Evaluating the Impact of Altered Electricity Systems

– Constructing a Model for Assessment of the GHG Impacts of Altered Electricity System Configurations in Northern Europe.

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Master's Thesis 2019
Environmental and Energy Systems Studies
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Sammandrag

Detta examensarbete ämnar att undersöka om och hur man skulle bygga en modell för att kunna beräkna utsläppen av växthusgaser vid förändringar av transmissionskapacitet. Arbetet avhandlar hur det nuvarande elsystemet är uppbyggt och påverkan på utsläppen av växthusgaser ifrån ökad produktion av förnyelsebar elproduktion och ökad transmission av elektricitet.

Utifrån att studera vind- och lastdata kunde en modell av linjärt beroende mellan olika områden upprättas. Kärnkraft och solkraft modellerades till att producera el på en konstant effekt, medan biokraft och vattenkraft antogs följa lasten proportionellt. Data för koldioxidutsläpp ifrån olika kraftslag erhölls ifrån en litteraturstudie.

Modellens algoritm påbörjas med en global optimering där de kraftverk med billigast marginalkostnad sätts igång för att mätta lasten av samtliga områden. Detta följs av en stegvis undersökning huruvida transmissionsledningarna mellan områden kunde balansera ut områden av (netto) över- och underproduktion. Ifall områden med underskott inte fullkomligt balanserats av importer initieras en lokal optimering, där den billigaste kraften produceras lokalt. Resultaten av att använda indata motsvarande 2018 kom relativt nära de verkliga siffrorna, men ett fel uppdagades, gällande att balanser beräknade ifrån modellerad transmission inte stämmer. Ett scenario gällande de planerade förändringarna i kärnkrafts- och transmissionskapacitet upp till år 2024 gav att växthusgasutsläppen ökar ifall alla andra parametrar ifrån 2018 hålls konstanta. Detta resultat är nog pålitligt, eftersom de mest avgörande beräkningarna avgörs innan balanserna i transmissionen har haft påverkan. Ett andra scenario, där alla relevanta ledningar i ENTSO_E:s tioårsplan (TYNDP 2018) förverkligades, gav dock inte några koldioxidbesparingar ifall alla produktionskapaciteter hölls konstanta. Resultatet kan förklaras med att den ökade transmissionskapaciteten inte användes för förnyelsebara tillskott, snarare att billig fossil kraft kunde färdas längre. Dock på grund av obalansen i transmissionen är kanske inte detta scenario pålitligt alls, då resultaten beror mer av effekterna av transmission även i modellen.

Det finns många sätt att förbättra modellen, bland de viktigaste ingår att lösa problemen kring obalanser, samt att modellera last, vind- och vattenkraft bättre. Efter att dessa förbättringar är gjorda är det möjligt att modellen tjänar sitt syfte.

Nyckelord
Linjär Programmering; Transmission; Energisystem; Växthusgaser; Utsläpp; Elsystem; Modellering.

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Abstract

In the light of the importance of climate change and the emissions that have induced it, the ability to calculate the effect on emissions by changing transmission capacity is vital. A model to perform such *indicative* calculations is developed in this thesis. After researching how the current electricity system is organised, the effects on GHG emissions that are expected from increased renewable electricity production and increased transmission are considered. For the model, wind and demand data was processed to form a model of linear dependence between areas. Nuclear and solar power production were assumed to maintain a constant level of generation, whilst bio- and hydro power generation were assumed to be proportional to demand. Carbon data was found by means of a literature search. The algorithm began with a linear optimisation segment, dispatching the cheapest power available. This was followed by a step-wise examination whether transmission capacities could balance out the production over the areas. If deficits remained, a second economic dispatch commenced locally. The results came reasonably close to the expected values in a base case, however a malfunction regarding exchange balances was discovered. A scenario considering the nuclear trends of Sweden, Finland, Germany and the UK gave that the shutdown of nuclear will lead to an increased amount of GHG emissions if all other generation capacities remain. This is likely a trustworthy result as it is mostly determined by the initial dispatch, before exchange balancing displays major faults. A scenario, where all the relevant interconnectors in the ENTSO_E's 2018 TYNDP were realised, did not however yield carbon savings if the parameters defining the 2018 base case remained. This result may be explained by the additional transmission capacity not being used for additional renewables, rather that cheaper fossil power could travel further. However due to the exchange imbalance this scenario may not be viable at all, as it is more dependent on the parts of the model handling transmission. There are many ways of improving the model, highlights being resolving the exchange imbalance bug, and building better models for demand, wind and hydro power production. After the improvements are made, the model may be capable of the tasks it was designed for.

