation is very different. SE1 has connections to both SE2, FI and NO4, which means that power transferring from for example SE2 to SE1 can transfer either directly over BZB1 or take the route via NO3 and NO4. Thus, even if the total power generated and consumed is the same in the Nordic46 model and in Svks model, the flows across specific BZBs differ. It is also worth noting that transfer limits are not enforced in PowerFactory, which means that specific lines can be loaded to over 200 % in the simulations. This is not the case in the LMA data, which is why there are overloads in both BZB1 and BZB2 in the simulation results, which are not present in the LMA data.

The reason for comparing the simulation results to the LMA data is not to be able to replicate the exact results of Svk, but more to make sure that the Nordic46 model gives reasonable outputs. Other than that the simulation results are not compared to the LMA data, since it is only of interest how the simulation results change when using a VPL or not.

## 5.7 Location

There are several factors making it difficult to discuss the localisation of the VPLs. The main factor is the coarseness of the Nordic46 model with the resulting coarseness in distribution of loads and generation in the network. Another related factor is the fact that the VPLs are used to improve the transmission capacity over the BZBs even though they are placed as reinforcement to individual power lines.

In an attempt to better simulate the reinforcement of entire BZBs, some of the simulations were carried out with all VPLs over each BZB active at the same time. These simulations roughly resulted in an average of the individual simulations. This average seems to be reasonable in theory, and since the entire BZB is studied this is expected. However, the solution with three separate VPLs on vastly different geographical locations with smaller capacities to reinforce the entire BZB is quite unlikely in a real-world application. The most likely approach in reality would probably be to reinforce the individual power lines over the BZB that experienced the most overload. Trying to reinforce the entire BZB at once by placing smaller BESSs at many different locations, with a varying degree of usefulness, is an ineffective approach with regards to time spent planning and acquiring permissions compared to developing larger VPLs at fewer locations. It should be noted that large BESSs could pose a problem to the N-1 criteria, since if they are to large, the system might not be able to stay stable if they are disconnected or malfunction.

It's hard to draw conclusions regarding individual VPLs over the different BZBs in the two scenarios. The biggest difference between VPLs across the same BZB is VPL1 over BZB1 in both scenarios where the improved performance of VPL1 probably can be attributed to the significantly higher load on the underlying actual power line. This is quite a specific case, and the general conclusion that can be drawn is that using VPLs over the most heavily loaded actual lines is the most beneficial.

The goal of this work is not to predict the exact placement of VPLs in the future, but rather to investigate their usefulness and their contribution to the system. Keeping that in mind, it's easier to draw conclusions on the level of BZBs in the Swedish electrical grid rather than individual power lines. Firstly, the need for VPLs is clearly the largest over BZB1, both in the EF and EP scenarios since there are a lot of overloaded hours occurring in these future scenarios even when no case with reduced capacity is studied.

When studying the system with Case2 and Case4 applied, reducing transmission capacities over BZB2 and BZB4, the next most important VPLs can be discerned. In the EF scenario, the VPLs over BZB2 are more important than the VPLs over BZB4 with regards to the amount of MWh overload that are reduced. The percentual reduction is larger for the VPLs over BZB4, but since the amount of MWh overload without VPLs is so much greater for BZB2, the overall benefit is larger for the VPLs over BZB2. In the EP scenario, the VPLs over BZB4 can be said to be more important than the VPLs over BZB2 since the amount of overloaded energy as well as overloaded hours reduces the most. In the EP scenario, the direction of flow over BZB4 is southbound, compared to northbound in the EF scenario.

## 5.8 Size

What the optimal size of the BESSs in a VPL is depends on many different parameters. To a large extent it is a trade-off between how many MWh overload one wishes to remove, and how expensive the VPL is. Profitability is important in order to realize projects like this, but seeing as economy is excluded from this work, no such profitability analysis is done. Thus, when discussing BESS size here it is only evaluated whether it is technically reasonable, and not whether it is economically reasonable. In reality however a profitability analysis of the VPL would need to be done.

The BESS energy ratings used in the thesis work, 1 000 to 10 000 MWh, are all reasonable examples of energy capacities in terms of the results gained from the simulations. There is a reduction in the amount of MWh overload for all simulations, and none of them results in a removal of more than 90 % of MWh overload. This indicates that no VPL is unreasonably small, since reductions could be seen for all, and no VPL is too large, since all overloads are not removed. If anything, BZB1 and BZB2 could make use of even larger VPLs than 10 000 MWh. However, a BESS of 10 000 MWh is large, even with projections of a booming battery market. For that reason, larger BESSs than that are not used, even if they may be feasible in 2045 if circumstances are favourable.

Current power ratings of VPLs are of a couple 100 MW. Considering the fact that the market for BESSs is booming at the moment and is expected to continue to grow, because of the high demand for batteries, it is not unreasonable to assume BESSs of a couple of 1 000 MW in 2045. Especially since ERCOT already has over 3 000 MW installed BESS used for ancillary services. It must however be noted that in the simulations in this thesis work only the total BZB capacity was studied when operating the VPL. In reality the VPL would be connected over one or several transmission lines, and only consider the loading of those specific lines. It seems unnecessary to have a VPL of 5 000 MW if the power line underneath has a maximum transfer capacity of 1 000 MW, because then the full capacity of the VPL is never needed. Thus, it would be over dimensioned. The VPL should hence not be larger than that the maximum capacity can be used. If, even after using one VPL, there is still a need for more transfer capacity across the BZB, it will be more efficient to use a second VPL between two new nodes across the BZB.

By looking at tables 8 and 10 it is clear that dimensioning a VPL for removing all overloads across a BZB results in an unrealistically large BESSs. Even if the size would be within reason to install, it would not be efficient to try to remove 100 % of the overloads with a VPL, since a much smaller BESS would probably remove 80 or 90 % of MWh overload, as illustrated in tables 8 and 10. This is also evident from figure 27, where it can be seen that a BESS of about 5 000 MWh would remove over 70 % of the AOEPs. It is therefore probably most reasonable to try to remove somewhere between 80 or 90 %, perhaps even less, with the VPL, and then try to remove the remaining overloads in some other way. A VPL is only meant to be one part in the solution to the problem with overloads in the transmission network.

The optimal size of a VPL is also dependent on which BZB it is placed over. This in turn is dependent on where large flows occur in the system, and especially where these occur together with bottlenecks. In the EF scenario, the largest VPL is required over BZB2, followed by BZB1 and BZB4. In the EP scenario the order is BZB1, BZB2 and BZB4, with in general higher maximum AOEPs compared to EF. Common for both scenarios are that the smallest VPL is required for BZB4. Also, if Case2 and Case4 are removed, there is no need, or a very small need, for a VPL at both BZB2 and BZB4. At BZB1 there is a need for VPL in both scenarios, and a size of 5 000 MWh and 10 000 MWh is not too large in any of the scenarios in terms of the number of removed MWh.

Adding to the complexity of optimal BESS energy rating, the usage time presented in tables 9 and 11 have to be regarded. The optimum is to achieve a VPL that is in standby the majority of the time, saving on charging cycles, but also managing to remove as many of the MWh overload as possible. A clear example of this is the VPLs over BZB4 where a larger BESS energy rating manages to remove more MWh overload (more than double the amount of MWh removed) while the usage increases less than a factor of 2. The same is true for the VPLs over BZB1 where a small increase in usage of the BESS, from 21 to 26 %, increases the MWh overload removed by 50%.

Another way of determining the optimum BESS energy capacity is to strive for as high a number of removed MWh as possible but as few cycles as possible. This way the batteries in the BESS last longer, which is more sustainable. However, this problem can be solved by simply increasing the BESS energy capacity so that it would be large enough that only a handful cycles would remove all overloads. This is unreasonable and unrealistic in terms of resources. A BESS must go through a certain number of cycles in order to be used so much that it is justified to be installed. Thus, the usage factor should only be considered within reasonable limits.

## 5.9 Legal framework

In the legal framework for ESSs in the electricity grid in Sweden, it is stated that network companies are not allowed to sell and buy electricity from an ESS in order to profit from it, since that affects the competition on the market. VPLs are in general power neutral, since they buy and sell at the same time. However, there might be a legal grey area when it comes to using VPLs across BZB, since from time to time, one BESS might buy electricity at a different price compared to what the other BESS sells for, while the VPL is still power neutral. Using the VPL to facilitate electricity transfer across the BZB could lead to lower price differences between the areas, which of course affects the market, but should be considered as beneficial. If the VPL increases the transfer capacity to such a degree as to which there are no bottlenecks left, and thus no price differences, there would no longer be profit in buying and selling at different prices, but the market would be affected. It could be argued that using power neutral VPLs across BZB does not affect the market in any other way than transmission lines, and that it thus should be considered acceptable. Whether VPLs crossing BZBs is within the current legal framework or if the effect on the market is unacceptable remains to be seen.

## 5.10 Climate and environmental impact

Since a VPL is primarily thought to be used while waiting for a decision and or construction of a transmission line, or if an increased need for transmission capacity arises for a shorter period of time, it is important to consider the climate and environmental impact of the VPL. As stated in section 2.6.2 the majority of the lithium-ion batteries produced today are manufactured using energy from fossil fuels, which gives them a relatively high climate impact. A VPL with two BESSs of 5 000 MWh capacity each would result in somewhere between 610 000 and 1 060 000 tonnes $CO_2$e based on the span 61-106 kg $CO_2$e/kWh battery capacity presented earlier. If Northvolt succeeds with their aim to provide lithium-ion batteries with a climate impact of 10 kg $CO_2$e/kWh, the total carbon footprint of the VPL would instead be 100 000 tonnes $CO_2$e. This can be compared to the climate impact of a transmission line. If it is assumed that the linear distance between Porjus and Grundfors, thus where VPL1 is placed, is 250 km, and that the climate impact is $\frac{55000}{50} = 1\ 100$ tonnes $CO_2$e/km, see figure 6, the total climate impact of building a new power line here would be $1100 * 250 = 275\ 000$ tonnes $CO_2$e. Thus, building a power line of 250 km has a smaller carbon footprint compared to the BESSs of a VPL, unless Northvolt succeed with their goal of low carbon batteries. One must also consider that building a VPL with a total BESS capacity of 10 000 MWh is not equivalent to a new 400 kV overhead line. Additionally, the VPL is useless unless there is an existing transmission system it can use to charge and discharge. The VPL can also only be used to a certain extent. When the transmission line it is placed across is constantly full in the studied direction, nothing more can be done with the VPL.