Keywords
Linear Programming; Transmission; Energy Systems; Green House Gas; Emissions; Electricity Systems; Modelling.

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ABBREVIATIONS

CHP	*Combined Heat and Power:* referencing power plants that produce usable energy in the form of heat and power at the same time.
DE	The German market area.
DK1, DK2	Market areas in Denmark. See figure 1 for geographic orientation.
EE	The Estonian market area.
ENTSO_E	*The European Network of Transmission System Operators.*
FI	Market area within Finland.
LCA	*Life Cycle Analysis:* A method of calculating the environmental impact of a product. In this thesis LCA generally references to calculations considering the carbon dioxide equivalents that a product gives rise to.
LT	The Lithuanian market area.
LV	The Latvian market area.
NL	The Dutch market area.
NO1-5	Market areas in Norway. See figure 1 for geographic orientation.
O&M	*Operations and Maintenance.*
PL	The Polish market area.
RES	*Renewable Energy Sources.*
SE1-4	Market areas in Sweden. See figure 1 for geographic orientation.
T&D	*Transmission and Distribution* (of power).
TSO	*Transmission System Operator.*
TYNDP	*Ten Year Network Development Plan*: a plan published by the ENTSO_E containing suggested projects for European grid development.
UK	Here references the market area of the United Kingdom frequently.

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1. INTRODUCTION

Before the first industrial revolution, how much energy you could use in a day may well be limited by how much fuel you would be capable to harvest. Imagine only being able to reach a given perimeter of land, as you may only travel it by foot or amount some working animal. Within these boundaries, you of course also must provide your family, livestock and yourself with enough food and fodder (Kander, et al., 2013). Then apply the limited amount of energy a human or draft animal can use to perform useful work (Kander, et al., 2013), and that such work must also cover all other tasks. The result that the (bio-)fuels you are able to gather are limited. Indeed, Kander et al (2013) describe that European energy use per person in the pre-modern age was very much bound to a low level, strongly defined by natural constraints. When the first industrial revolution came - with the synergistic reinforcement of cheaper coal leading to cheaper steel, in turn leading to cheaper steam engines, providing yet cheaper coal (decreasing mining and eventually transport costs) – energy consumption strongly rose (Kander, et al., 2013). In Europe, this increase continued until 2006, yet since then consumption has begun to decline (Eurostat, 2019).

Fossil fuels have thereby taken strong part in forming European society as we know it. On the other hand, it has been widely known for an extended period of time that adverse effects of climate change will concretise (Caney, 2010). The Paris Agreement of 2015 was agreed on by countries that pledged to keep the average global heating below 2 °C (United Nations Framework on Climate Change, 2019). In Paris, the EU promised to contribute with a plan which is largely similar to the 20-20-20 climate and energy package (Schleicher, et al., 2016). The package aims to ensure a 20 % GHG emission reduction compared to 1990, 20 % energy efficiency increase and 20 % of EU energy coming from renewables, all by the year of 2020 (European Commission, u.d.). The same year, all EU countries are also to have interconnector capacity of at least 10 % of the national electricity production capacity (European Commission, u.d.). The European Commission has intentions of making Europe climate neutral by 2050 (European Commission, u.d.). In a recent communication, “A Clean Planet for All”, the Commission acknowledges that 75 % of the EU GHG emissions come from the energy sector (European Commission, 2018). This is reflected in the suggestions they provide to keep course towards the mid-century goal - such as installing more renewables and increasing electrification to entirely decarbonise the energy supply within Europe (European Commission, 2018). By 2030, GHG emissions are supposed to be reduced by at least 40 %, and renewable energy used for a minimum 32 % of the final energy consumption (European Commission, u.d.). Sweden is premiering this development by setting goals of achieving net neutrality by 2045 and ensuring a fully renewable electricity production by 2040 (Regeringskansliet, 2016).