Since there is most often not a question about replacing a transmission line with a VPL, but rather to use the VPL while waiting for the transmission line it might be more interesting to think of the climate impact from the BESSs in the VPL as additional climate impact. If this climate impact would be added to the climate impact from the transmission line, the total climate impact from the transmission line would increase between 36 and 285 % if Northvolts goal is considered as the lower limit. An increase with 36 % could perhaps be considered as acceptable, but 285 % would rarely be seen as acceptable. However, arguing that a 36 % increase is acceptable could make it seem as additional carbon emissions do not matter, which they do in terms of climate change. Therefore, it would be preferable to shorten the process time for building new transmission lines, so that these additional emissions do not have to emerge. If this is not possible, then it can be argued that since a VPL decreases the number of hours when a BZB acts as a bottleneck, and therefore facilitates the transfer of electricity in Sweden, it also facilitated the transition to green energy. This in turn could come with carbon savings. In that way it could be argued the carbon footprint of the VPL can be acceptable.

The carbon footprint of a transmission line is dependent of its length. The carbon footprint for a VPL on the other hand only depends on its BESS's energy rating. Comparing a VPL from Hjälta to Ringhals gives a more favourable result than the one in the previous paragraph. The distance between Hjälta and Ringhals is around 720 km as the crow flies, giving a carbon footprint of 720 * 1 1000 = 792 000 tonnes of CO2e. If the capacity between these buses would need to be increased by a VPL ahead of building a transmission line, the carbon footprint of the transmission line would increase by 13 to 34 % over this longer distance. Thus the longer the transmission line is, and the smaller the BESSs, the more acceptable the VPL would become in terms of climate impact. A large VPL over a short distance is hence unreasonable to use.

In addition to the climate impact from the lithium-ion batteries there are also several different environmental impacts. Unless these can be avoided through for example changing the process through which raw materials are extracted, these impacts must be weighed against the advantages of using a VPL in each case where a VPL is considered. In addition to this, there is currently no recycling method that provides pure and separated materials, which can easily be used to manufacture new batteries, even if Northvolt aims to accomplish this. Recycling is thus also an issue which must be considered and solved if it's going to be possible to use lithium-ion batteries in the transmission grid in a sustainable way.

# 6 Conclusions

Based on the simulations carried out for the scenarios EF and EP from Svk, it is clear that VPLs can benefit the future Swedish power system, if society progresses in a direction similar to scenarios EF and EP. Thus, VPLs can benefit the system no matter if nuclear power is included or not. If all grid expansion and reinforcement packages are fulfilled by 2045, there will primarily be a need for reinforcement at BZB1, both in the EF and EP scenario. At BZB2 there are no overloads in either EF or EP, which means that there is no need for a VPL. At BZB4 there are some overloads for the EP scenario, but not for the EF scenario. Hence, a VPL of 1 000 MWh or less could benefit BZB4 in the EP scenario, but there is no need for a VPL in the EF scenario.

If the reinforcement package scheduled for 2040 for BZB2 is delayed, there are overloads which a VPL can be used to remove both in the EF and EP scenario. The amount of overloads is significantly higher in the EF scenario compared to the EP scenario, which indicated a larger benefit can be reached for the EF scenario compared to the EP scenario. If the transfer capacity at BZB4 equals that in Case4, there are overloads on which a VPL can be used, primarily for the EP scenario. The amount of overloads at BZB4 in the EF scenario is somewhat lower, and therefore, so is the need for a VPL.

Reducing the transfer capacity at BZB2 and BZB4 according to Case2 and Case4 can be interesting even if the reinforcement packages are fulfilled by 2045. The VPLs could be used during longer maintenance work which decreases the transfer capacity across a BZB. If the VPL is relocatable, this would be particularly beneficial, since one VPL could be used to facilitate transmission in maintenance work all over Sweden.

It can also be concluded by the simulations that using VPLs in the Swedish power system could work. They help decrease the amount of overloads on all three Swedish BZB. Using logic conditions as a control system for a VPL is also concluded to work, since the simulated VPLs charge and discharge when they are supposed to.

There are several factors that are important to consider when determining both the energy rating and the power rating from a VPL. The power rating has to be chosen both with regards to the battery technology at hand as well as the needed power rating to the network. Also, the BESS's ability to charge with the power ratio provided has to be considered. In general, with regards to current technologies, the power rating of the VPLs should not be a limiting factor.

The main conclusion regarding the capacity of the BESSs in the VPLs is that it would be unpractical to use VPLs to remove 100% of the overloads in any of the simulated situations since the capacities of the BESSs would need to be unreasonably large. The task of choosing a suitable BESS energy rating then comes down to choosing the amount of AOEPs to reduce. The question of the lifetime of the BESS also comes into play where a hard-working BESS with a lot of deep discharges degrades a lot faster than if it was used more sparingly. Optimizing the reduction in MWh overload while keeping down the number of cycles of the BESS would prolong its life. The 1 000 to 10 000 MWh of energy rating used in this work seems to be reasonable in terms of technological limits, but since economic factors are out of scope, these would also need to be studied before any kind of investment discussions could start. It should also be noted that there seems to be a diminishing return in the removal of overloaded MWh when increasing the energy rating of the VPL.

Lastly, it can be concluded that even if VPLs are one solution to the problem with lack of transfer capacity across the Swedish BZBs, there are other factors which will need to be studied in order to decide if it is a satisfactory solution. Most important of these is probably to study the profitability of a VPL, since an unprofitable system never would be implemented without heavy subsides. Finally, one must also weight the environmental and climate impact for the VPL against the benefits the VPL generates for the system, in order to decide if VPLs should be a part of the future energy system. From a climate perspective it is unreasonable to use a large VPL instead of a short transmission line, but more reasonable to use a small VPL instead of a long transmission line. However, if it is a matter of using the VPL while waiting for the power line to be built, it is, from a climate perspective, wiser to speed up the time it takes to permit and build new power lines, so that the VPL is not needed in the first place.

# 7 Further studies

There are several interesting aspects that surfaced during the work process that there was not enough time to explore. These are presented here as suggestions for future work.

Since the aim of this thesis work was to try to remove all overload energy, no consideration was given to reduce the maximum overloaded power. As a too high power can damage equipment this should be studied. A suggestion is to introduce a maximum power limit for the active power transfer across the BZBs and use the VPL to remove everything above that limit.

There are several changes that could be made in order to make the simulated VPLs more realistic. For example losses could be added to the VPL. The control system of the VPL could also be changed to for example a PID regulator or with AI/Machine learning in order to make the control system better. The VPLs could also be controlled based on the individual power lines or smaller areas across which they are connected, and not based on an entire BZB. If possible, it would also be interesting to conduct a similar study on a model with a higher resolution, so that VPLs can be studied in specific locations. This could be done by adding more nodes in Sweden in the model to better represent the Swedish power grid. That way, VPLs crossing Sweden from the east to the west, or west to east, could also be studied.

To use VPLs as a single solution for removing overloads in the system is probably not going to happen in reality. It would therefore be interesting to combine VPLs with other flexibility solutions to see how that changes the results. Carrying out an economic analysis on whether or not it is profitable to use VPLs in the Swedish power system is also interesting. Ideally an optimisation between the cost and the number of removed MWh would be performed to determine a suitable size of the VPL for each BZB, both considering current ESS prices and future prices.

To cover more cases there are several other scenarios for the future power system in Sweden available. The study could be performed for some of these other scenarios in order to check if the results differ from the ones gained in this work. Other variations of VPLs would also be interesting to study. For example, bidirectional VPLs, VPLs between Sweden and other countries and VPLs connected between two nodes between which there are no direct power lines. It could also be interesting to study other types of ESS than BESS, for example pumped hydro. Another possibility is to do dynamic simulations of the VPLs and the surrounding power system.

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# A Changes in the Nordic 44 model

## A.1 Nomenclature of loads and generation

In table 12 the nomenclature in the Nordic46 model is explained.

Table 12: *Explanation of nomenclature of added parts in the Nordic46 model.*

| **Name** | **Representation** |
|---|---|
| ons_ *busnumber* _1 | Onshore wind generation |
| offs_ *busnumber* _1 | Offshore wind generation |
| pv_ *busnumber* _1 | Solar generation |
| lod_ *busnumber* _1 | Consumption + LoadCurtail |
| lod_ *busnumber* _5 | HVDC linc |
| lod_ *busnumber* _6 | RESCurtail |
| sym_ *busnumber* _11 | Turbine OR Hydro generation |
| sym_ *busnumber* _12 | Synchronous compensators |

## A.2 HVDC - lincs

The HVDC links originally present in the Nordic44 model are listed in table 13.

Table 13: *HVDC links modelled in Nordic44.*

| **Name** | **From** | **To** |
|---|---|---|
| Swepol | Sweden | Poland |
| Baltic Cable | Sweden | Germany |
| Estlink | Finland | Estonia |
| Fennoscan | Sweden | Finland |
| Kontiskan | Sweden | Denmark |
| Skagerak | Norway | Denmark |
| Norned | Norway | Netherlands |

In table 14 the changes concerning the NVDC links in the Nordic46 model can be seen.

Table 14: *Changes concerning the HVDC-links in the Nordic46 model.*

| **Mothernode** | **HVDC-node** | **Changes** |
|---|---|---|
| 7000 | 7010 Fennoskan | Name changed to 7010 Fennoskan+Estlink. Load from 7020 Estlink-HVDC moved here. |
| 7000 | 7020 Estlink | Removed because added to 7010. |
| 8500 | 8600 Baltic cable | Name changed to 8600 South.<br>Three loads are added which represent the Baltic cable, Swepol and Nordbalt. |
| 8500 | 8700 Swepol | Removed because added to 8600. |
| 5600 | 5620 Norned | Name changed to 5620 NO2South.<br>Two loads added, 5620-5 and 5621-5, which represent NorNed and Nord.link. |
| 5300 | 5310 NO5GB | New HVDC link representing the HVDC linc between Norway and GB. |
| 6000 | 6010 North Sea link | New HVDC link representing the North Sea linc. |
| 3100 | 3110 Fennoskan 3 | New HVDC link representing Fennoskan 3. |
| 7100 | 7110 Fennoskan 3 | New HVDC link representing Fennoskan 3. |

## A.3 Changes concerning power lines

In table 15 the current and future transfer capacities are listed, based on projects undertaken by Svk which increases the transmission capacity across the BZBs [12]. The transfer capacities for 2045 are the ones on which the changes concerning the transmission capacity in the Nordic46 model are based. These changes can be seen in table 16.

Table 15: *Current and future transmission capacities across BZBs based on planned changes according to Svk [12].*

| **Bidding zone border** | **Current capacity [MW]** | **Capacity 2035 [MW]** | **Capacity 2045 [MW]** |
|---|---|---|---|
| SE1 ↔ SE2 | 3300 | 3300 | 3300 |
| SE2 ↔ SE3 | 7300 | 8100 | 10500 |
| SE3 → SE4 | 6200 | 6800 | 6800 |
| SE4 → SE3 | 2800 | 3200 | 3200 |
| SE1 → FI | 1500 | 2000 | 2000 |
| SE2/SE3 → FI | 1200 | 1200 | 3600 |
| SE1 → NO4 | 600 | 600 | 600 |
| NO4 → SE1 | 700 | 700 | 700 |
| SE2 → NO4 | 300 | 300 | 300 |
| NO4 → SE2 | 250 | 250 | 250 |
| SE2 → NO3 | 1000 | 1000 | 1000 |
| NO3 → SE2 | 600 | 600 | 600 |
| SE3 → NO1 | 2095 | 2095 | 2095 |
| NO1 → SE3 | 2145 | 2145 | 2145 |
| SE3 → DK1 | 715 | 715 | 715 |
| SE4 → DK2 | 1300 | 1300 | 1300 |
| DK2 → SE4 | 1700 | 1700 | 1700 |
| SE4 → DE | 615 | 615 | 615 |
| DE → SE4 | 600 | 1315 | 1315 |
| SE4 ↔ PL | 600 | 600 | 600 |
| SE4 ↔ LT | 700 | 700 | 700 |

Table 16: *Power lines where alterations in the number of parallel lines were made in the base case, Case2 and Case4.*

| **Bidding zone border** | **Power line** | **# of parallell lines base case** | **# of parallell lines Case2** | **# of parallell lines Case4** |
|---|---|---|---|---|
| SE1 ↔ SE2 | lne_3115_3244_1 | 3 | 3 | 3 |
| SE1 ↔ SE2<br>SE2 ↔ SE3 | lne_3000_3115_1 | 2 | 2 | 2 |
| SE2 ↔ SE3 | lne_3100_3359_1 | 2 | 2 | 2 |
| SE2 ↔ SE3 | lne_3100_3359_2 | 2 | 2 | 2 |
| SE2 ↔ SE3 | lne_3100_3200_1 | 2 | 1 | 2 |
| SE2 ↔ SE3 | lne_3100_3200_2 | 2 | 1 | 2 |
| SE2 ↔ SE3 | lne_3100_3200_3 | 2 | 2 | 2 |
| SE2 ↔ SE3 | lne_3000_3245_1 | 2 | 1 | 2 |
| SE2 ↔ SE3 | lne_3000_3245_2 | 2 | 2 | 2 |
| SE3 ↔ SE4 | lne_3359_8500_1 | 2 | 2 | 2 |
| SE3 ↔ SE4 | lne_3359_8500_2 | 2 | 2 | 1 |
| SE3 ↔ SE4 | lne_3200_8500_1 | 2 | 2 | 2 |
| SE3 ↔ SE4 | lne_3300_8500_1 | 2 | 2 | 2 |
| SE3 ↔ SE4 | lne_3300_8500_2 | 2 | 2 | 2 |

## A.4 Changes concerning generators

A choice was also made to keep all generators that was previously present in the model. It is possible to aggregate all generators of the same type on the same bus to one big generator. It is however decided that keeping all generators better enables any future dynamic simulations. There is no change in which generators represent hydro power, HYGOV, and which represent steam turbines, IEESGO. In IEESGO nuclear power and thermal power are included. In order to be able to add hydro power, nuclear and thermal power to all bidding zones, generators are added so that there is at least one generator of each type in every real bidding zone. The added generators are copied from generators that are already present in the system, with the goal of them being around the same size, 500 MW. The generators that are added in order to have one generator of each type in each area can be seen in table 17. No generators are added in Finland, since Finland already has both types of generators.

Table 17: *Hydro or turbine generators added to Nordic 44.*

| **Name** | **Bidding zone (real)** | **Location** | **Type** | **Size [MW]** | **Copied from** |
|---|---|---|---|---|---|
| sym_3115_11 | SE1 | Porjus | IEESGO | 500 | sym_8500_5 |
| sym_3245_11 | SE2 | Järpströmmen | IEESGO | 540 | sym_3359_5 |
| sym_3359_11 | SE3 | Ringhals | HYGOV | 512 | sym_3249_7 |
| sym_8500_11 | SE4 | Malmö | HYGOV | 425 | sym_3115_3 |
| sym_6700_11 | NO4 | Rössåga | IEESGO | 500 | sym_8500_4 |
| sym_6500_11 | NO3 | Trondheim | IEESGO | 500 | sym_8500_4 |
| sym_5500_11 | NO1 | 5500 | IEESGO | 540 | sym_3359_5 |
| sym_5600_11 | NO2 | Kristiansand | IEESGO | 500 | sym_8500_4 |
| sym_5300_11 | NO5 | Sima | IEESGO | 500 | sym_8500_4 |

# B Python Code

```
#The battery_controller function is the logic behind the VPLs.
#    input arguments:
#        PflowBus1: old simulation results used in comparaisons
#        PflowBus2: old simulation results used in comparaisons
#        SnittKapacitet: Dictionary containing the BZB capacities
#        SoC: Dictionary containing State of Charge of the batteries and their names
#        charge_dict: Dictionary containing info about what values to assigne to the PF objects
#        index: index of current iteration
#        Name_List_Battery: list of VPL batteries
#    return:
#        charge_dict: Dictionary containing info about what values to assigne to the PF objects
#        SoC: Dictionary containing State of Charge of the batteries and their names

def battery_controller(PflowBus1, PflowBus2, SnittKapacitet, SoC, charge_dict, index,
     Name_List_Battery):
    #Defining lines that cross BZBs
    snitt1 = [’lne_3115_3245_1’, ’lne_3115_3249_1’, ’lne_3100_3115_1’, ’lne_3000_3115_1’]# Lines in
         opposite direction: lne_3100_3115_1 and lne_3000_3115_1
    snitt2 = [’lne_3100_3359_1’, ’lne_3100_3359_2’, ’lne_3100_3200_1’,  ’lne_3100_3200_2’, ’
         lne_3100_3200_3’, ’lne_3000_3245_1’, ’lne_3000_3245_2’, ’lne_3000_3115_1’] # Lines in
         opposite direction: lne_3000_3245_1, lne_3000_3245_2, lne_3000_3115_1
    snitt4 = [’lne_3359_8500_1’, ’lne_3359_8500_2’, ’lne_3200_8500_1’, ’lne_3300_8500_1’, ’
         lne_3300_8500_2’]

    P_flow_snitt = pd.DataFrame(columns=[’Snitt1’, ’Snitt2’, ’Snitt4’])

    #Calculating active power over the different BZBs
    P_flow_snitt[’Snitt1’] =[ PflowBus1[snitt1[0]] + PflowBus1[snitt1[1]] + PflowBus2[snitt1[2]] +
         PflowBus2[snitt1[3]]]
    P_flow_snitt[’Snitt2’]= [PflowBus1[snitt2[0]] + PflowBus1[snitt2[1]] + PflowBus1[snitt2[2]] +
         PflowBus1[snitt2[3]] + PflowBus1[snitt2[4]] + PflowBus2[snitt2[5]] + PflowBus2[snitt2[6]] +
         PflowBus2[snitt2[7]]]
    P_flow_snitt[’Snitt4’] = [PflowBus1[snitt4[0]] + PflowBus1[snitt4[1]] + PflowBus1[snitt4[2]] +
         PflowBus1[snitt4[3]] + PflowBus1[snitt4[4]]]

    for ind,row in Name_List_Battery.iterrows():
        Snitt = row[’Snitt’]
        if row[’flow_direction’] == ’North’: #The direction of the VPL is south to north
            if P_flow_snitt[Snitt][0][index] <= 0: # Power flow from south to north
                if row[’Snitt’] == ’Snitt4’:
                    SnittKapacitet[’Snitt4’] = SnittKapacitet[’Snitt43’]
                diff = abs(P_flow_snitt[Snitt]) - SnittKapacitet[Snitt] # Diff is the excess power
                if P_flow_snitt[Snitt][0][index] < -SnittKapacitet[Snitt]: #The flow is larger than
                     BZB capacity
                    if SoC[row[’demand_names’]][1] > 0: # If the battery is charged and can be used
                        result = discharge(diff[0][index], SoC[row[’demand_names’]])
                        charge_dict[row[’demand_names’]] = - result # Discharge the demand side
                             battery
                        charge_dict[row[’supply_names’]] = result  # Charge the supply side battery
                        SoC[row[’demand_names’]][1] = SoC[row[’demand_names’]][1] - result # Remove
                             used energy from the battery
                        SoC[row[’supply_names’]][1] = SoC[row[’supply_names’]][1] + result
                    else: # Tha battery isn’t charged, standby
                        charge_dict[row[’demand_names’]] = 0
                        charge_dict[row[’supply_names’]] = 0
                elif P_flow_snitt[Snitt][0][index] == -SnittKapacitet[Snitt]: #BZB at capacity,
                     standby
                    charge_dict[row[’demand_names’]] = 0
                    charge_dict[row[’supply_names’]] = 0
                else: # BZB not at capacity
                    if SoC[row[’demand_names’]][1] < SoC[row[’demand_names’]][0]: # If SoC is less
                         than the battery capacity
                        result = charge(diff[0][index], SoC[row[’demand_names’]])
                        charge_dict[row[’demand_names’]] = result # Charge the demand side battery
                        charge_dict[row[’supply_names’]] = - result  # Discharge the supply side
                             battery
                        SoC[row[’demand_names’]][1] = SoC[row[’demand_names’]][1] + result # Add
                             energy to the battery
                        SoC[row[’supply_names’]][1] = SoC[row[’supply_names’]][1] - result
                    else: # Battery is already fully charged, standby
                        charge_dict[row[’demand_names’]] = 0
                        charge_dict[row[’supply_names’]] = 0
            else: # The direction of the VPL is norht to south, standby
                charge_dict[row[’demand_names’]] = 0
                charge_dict[row[’supply_names’]] = 0
        else: # Direction south, same principle as northbound VPL
            if P_flow_snitt[Snitt][0][index] >= 0:
                if row[’Snitt’] == ’Snitt4’:
                    SnittKapacitet[’Snitt4’] = SnittKapacitet[’Snitt34’]
                diff = P_flow_snitt[Snitt] - SnittKapacitet[Snitt]
                if P_flow_snitt[Snitt][0][index] > SnittKapacitet[Snitt]:
                    if SoC[row[’demand_names’]][1] > 0:
```

```
                        result = discharge(diff[0][index], SoC[row['demand_names']])
                        charge_dict[row['demand_names']] = - result
                        charge_dict[row['supply_names']] = result
                        SoC[row['demand_names']][1] = SoC[row['demand_names']][1] - result
                        SoC[row['supply_names']][1] = SoC[row['supply_names']][1] + result
                    else:
                        charge_dict[row['demand_names']] = 0
                        charge_dict[row['supply_names']] = 0
                elif P_flow_snitt[Snitt][0][index] == SnittKapacitet[Snitt]:
                    charge_dict[row['demand_names']] = 0
                    charge_dict[row['supply_names']] = 0
                else:
                    if SoC[row['demand_names']][1] < SoC[row['demand_names']][0]:
                        result = charge(diff[0][index], SoC[row['demand_names']])
                        charge_dict[row['demand_names']] = result
                        charge_dict[row['supply_names']] = - result
                        SoC[row['demand_names']][1] = SoC[row['demand_names']][1] + result
                        SoC[row['supply_names']][1] = SoC[row['supply_names']][1] - result
                    else:
                        charge_dict[row['demand_names']] = 0
                        charge_dict[row['supply_names']] = 0
            else:
                charge_dict[row['demand_names']] = 0
                charge_dict[row['supply_names']] = 0

    return charge_dict, SoC


#The separate discharge and charge functions both the same arguments.
#    diff: The difference between available capacity and wanted power flow
#    SoC_bat: The state of charge of the batteries in the VPL
#    return: b, the amount to charge or discharge.

def discharge(diff, SoC_bat):
    b = 0
    limit = 250 # Here is the possibility of limiting power rating of the battery
    if diff >= SoC_bat[1]:# Empty all of the energy in the battery
        if diff<=limit: #if the needed power is less than the limited power rating
            b = SoC_bat[1]
        else: # if the needed power is greater than the limited power rating
            d = limit
    else: # There is more energy than needed stored
        if diff<= limit: # if the needed power is less than the limit
            b = diff
        else: # if the needed power is greater than the limit
            b=limit
    return b

def charge(diff, SoC_bat): # The principle is the same as above
    b = 0
    limit = 250
    diff = - diff
    how_much_can_we_load = SoC_bat[0] - SoC_bat[1]
    if diff > how_much_can_we_load:
        if how_much_can_we_load<=limit:
            b = how_much_can_we_load
        else:
            b = limit
    else:
        if diff<= limit:
            b = diff
        else:
            b = limit
    return b
```