Some the carbon dioxide release can be acclaimed to land use change; however, this is eclipsed by the burning of fossil fuels (Global Carbon Project, 2018), putting the energy sector in a central role to impede climate change. Surely, there has been growth of renewable energy sources (RES) globally, yet there are other trends one must consider, some selected here. Firstly, there may be evolution towards electrification– transport (EVs), industry, heating etcetera is increasingly run on electricity (IEA, 2018). Then there is substantial population growth expected, meaning that demand is to increase, even if it may be partially offset by increases in efficiency (IEA, 2018). Further, one must consider the effects of increased digitalisation in the energy sector (IEA, 2018).

Closer to home, some global trends are expected to be reflected in the Nordic countries. According to a report from the Nordic TSOs, the most important developments occurring in their areas are indeed the increased amount of RES in the system, alongside how the configuration of thermal (including nuclear) power will change and the increased interconnections to other regions (Statnett, Fingrid, Energinet DK, Svenska Kraftnät, 2016). The TSOs also expect further electrification of the transport and domestic sectors, new market participants such as prosumers and aggregators and new "enablers" of the power system in the form of smart meters, microgrids etcetera, part of the digitalisation trend (Statnett, Fingrid, Energinet DK, Svenska Kraftnät, 2016). Also, it is also possible that Swedish industry may become increasingly electrified, and that industrial market participants may adjust their role on the electricity market – for instance through demand response (Statens Energimyndighet, 2016) – to aid the function of the power system.

An integral part of the electricity system, connecting the production and the loads, are the transmission and distribution systems, which will need to evolve to suit the new circumstances – more renewables, increased electrification and changed nuclear production attribute to that the locations and sizes of load and generation are likely to shift – requiring more transmission and distribution capacity. In the light of the importance of climate change and the emissions that have induced it, the ability to calculate the effect on emissions by altering transmission and generation capacity is imperative, which is precisely what the model this thesis considers aims to do. The following research questions are to be answered:

Main Research Question

How can a model be designed and used for evaluating climate implications of investments in transmission capacity in the long and short term?

As it is unsure if it is even possible that a broadly applicable model or tool can be determined, the outcome may be that such a model may not be formed at all. Climate implications here mean saved or additional carbon dioxide (equivalent) emissions. Attempts to answer the main research question will be made on a substantial basis of knowledge. To structure the search of such knowledge, four sub-questions to the research question are given:

Sub-Questions

1. What are the functions and effects of the transmission grid?
2. What aspects are important to consider when evaluating the benefits for the climate when increasing transmission capacity?
3. How is the current electricity system configured in Northern Europe?
4. What scenarios are currently relevant to develop and do the model results verify the models functioning?

Sweden and the closest national neighbours are at the heart of this thesis, however as the Swedish network is growing increasingly interconnected (Svenska Kraftnät, 2017) it is vital to include a larger geographic area. Further, the following topics are intendedly neglected:

Demarcations

1. Flexibility solutions, such as energy storage or demand response etcetera, which may be used to avoid or postpone an investment in the transmission network will not be considered.
2. No recommendations on which investments should be prioritised from a socio-economic perspective will be provided.

3. The maintenance of high power quality (frequency, diversions from pure sinewaves and voltage maintenance) will not be considered.
4. The distribution networks are not considered.

The next chapter will disclose the methods used to produce this thesis. Chapter 3 will provide the background needed to grasp the present-day electricity system of Northern Europe and technical matters important for the evaluation of climate effects in the transmission system. The calculation model is presented in chapter 4 and the scenarios it will be applied to are found in chapter 5. This is followed by the results of the application in chapter 6. These are then discussed in chapter 7 and chapter 8 holds concluding remarks.

2. METHOD

In order to answer the research questions, a study researching the purpose and function of the transmission system was undertaken. Sources were found through searches by means of Lund University's library portal, through recommendations from tutors and peers and from popular internet search-engines. The product of this study can be found in section 3.1.

When the general traits of the transmission system were defined, a deeper understanding of the separate systems in the countries of Northern Europe was gathered, partially by collecting data from providers such as Nord Pool and ENTSO_E and partially by acquiring facts from authorities, companies and news articles. The outcome of this study can be seen in section 3.2.

To acquire perception on the matter of the effects of transmission in the electricity system from a GHG-emissions perspective, more information was gathered, mainly from Lund University's library portal, yet also common search engines, companies and through consulting staff at Pöyry Sweden AB.