# C Figures

## C.1 Limited power rating

In figure 31 the state of charge can be seen for a selected period of time both for one unlimited simulation with VPL1 and one with a limited power rating of 250 MW. Some small differences can be seen, but they largely show the same trends.

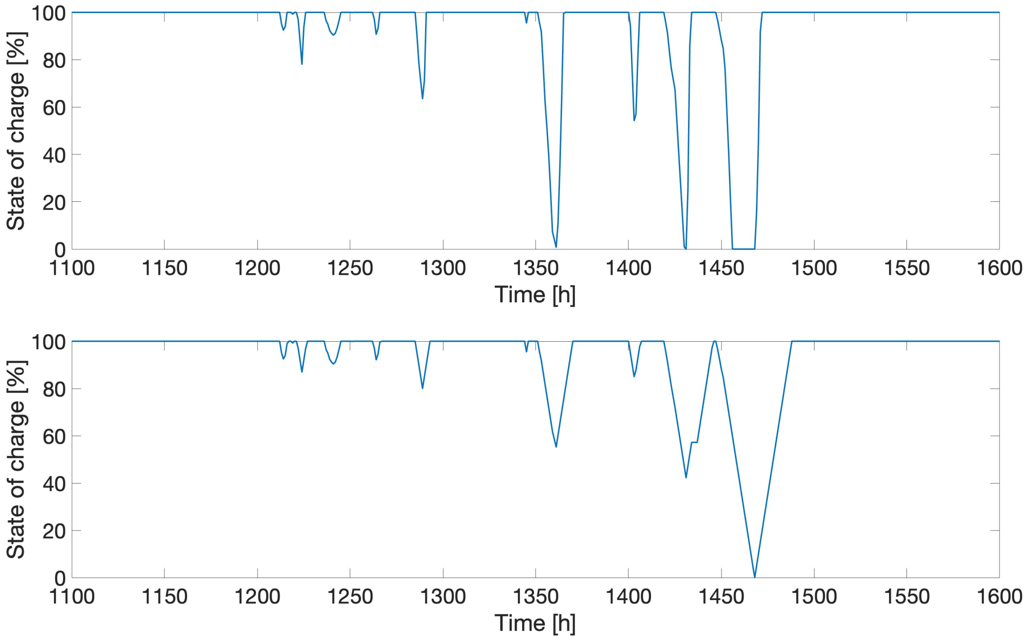
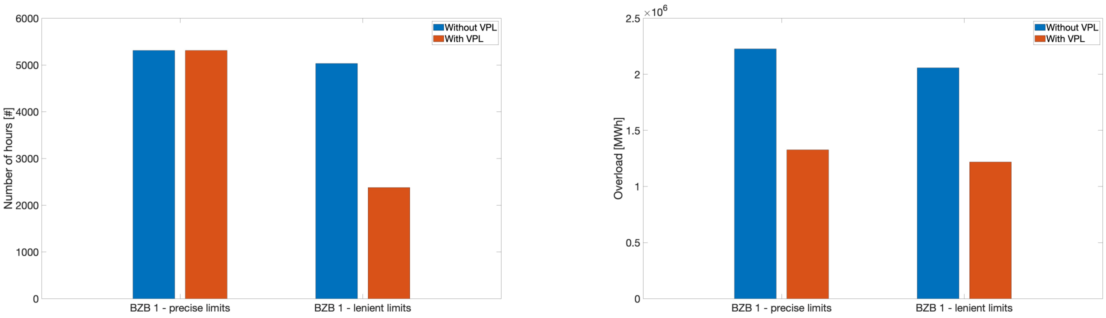


Figure 31: *The state of charge of the demand side BESS for VPL1. The upper graph represents the state of charge when the BESS system has an unlimited power rating, and the lower graph shows when the BESS has a limited power rating of 250 MW. The rate of changes in state of charge is lower when the power rating is limited.*

## C.2 Measuring the effect of VPLs

Using a precise limit of 100% of the BZB transfer capacity measures exactly how many overloaded hours or MWh overload that are reduced, while the lenient limit of 101% measures everything with an added error margin of one percent. This is done to capture what truly happens with the VPL and is in almost every case a better representation of what actually happens. Observing figures 32a and 32b the effects of the precise and lenient limits can be seen clearly. In figure 32a there is no difference in the number of overloaded hours with a VPL connected using the precise limit. This is due to the fact that the VPL does not reduce the overloads down to or below the limit. Comparing to the bar to the right in the same figure, the blue bar, representing overloads without the VPL, is slightly lower than the one using precise limits, since really small overloads are not counted. However, the big difference is in the bar representing overloaded hours using a VPL, which has shrunken a lot. In figure 32b the same differences can be spotted, but not as clearly. Since the MWh overload are calculated as the size of the overload in MW times the number of hours, the reduction in MWh with the VPL is visible both using precise and lenient limits.



(a) *The overloaded hours at BZB1 using VPL1 in the EF scenario.*

(b) *The MWh overload at BZB1 using VPL1 in the EF scenario.*

Figure 32: *Measuring the VPLs effect with a precise and a lenient limit.*

## C.3 Electrification renewable

### C.3.1 VPL4: Forsmark - Järpströmmen

In this section results from simulations with VPL4 are presented in more detail. VPL4 crosses BZB2 between Forsmark and Järpströmmen. In figure 33 the active power transfer across BZB2 is shown together with the active power for the two BESSs in VPL4 as well as the state of charge for one of the batteries for a chosen period of time. In the upper graph the blue curve shows the simulation results without the VPL and the red curve shows the simulation results with the VPL. In the upper graph positive flow means that power flows southward. It can be seen that some of the blue peaks over 8 100 MW are eliminated by using the VPL, since the red curve has fewer of those peaks. Note that the red curve sometimes stays at a level of approximately 8 100 MW even though the blue curve dips lower, see for example between hours 1500 and 1550. This means that the demand side of the VPL is using the available transfer capacity to charge. Note that the two BESSs in the VPL are active both at all events when the red and blue curve are not overlapping. By looking at the middle graph it is also evident that the two BESSs work in symmetry. When the red curve is positive in the lower graph it means that the VPL discharges on the demand side. Alternatively, when it is blue on the positive side it means that the demand side is charging. By studying the peak at approximately hour 1750 in the upper graph it can be seen that the size of the BESSs cannot cover the entire peak. When the two curves join it means that the demand side BESS is empty. In the bottom graph, the state of charge for the demand side BESS can be seen. The rapid changes in the state of charge is a result of there being no restrictions on how fast the BESS can charge or discharge.