When a sufficient reserve of knowledge had been assembled, work on the model begun by collecting and assessing wind and demand data to investigate how best to model it. Due to the simplicity and speed of linear modelling, linear correlations were sought. Based on the found correlations of wind power production and demand in different areas a linear model was developed for emulating the two parameters. The details on the modelling can be found in section 4.1.1-4.1.3. To find reasonable values for estimate greenhouse gas emissions from the power production, a smaller literature study commenced, results found in section 4.1.4.

To be able to perform estimations of GHG emissions, a model was built. The model is based on linear programming for all power dispatches, as this is fast and sufficient for the purposes. The algorithm first considers all the areas and dispatches the cheapest power production methods to match total demand. This indicates that areas with less costly production may produce more than their internal demand, and that areas with more expensive production may have a local deficit. To ensure that the balancing of all areas is correct, the algorithm proceeds to investigate if there is sufficient capacity to import power from an area with excess to an area with a deficit. If areas still remain unbalanced, the most expensive power production is removed from an overproducing area. If an area has a remaining deficit, a local redispatch for the area itself and the closest neighbours (subject to residual transmission capacity) balances the area. This is a simplification, as a more advanced model may be able to import the needed power from the least expensive sources available in the entirety of the areas, however it is improved from simply redispatching the power sources in the deficit area. For an extensive account on the model see chapter 4.2.

To assess the capabilities and trustworthiness of the model, the model output was to be compared against the actual production data of the modelled year (2018) and two scenarios developed. The evaluation against the real data was performed to investigate if the general function of the model seemed promising. One scenario was conceived due to the recently planned developments regarding nuclear power in Europe, for the purpose of studying the impacts on the emissions and testing the parts of the algorithm related to dispatching power. A second scenario was developed to investigate if increased transmission truly could decrease carbon emissions, yet also for validating that the components in the model handling transmission were correct. Details on the scenarios can be found in chapter 5.

3. BACKGROUND

3.1. FUNCTIONS AND EFFECTS OF ELECTRICAL TRANSMISSION LINES

A Brief Overview of the Electricity System

On the most basic level, a transmission line exists to transport electrical energy from one area to another. Technically, the electricity system is composed of four main elements: generators, consumers and what connects them – transmission and distribution networks. In the currently dominating centralized system, large-scale generators produce electricity at some voltage, which must then be transformed to a given voltage suited for the transmission network. The transmission network in the Nordic countries operates at voltages between 220-400 kV (Svenska Kraftnät, 2017). Transporting electricity at higher voltages allows for smaller losses and is therefore of great importance when electricity is to be transported over longer distances (von Meier, 2006). However, higher voltages would pose serious threats in domestic setting, why the voltage again must be transformed, sometimes in several steps (von Meier, 2006). Electricity at lower voltages is transmitted over shorter distances in the distribution network, all the way down to the lowest voltage found in the common residential socket (von Meier, 2006) – 230 V in Sweden. However, larger consumers may withdraw power from the grid at higher voltages (von Meier, 2006).

The Evolution of the Electricity System to Present Day

The earliest commercial electric systems were standalone – a generator and load separate from any larger system (von Meier, 2006). However, in the start of the twentieth century these smaller systems began to interconnect increasingly (von Meier, 2006). Alexandra von Meier (2006) identifies three technical reasons for this development: load factor improvement, benefits from economies of scale alongside with increased reliability. The load factor, the ratio between the average load and peak load, is important economically (von Meier, 2006), as if capacity to maintain a rare and high peak load is necessary, plenty of excess capacity will be redundant most of the time. By aggregating loads in a larger electric system, the demand profile is smoothed. The production capacity can then be designed accordingly, and a higher load factor is reached. Economies of scale imply that, by for instance dividing fixed costs over more units, the price of an individual unit decreases the more units are produced. Finally, reliability increased, as if one generator failed, another may can cover the lost production (von Meier, 2006). However, the increased interconnectivity also has drawbacks - a local disturbance can have widespread effects and the system is more prone to issues with stability (von Meier, 2006).

Physical Description

As power plants are usually dispersed over a given area, the electrical transmission system should be formed so that power can be inserted at multiple locations and flow in different directions in the lines, depending on where the loads and active power plants are. In such a networked (meshed) system, there is a certain degree of redundancy – if one line fails, the power may be re-routed. Keeping redundant lines are of course costlier than a system with no back-ups (if they are not cheaper than outage compensation) and it is also relatively complicated to grasp the direction and size of power flows in the network. The latter is especially an issue if a fault occurs, as it must then be isolated on both sides, compared to one in a system where the flow is known to always be unidirectional. Also, if a line becomes congested, it is of great importance to know which generators should change their outputs to alleviate it. (von Meier, 2006)

Stations exist at various system levels. There, transmission lines may convene, or the voltage may be transformed and sent on into a segment of the grid with another voltage. The voltage is shifted by the transformer[1]. Also, important elements are circuit breakers, which switch when exceedingly high currents are detected, and switches used, as an example for rerouting. Switching on transmission level is uncommon, however in radially arranged distribution networks, different loads are commonly redirected between different circuits, for instance for the sake of load balancing. Sub-/stations also may contain capacitator banks[2] for voltage support. (von Meier, 2006)

In the Nordic transmission network, the electricity has the shape of three-phase alternating current (Svensk Energi, Svenska Kraftnät, 2014). This has several advantages. Firstly, a three-phase generator is subjected to constant torque, which is favoured from a mechanical view, compared to the torque pulsating (von Meier, 2006). Further, it is due to that only three wires are required for a perfectly balanced multiple phase system; if the phases are set equally apart and the amplitudes are the same, the sum of the sinusoidally fluctuating currents at any time equal to 0 (von Meier, 2006). The three circuits then form, in von Meier's (2006) words, "a single hypothetical return wire". The voltage alternates in a sinusoidal form and just as the currents, the sum of all three voltages is in any given moment equal to 0 (von Meier, 2006). If the phases were to serve equal loads (the phases and magnitudes remain the equal) and then be grounded collectively, the potential between the generator and the grounding would always be equal to 0, and hence three separate return wires are not necessary (von Meier, 2006). These results would of course apply to balanced systems of more than three phases as well, however three phase is chosen as it is the least expensive (number of wires, units etcetera) and least complicated (von Meier, 2006).

If each phase experiences an equal load, the phasing remains equidistant and the altitude of the wave remains the same. Some applications, such as industrial motors indeed use balanced three phase power. However, in a domestic setting, the socket provides single phase electricity, tasking the distribution planner to balance the load between the phases. When this is not perfectly successful, the electricity must return, travelling through the ground in distribution systems. The difference diminishes at high levels of aggregation (for instance for transmission). Transmission can also be performed by direct current (DC). In history, DC has been associated with high line losses. With the voltages possible today, DC is very efficient. (von Meier, 2006)

Power lines should have low resistance to limit losses and capacity loss (which decreases with heating). The impedance[3] of a line is however usually dominated by reactance. Inductance can for instance be found between the conductors of the different phases, and capacitance between different power lines. Further, lines are subject to several limitations. Thermal limits bound the current to not overheat the line. For long lines, stability limits are of importance, which consider maintaining the synchronicity between different generators; so, more load is applied on a generator that is attempting to accelerate and decreasing the load for generators in the opposite situation. (von Meier, 2006)

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[1] A transformer is a unit that via electromagnetic induction induces a flow of electricity in a connected coil if electricity is flowing in another attached coil. By adjusting the number of loops in the coil where electricity is induced, one can adjust the voltage of the output.

[2] The term" bank" refers to equipment coming in sets of three, one unit per phase (in a three-phase system).

[3] Reactance and resistance. Reactance is composed of inductive reactance and capacitive reactance (von Meier, 2006)

Important aspects for a well-functioning power system include reliability, security, stability and power quality (von Meier, 2006). If there is enough generating and transmitting capacity so customers can continuously receive the power they demand, the system is reliable (von Meier, 2006). Security considers how many alternative solutions for providing power to the customers are available before it is not possible at all (von Meier, 2006). Stability considers the predisposition of an AC system to keep a balanced and synchronous operating state (von Meier, 2006). Finally, power quality covers that voltage, waveform and frequency are compatible with the load (von Meier, 2006). To not experience detrimental effects in the system it is essential that there is an equal amount of power produced as there is consumed, which also has a large impact on how electricity is traded (Kirchen & Strbac, 2004).

In conclusion, the function of transmission lines is to connect different locations with different levels of production (such as large-scale generators) and demand (such as a substation interfacing a radial distribution grid) in an efficient manner (without significant losses). Transmission lines are needed to perform long distance power transfers to enable the entire system to meet the criteria to provide the customers with a fair service. Further, transmission also implies higher load factors and larger economies of scale.