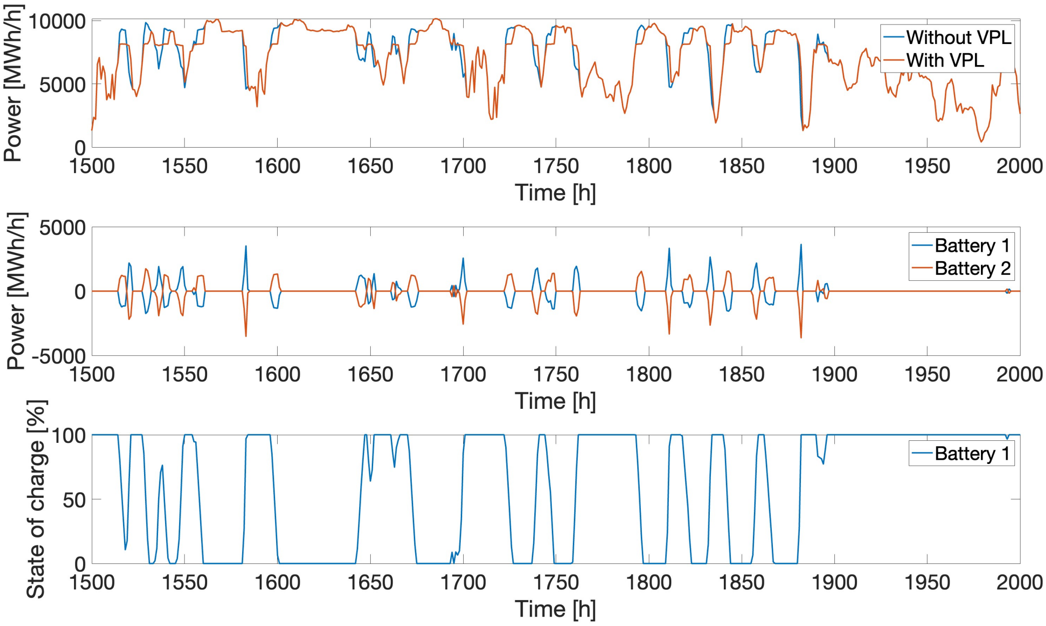


Figure 33: *The upper graph shows active power transfer across BZB2 both with and without VPL4 for a chosen period of time. The middle graph shows active power for the BESSs in VPL4 for the same chosen period of time for scenario Electrification renewable. The bottom graph shows the state of charge of BESS 1.*

The active power transfer, in % of the maximum transfer capacity, across BZB2 both with and without VPL4 can be seen in figure 34. The blue bars indicate the simulation results without VPL4 and the yellow ones represent the simulation with VPL4. Active power flow going southward is positive. When studying the right part of the graph between 100 % and 150 %, thus the number of hours with overloads across BZB2 from SE2 to SE3, it is clear that the yellow bars are lower than the blue bars for each bin. This means that the number of overloaded hours has decreased, which is done when the VPL discharges on the demand side. Consequently, it can also be seen that in bin 100 % the yellow bar is considerably larger compared to the blue bar. This is because the VPL use the hours when the BZB is less than 100 % loaded to charge, which increases the loading and fills the BZB capacity to a 100 % in situations when it before had spare capacity. The active power flow in the northward direction does not change between the two simulations, which is expected since it is a one direction VPL.

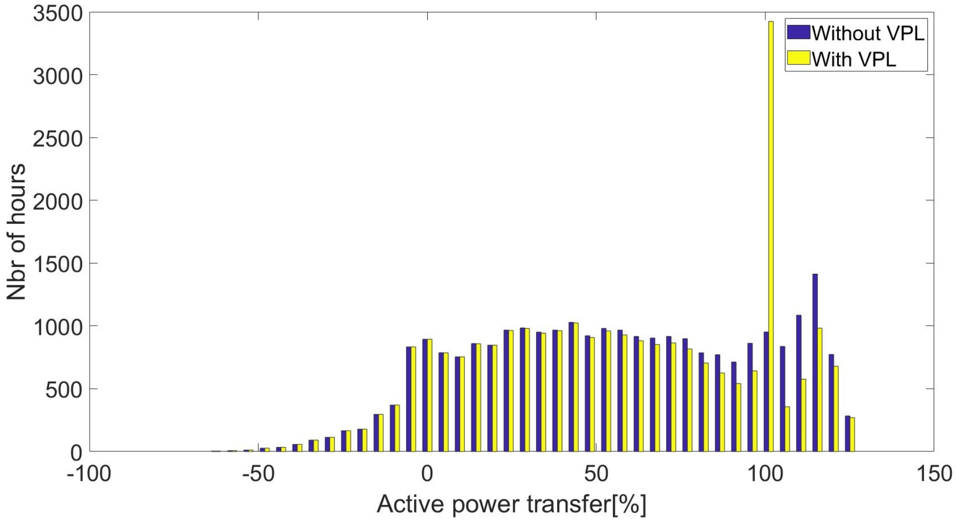


Figure 34: *The loadings on BZB2 both with and without VPL4 connected from Forsmark to Järpströmmen for scenario Electrification renewable.*

### C.3.2 VPL8: Ringhals - Malmö

In this section graphs from the simulations for VPL8 connected over BZB4 between Ringhals and Malmö, are presented. In figure 35 the active power transfer across BZB4 is shown together with the active power for the two BESSs in VPL8 as well as the state of charge for the demand side BESS for a chosen period of time. In the upper graph the blue curve shows the simulation results without the VPL and the red curve shows the simulation results with the VPL. In the upper graph negative flow means that power flows northward. It is clear that the red curve avoids some of the overload peaks in the northward direction, since it eliminates most of the dips below -2 800 MW, which are done by the blue curve. It is important to note that the two BESSs in the VPL are active during those peaks. By looking at the middle graph it is also evident that the two BESSs work in symmetry. When the red curve is positive in the lower graph it means that the VPL discharges on the demand side. Alternatively, when it is blue on the positive side it means that the demand side is charging. In the bottom graph, the state of charge for the demand side BESS can be seen. The rapid changes in the state of charge are a consequence of there being no restrictions on how fast the BESS can charge or discharge.

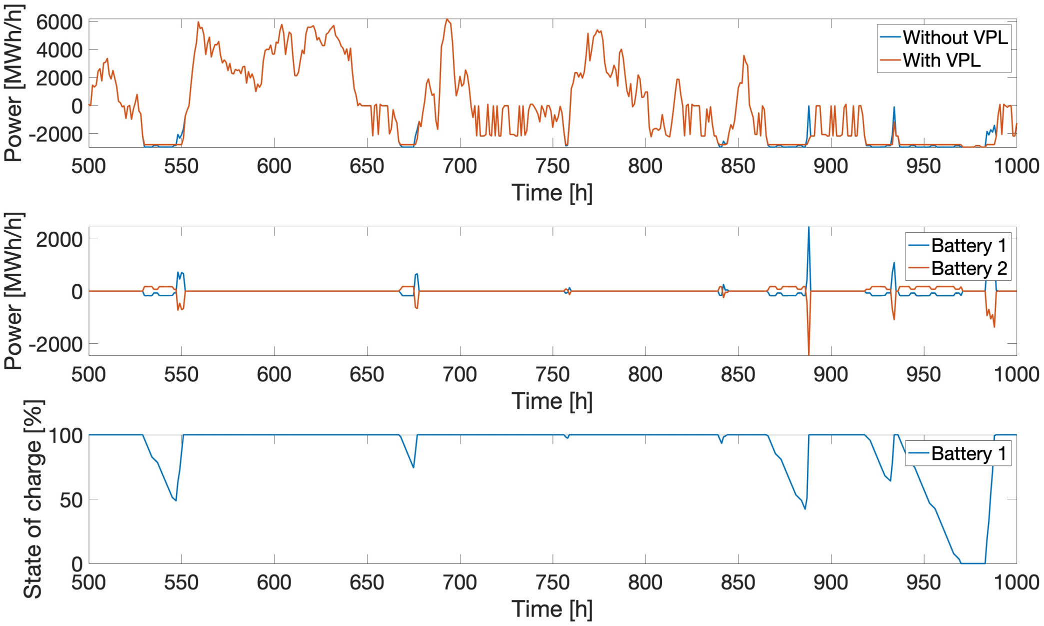


Figure 35: *The upper graph shows active power transfer across BZB4 both with and without VPL8 for a chosen period of time. The middle graph shows active power for the BESSs in VPL8 for the same chosen period of time for scenario Electrification renewable. The bottom graph shows the state of charge for the demand side BESS*

The active power transfer, in % of the maximum transfer capacity, across BZB4 both with and without VPL8 can be seen in figure 36. The blue bars indicate the simulation results without VPL8 and the yellow ones represent the simulation with VPL8. Active power flow going northward is negative. When studying the bar slightly over -100 %, thus the number of hours with overloads across BZB4 from SE4 to SE3, it is clear that the yellow bar is lower than the blue bar. This means that the number of overloaded hours has decreased, which is done when the VPL discharges on the demand side. Consequently, it can also be seen that in bin -100 % the yellow bar is larger compared to the blue bar. This is because the VPL use the hours when the BZB is less than 100 % loaded to charge, which increases the loading and fills the BZB capacity to a 100 % or close to it in situations when it before had spare capacity. The active power flow in the southward direction does not change between the two simulations, which is expected since it is a one direction VPL.

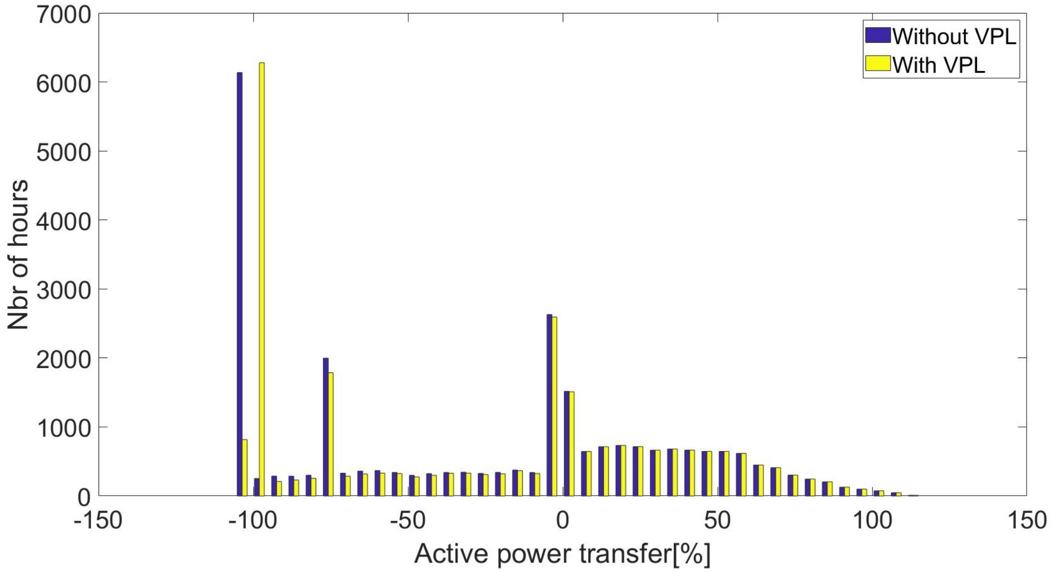


Figure 36: *BZB2 loadings both when VPL8 is connected and when it is not connected for scenario Electrification renewable.*

## C.4 Electrification dispatchable

### C.4.1 VPL1: Porjus-Grundfors

For the EP scenario, the results that follow are not commented, but can hopefully provide deeper insights for the interested reader.

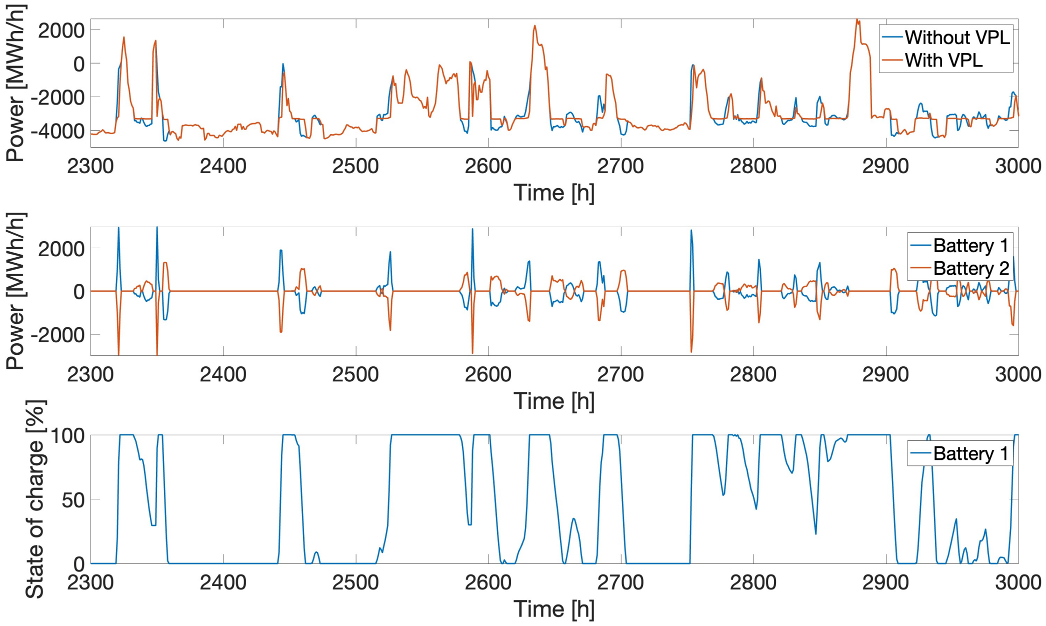


Figure 37: *The upper graph shows active power transfer across BZB1 both with and without VPL1 for a chosen period of time. The middle graph shows active power for the BESSs in VPL1 for the same chosen period of time for scenario Electrification dispatchable. The bottom graph shows the state of charge for the demand side BESS.*

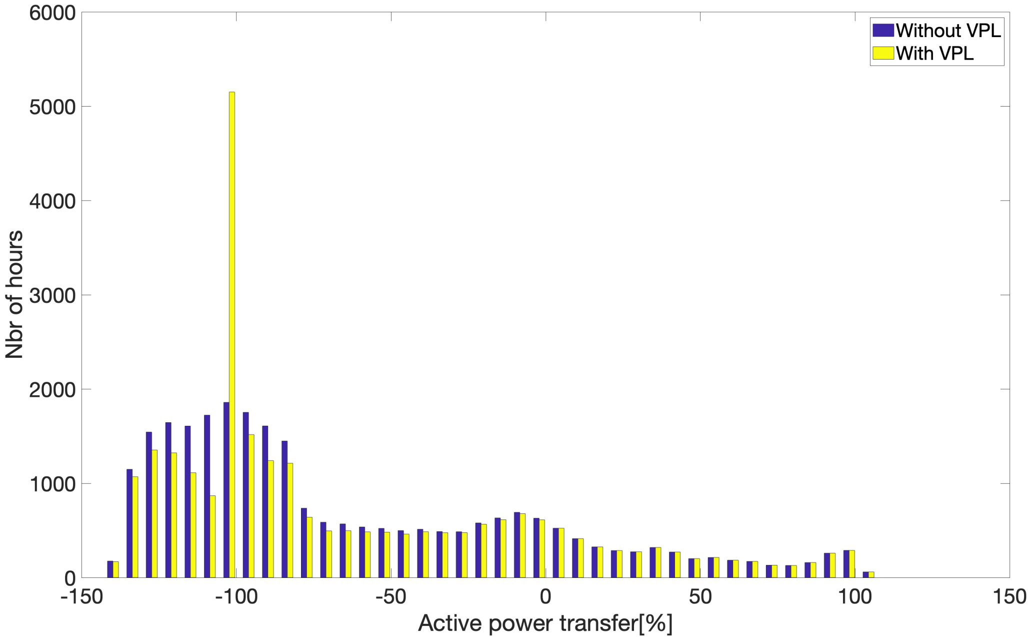


Figure 38: *BZB1 loadings both when VPL1 is connected and when it is not connected for scenario Electrification dispatchable.*

### C.4.2 VPL4: Forsmark-Järpströmmen

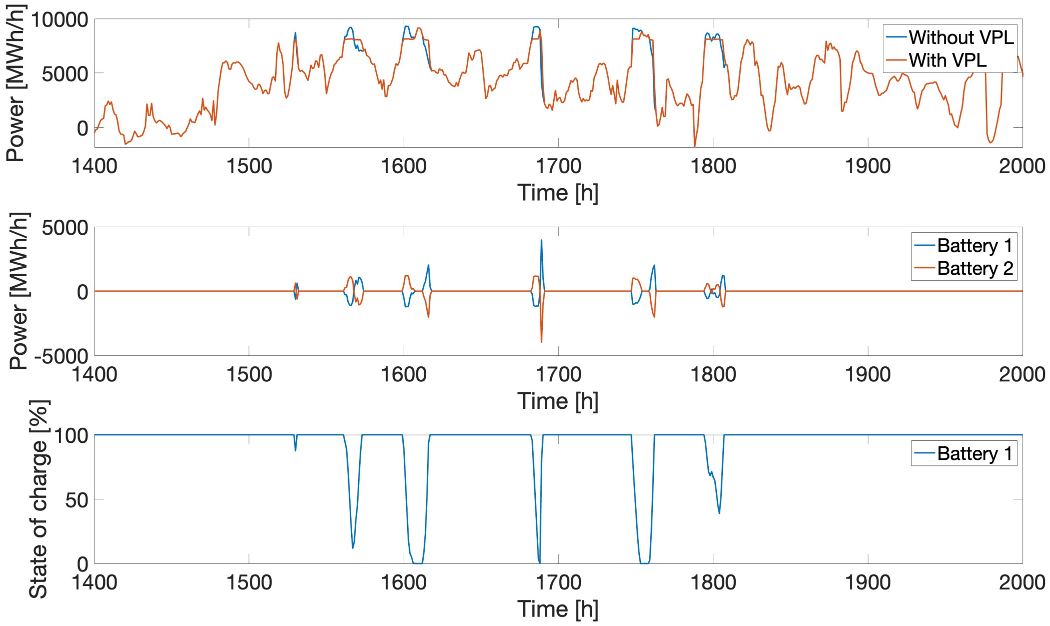


Figure 39: *The upper graph shows active power transfer across BZB2 both with and without VPL4 for a chosen period of time. The middle graph shows active power for the BESSs in VPL1 for the same chosen period of time for scenario Electrification dispatchable. The bottom graph shows the state of charge for the demand side BESS.*

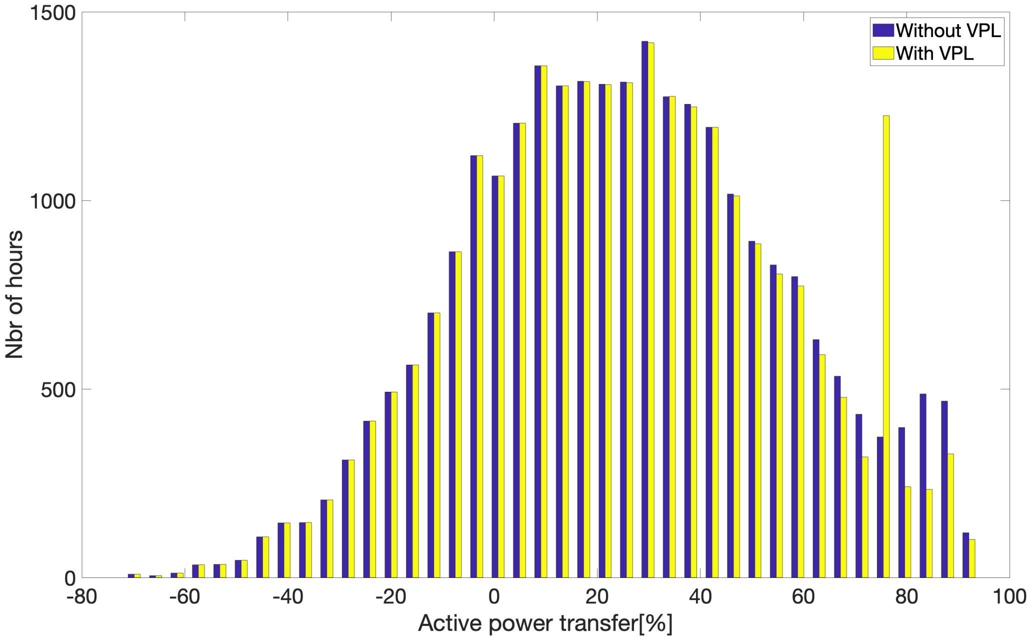


Figure 40: *BZB2 loadings both when VPL4 is connected and when it is not connected for scenario Electrification dispatchable.*