3.2 THE ENERGY SYSTEM(S) OF NORTHERN EUROPE

It will in the following section become clear that the electricity system in a country today cannot be considered in isolation – due to interconnection and cross-border electricity trade countries have become increasingly co-dependent, and to grasp the occurrences in one country one must also consider the neighbouring nations. This section provides an overview of areas in northern Europe and attempts to describe the various electricity systems, electricity production mixes and patterns of production, demand and exchange.

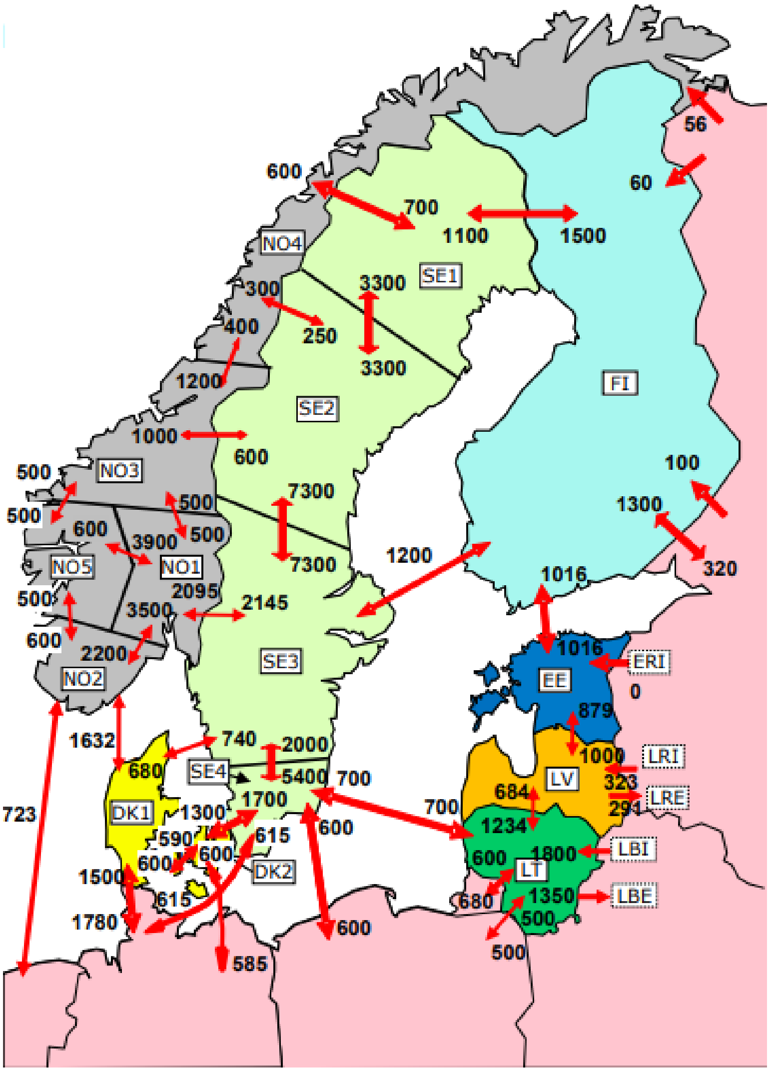

Figure 1. Interconnector capacities in MW. *Courtesy of Nord Pool: https://www.nordpoolgroup.com/globalassets/download-center/tso/max-ntc.pdf.*

In figure 1, the interconnectors between most of the market areas relevant for this study are depicted, by courtesy of Nord Pool. Sweden has many connections to other countries, the most sizeable being towards Norway, followed by Finland and Denmark. Sweden is also connected to Lithuania, Germany and Poland. These countries can, through the interconnections, impact the Swedish (or Nordic) electricity system. Connecting countries physically through interconnectors (and economically through shared markets) affect which power plants dispatch at what level and the (regional) price of electricity (Anderson, et al., 2007). However, it is also of interest to consider the actual flows, not only the limitations of the capacity. In figure 2, the transferred amounts of energy are provided, courtesy of ENTSO_E.