### C.4.3 VPL8: Ringhals-Malmö

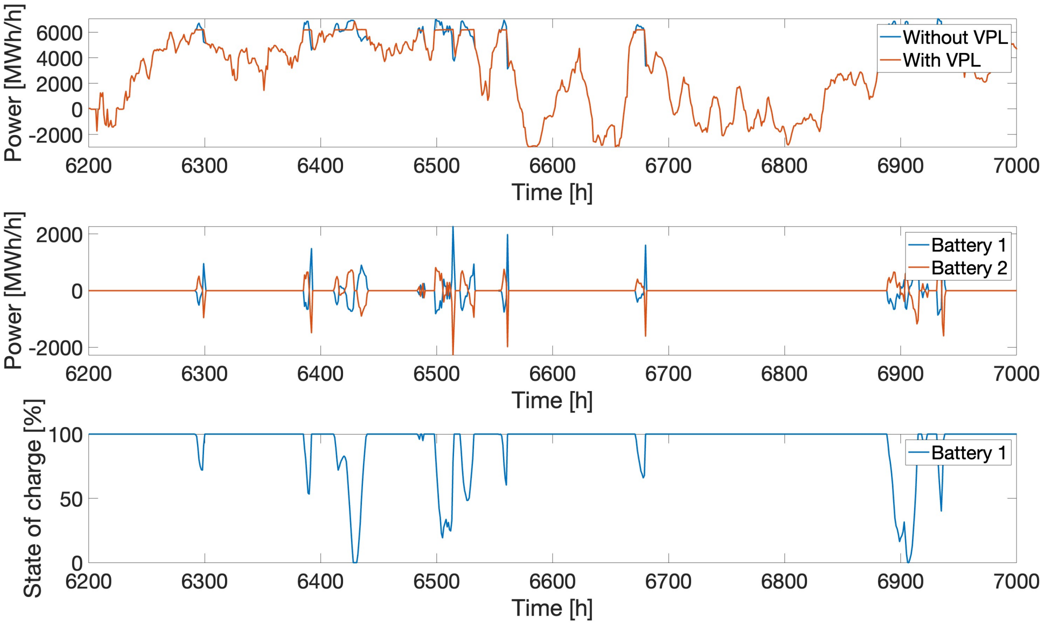


Figure 41: *The upper graph shows active power transfer across BZB4 both with and without VPL8 for a chosen period of time. The middle graph shows active power for the BESSs in VPL1 for the same chosen period of time for scenario Electrification dispatchable. The bottom graph shows the state of charge for the demand side BESS.*

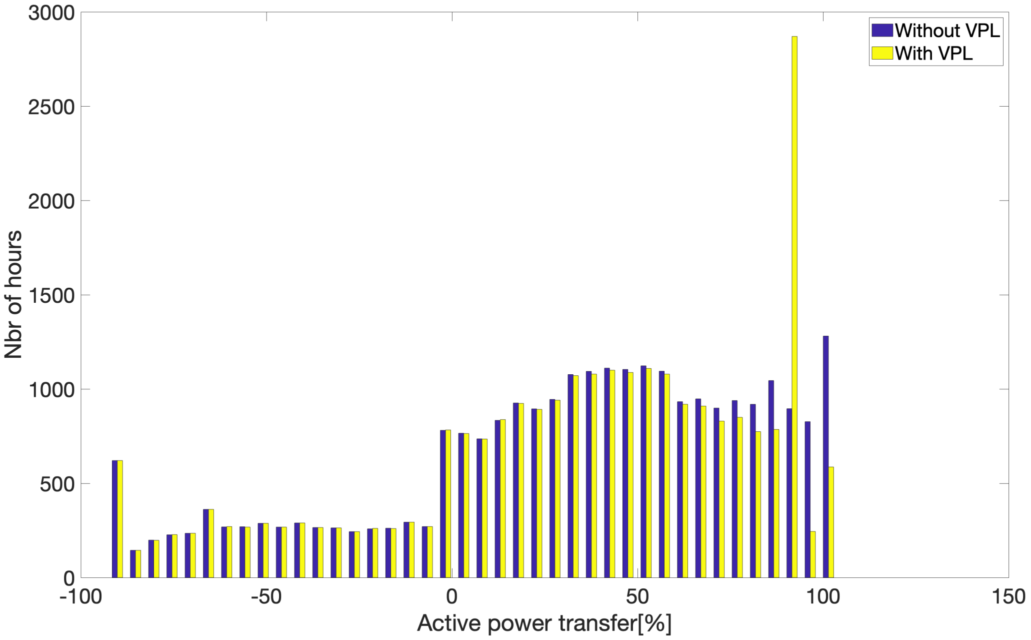


Figure 42: *BZB4 loadings both when VPL8 is connected and when it is not connected for scenario Electrification dispatchable.*

# D Result tables

## D.1 Electrification renewable

Table 18: *Changes in number of overloaded hours for all simulations for scenario Electrification renewable in 2045. The values in parentheses indicate simulations with limited power rating for the VPL in MW.*

| **VPL** | **BZB** | **Size [MWh]** | **# of overloaded hours w.o. VPL precise limit** | **# of overloaded hours with VPL precise limit** | **# of overloaded hours w.o. VPL lenient limit** | **# of overloaded hours with VPL lenient limit** |
|---|---|---|---|---|---|---|
| 1 | 1 | 5 000 | 5 310 | 5 310 | 5 031 | 2 379 |
| 2 | 1 | 5 000 | 5 310 | 5 310 | 5 031 | 3 486 |
| 3 | 1 | 5 000 | 5 310 | 5 310 | 5 031 | 3 144 |
| 1, 2, 3 | 1 | 1 667 | 5 310 | 5 310 | 5 031 | 3 061 |
| 1 | 1 | 5 000 (500) | 5 310 | 5 310 | 5 031 | 2 730 |
| 1 | 1 | 5 000 (250) | 5 310 | 5 310 | 5 031 | 3 356 |
| 1 | 1 | 10 000 | 5 310 | 5 310 | 5 031 | 1 776 |
| 2 | 1 | 10 000 | 5 310 | 5 310 | 5 031 | 3 299 |
| 3 | 1 | 10 000 | 5 310 | 5 310 | 5 031 | 2 870 |
| 4 | 2 | 5 000 | 5 044 | 5 044 | 4 854 | 3 032 |
| 5 | 2 | 5 000 | 5 044 | 5 044 | 4 854 | 3 029 |
| 6 | 2 | 5 000 | 5 044 | 4 190 | 4 854 | 3 017 |
| 4, 5, 6 | 2 | 1 667 | 5 044 | 5 044 | 4 854 | 3 025 |
| 4 | 2 | 10 000 | 5 044 | 5 044 | 4 854 | 2 260 |
| 5 | 2 | 10 000 | 5 044 | 5 044 | 4 854 | 2 258 |
| 6 | 2 | 10 000 | 5 044 | 3 700 | 4 854 | 2 249 |
| 7 | 4 | 5 000 | 6 299 | 6 299 | 6 235 | 923 |
| 8 | 4 | 5 000 | 6 299 | 6 299 | 6 235 | 923 |
| 9 | 4 | 5 000 | 6 299 | 5 888 | 6 235 | 923 |
| 7, 8, 9 | 4 | 1 667 | 6 299 | 5 952 | 6 235 | 923 |
| 7 | 4 | 1 000 | 6 299 | 6 269 | 6 235 | 3 538 |
| 8 | 4 | 1 000 | 6 299 | 5 410 | 6 235 | 3 538 |
| 9 | 4 | 1 000 | 6 299 | 6 118 | 6 235 | 3 538 |
| 1, 6 | 1 | 5 000 | 5 252 | 5 251 | 4 978 | 2 344 |
|  | 2 | 5 000 | 5 044 | 4 194 | 4 854 | 3 017 |
| 1, 9 | 1 | 5 000 | 5 310 | 5 304 | 5 036 | 2 380 |
|  | 4 | 5 000 | 6 299 | 6 289 | 6 235 | 923 |
| 6, 7 | 2 | 5 000 | 5 060 | 4 213 | 4 867 | 3 030 |
|  | 4 | 5 000 | 6 298 | 6 280 | 6 234 | 920 |
| 1, 6, 7 | 1 | 5 000 | 5 252 | 5 244 | 4 978 | 2 345 |
|  | 2 | 5 000 | 5 044 | 4 195 | 4 854 | 3 017 |
|  | 4 | 5 000 | 6 295 | 6 274 | 6 235 | 919 |

Table 19: *Changes in amount of MWh overload for all simulations for scenario Electrification renewable in 2045. The values in parentheses indicate simulations with limited power rating for the VPL in MW.*

| **VPL** | **BZB** | **Size [MWh]** | **amount of MWh overload w.o. VPL precise limit** | **amount of MWh overload with VPL precise limit** | **amount of MWh overload w.o. VPL lenient limit** | **amount of MWh overload with VPL lenient limit** |
|---|---|---|---|---|---|---|
| 1 | 1 | 5 000 | 2 226 390 | 1 326 040 | 2 057 930 | 1 218 320 |
| 2 | 1 | 5 000 | 2 226 390 | 1 406 590 | 2 057 930 | 1 264 100 |
| 3 | 1 | 5 000 | 2 226 390 | 1 375 830 | 2 057 930 | 1 242 170 |
| 1, 2, 3 | 1 | 1 667 | 2 226 390 | 1 369 370 | 2 057 930 | 1 238 000 |
| 1 | 1 | 5 000 (500) | 2 226 390 | 1 386 580 | 2 057 930 | 1 276 230 |
| 1 | 1 | 5 000 (250) | 2 226 390 | 1 536 910 | 2 057 930 | 1 415 460 |
| 1 | 1 | 10 000 | 2 226 390 | 929 462 | 2 057 930 | 831 686 |
| 2 | 1 | 10 000 | 2 226 390 | 1 045 800 | 2 057 930 | 905 467 |
| 3 | 1 | 10 000 | 2 226 390 | 1 001 360 | 2 057 930 | 871 248 |
| 4 | 2 | 5 000 | 5 010 870 | 3 631 370 | 4 610 520 | 3 333 620 |
| 5 | 2 | 5 000 | 5 010 870 | 3 619 660 | 4 610 520 | 3 332 640 |
| 6 | 2 | 5 000 | 5 010 870 | 3 579 660 | 4 610 520 | 3 327 730 |
| 4, 5, 6 | 2 | 1 667 | 5 010 870 | 3 605 070 | 4 610 520 | 3 331 110 |
| 4 | 2 | 10 000 | 5 010 870 | 2 843 940 | 4 610 520 | 2 575 700 |
| 5 | 2 | 10 000 | 5 010 870 | 2 825 990 | 4 610 520 | 2 574 980 |
| 6 | 2 | 10 000 | 5 010 870 | 2 763 770 | 4 610 520 | 2 571 290 |
| 7 | 4 | 5 000 | 839 694 | 121 406 | 667 456 | 88 754 |
| 8 | 4 | 5 000 | 839 694 | 115 703 | 667 456 | 88 740 |
| 9 | 4 | 5 000 | 839 694 | 116 314 | 667 456 | 88 670 |
| 7, 8, 9 | 4 | 1 667 | 839 694 | 117 123 | 667 456 | 88 648 |
| 7 | 4 | 1 000 | 839 694 | 463 143 | 667 456 | 361 816 |
| 8 | 4 | 1 000 | 839 694 | 460 424 | 667 456 | 361 721 |
| 9 | 4 | 1 000 | 839 694 | 460 984 | 667 456 | 361 747 |
| 1, 6 | 1 | 5 000 | 2 192 700 | 1 300 450 | 2 026 060 | 1 193 950 |
|  | 2 | 5 000 | 5 010 870 | 3 579 920 | 4 610 520 | 3 327 410 |
| 1, 9 | 1 | 5 000 | 2 226 670 | 1 326 260 | 2 058 220 | 1 218 320 |
|  | 4 | 5 000 | 839 694 | 117 296 | 667 456 | 88 743 |
| 6, 7 | 2 | 5 000 | 5 050 460 | 3 614 700 | 4 648 390 | 3 359 110 |
|  | 4 | 5 000 | 838 131 | 120 932 | 665 903 | 88 318 |
| 1, 6, 7 | 1 | 5 000 | 2 192 860 | 1 300 440 | 2 026 060 | 1 194 010 |
|  | 2 | 5 000 | 5 010 870 | 3 580 950 | 4 610 520 | 3 327 670 |
|  | 4 | 5 000 | 837 254 | 120 544 | 665 033 | 88 101 |

## D.2 Electrification dispatchable

Table 20: *Changes in number of overloaded hours for simulations on VPLs 1 to 9 for scenario Electrification dispatchable in 2045. The values in parentheses indicate simulations with limited power rating for the VPL in MW.*

| **VPL** | **BZB** | **Size [MWh]** | **# of overloaded hours w.o. VPL precise limit** | **# of overloaded hours with VPL precise limit** | **# of overloaded hours w.o. VPL lenient limit** | **# of overloaded hours with VPL lenient limit** |
|---|---|---|---|---|---|---|
| 1 | 1 | 5 000 | 9 563 | 9 563 | 9 228 | 6 626 |
| 2 | 1 | 5 000 | 9 563 | 9 563 | 9 228 | 7 897 |
| 3 | 1 | 5 000 | 9 563 | 9 563 | 9 228 | 7 530 |
| 1, 2, 3 | 1 | 1 667 | 9 563 | 9 563 | 9 228 | 7 446 |
| 1 | 1 | 5 000<br>(500) | 9 563 | 9 563 | 9 228 | 7 100 |
| 1 | 1 | 5 000<br>(250) | 9 563 | 9 563 | 9 228 | 7 790 |
| 1 | 1 | 10 000 | 9 563 | 9 563 | 9 228 | 5 971 |
| 2 | 1 | 10 000 | 9 563 | 9 563 | 9 228 | 7 755 |
| 3 | 1 | 10 000 | 9 563 | 9 563 | 9 228 | 7 310 |
| 4 | 2 | 5 000 | 1 501 | 1 501 | 1 454 | 822 |
| 5 | 2 | 5 000 | 1 501 | 1 501 | 1 454 | 820 |
| 6 | 2 | 5 000 | 1 501 | 1 251 | 1 454 | 820 |
| 4, 5, 6 | 2 | 1 667 | 1 501 | 1 501 | 1 454 | 820 |
| 4 | 2 | 10 000 | 1 501 | 1 501 | 1 454 | 553 |
| 5 | 2 | 10 000 | 1 501 | 1 501 | 1 454 | 552 |
| 6 | 2 | 10 000 | 1 501 | 1 061 | 1 454 | 552 |
| 7 | 4 | 5 000 | 3 233 | 2 351 | 3 049 | 1 503 |
| 8 | 4 | 5 000 | 3 233 | 2 372 | 3 049 | 1 514 |
| 9 | 4 | 5 000 | 3 233 | 2 365 | 3 049 | 1 503 |
| 7, 8, 9 | 1 667 | 4 | 3 233 | 2 366 | 3 049 | 1 503 |
| 7* | 4 | 1 000 | 1 130 | 443 | 431 | 85 |
| 7 | 4 | 1 000 | 3 233 | 2 949 | 3 049 | 2 415 |
| 8 | 4 | 1 000 | 3 233 | 2 961 | 3 049 | 2 415 |
| 9 | 4 | 1 000 | 3 233 | 2 968 | 3 049 | 2 416 |
| 1, 6 | 1 | 5 000 | 9 524 | 9 526 | 9 203 | 6 610 |
|  | 2 | 5 000 | 1 501 | 1 244 | 1 454 | 819 |
| 1, 9 | 1 | 5 000 | 9 555 | 9 558 | 9 220 | 6 624 |
|  | 4 | 5 000 | 3 241 | 2 420 | 3 055 | 1 511 |
| 6, 7 | 2 | 5 000 | 1 523 | 1 708 | 1 462 | 837 |
|  | 4 | 5 000 | 3 242 | 2 144 | 3 057 | 1 510 |
| 1, 6, 7 | 1 | 5 000 | 9 520 | 9 515 | 9 200 | 6 608 |
|  | 2 | 5 000 | 1 523 | 1 471 | 1 462 | 834 |
|  | 4 | 5 000 | 3 242 | 2 425 | 3 057 | 1 511 |

* This simulation is done without Case4, thus with full transmission capacities over BZB4.

Table 21: *Changes in amount of MWh overload for simulations on VPLs 1 to 9 for scenario Electrification dispatchable in 2045. The values in parentheses indicate simulations with limited power rating for the VPL in MW.*

| **VPL** | **BZB** | **Size [MWh]** | **amount of MWh overload w.o. VPL precise limit** | **amount of MWh overload with VPL precise limit** | **amount of MWh overload w.o. VPL lenient limit** | **amount of MWh overload with VPL lenient limit** |
|---|---|---|---|---|---|---|
| 1 | 1 | 5 000 | 5 436 620 | 4 417 700 | 5 129 150 | 4 167 570 |
| 2 | 1 | 5 000 | 5 436 620 | 4 509 730 | 5 129 150 | 4 226 290 |
| 3 | 1 | 5 000 | 5 436 620 | 4 474 250 | 5 129 150 | 4 198 600 |
| 1, 2, 3 | 1 | 1 667 | 5 436 620 | 4 467 110 | 5 129 150 | 4 193 520 |
| 1 | 1 | 5 000 (500) | 5 436 620 | 4 496 750 | 5 129 150 | 4 243 030 |
| 1 | 1 | 5 000 (250) | 5 436 620 | 4 672 600 | 5 129 150 | 4 406 740 |
| 1 | 1 | 10 000 | 5 436 620 | 3 896 200 | 5 129 150 | 3 655 360 |
| 2 | 1 | 10 000 | 5 436 620 | 4 035 830 | 5 129 150 | 3 754 760 |
| 3 | 1 | 10 000 | 5 436 620 | 3 982 030 | 5 129 150 | 3 709 760 |
| 4 | 2 | 5 000 | 1 142 980 | 741 028 | 1 023 470 | 658 457 |
| 5 | 2 | 5 000 | 1 142 980 | 736 859 | 1 023 470 | 658 178 |
| 6 | 2 | 5 000 | 1 142 980 | 726 011 | 1 023 470 | 657 096 |
| 4, 5, 6 | 2 | 1 667 | 1 142 980 | 732 829 | 1 023 470 | 657 863 |
| 4 | 2 | 10 000 | 1 142 980 | 540 670 | 1 023 470 | 471 241 |
| 5 | 2 | 10 000 | 1 142 980 | 534 356 | 1 023 470 | 471 064 |
| 6 | 2 | 10 000 | 1 142 980 | 570 204 | 1 023 470 | 486 979 |
| 7 | 4 | 5 000 | 1 208 250 | 507 556 | 1 051 530 | 443 491 |
| 8 | 4 | 5 000 | 1 208 250 | 509 843 | 1 051 530 | 443 543 |
| 9 | 4 | 5 000 | 1 208 250 | 508 483 | 1 051 530 | 443 459 |
| 7, 8, 9 | 4 | 1 667 | 1 208 250 | 508 218 | 1 051 530 | 443 398 |
| 7* | 4 | 5 000 | 96 875 | 19 918 | 31 233 | 5 980 |
| 7 | 4 | 1 000 | 1 208 250 | 961 962 | 1 051 530 | 845 366 |
| 8 | 4 | 1 000 | 1 208 250 | 962 021 | 1 051 530 | 845 290 |
| 9 | 4 | 1 000 | 1 208 250 | 962 157 | 1 051 530 | 845 235 |
| 1, 6 | 1 | 5 000 | 5 413 550 | 4 399 350 | 5 107 170 | 4 150 220 |
| | 2 | 5 000 | 1 142 980 | 725 681 | 1 023 470 | 656 786 |
| 1, 9 | 1 | 5 000 | 5 431 020 | 4 413 180 | 5 123 770 | 4 163 000 |
| | 4 | 5 000 | 1 216 090 | 515 445 | 1 058 980 | 449 017 |
| 6, 7 | 2 | 5 000 | 1 178 300 | 774 400 | 1 057 510 | 693 400 |
| | 4 | 5 000 | 1 217 340 | 509 200 | 1 060 140 | 446 100 |
| 1, 6, 7 | 1 | 5 000 | 5 409 000 | 4 395 000 | 5 103 000 | 4 146 000 |
| | 2 | 5 000 | 1 178 000 | 763 600 | 1 058 000 | 688 300 |
| | 4 | 5 000 | 1 217 000 | 515 200 | 1 060 000 | 449 800 |

* This simulation is done without Case4, thus with full transmission capacities over BZB4.