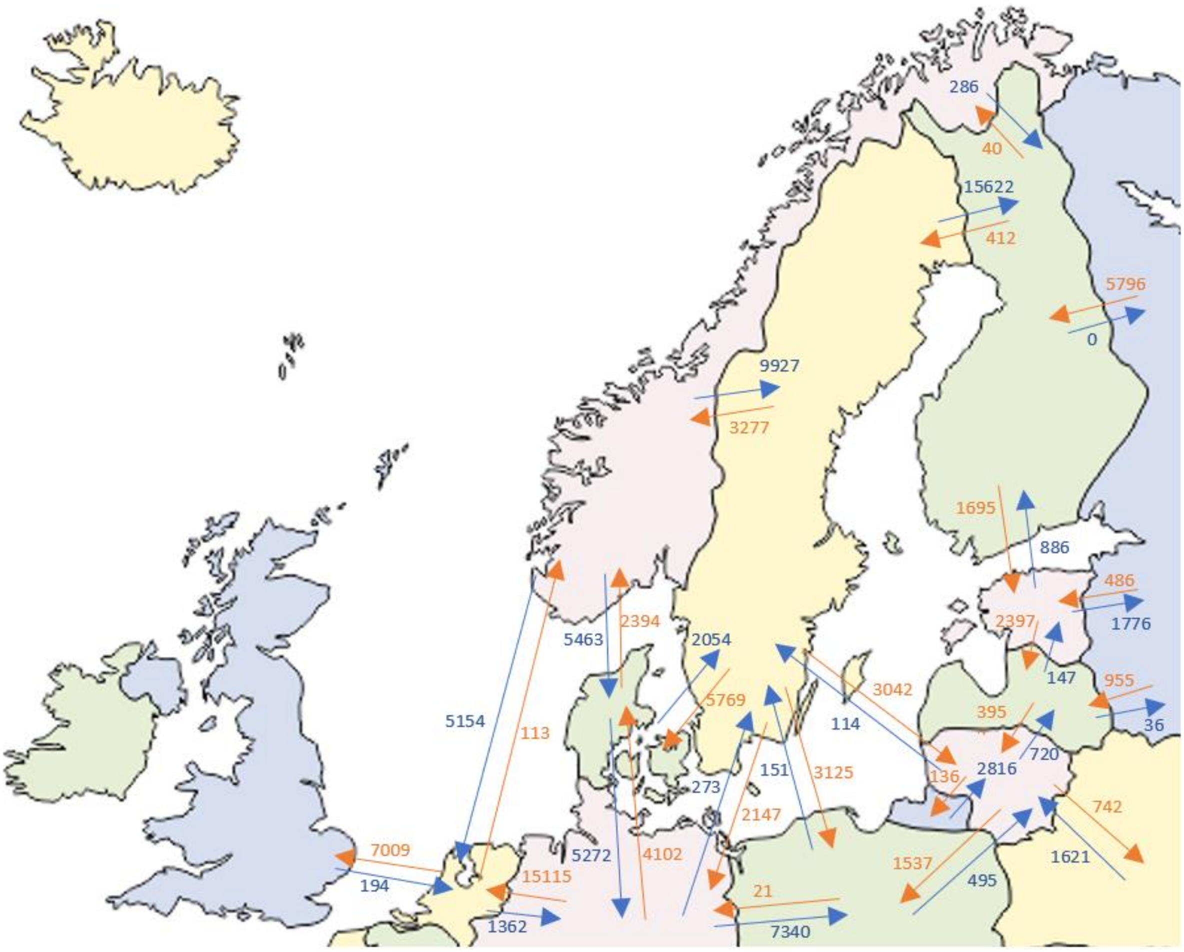

Figure 2. Physical energy flows in Northern Europe in GWh for 2017 (ENTSO-E, 2018). Map reproduced from https://d-maps.com/carte.php?num_car=4579&lang=en. Positioning of arrows not related to geographic organisation of power lines.

Figure 2 reveals more about the dynamics of the electricity system. For instance, one may conclude that power may flow from Sweden and Norway south- and eastbound. The image also shows the central role Germany has considering energy exports and indicate which nations are net importers (Finland, Great Britain) whilst some seem to be used as pathways to transport the electricity on to the next country (or at least in part; Netherlands, Denmark, Estonia).

3.2.1 The Nordic Electricity System

Here the Nordic electricity system is comprised of Sweden, Norway, Finland and Denmark. ENTSO_E, the collective organ for the transmission system operators in the EU (and closely associated nations) collect and publish electricity related data regarding the various countries. Figures 3 and 5.A-D are based on ENTSO_E data and depict the mix of sources used to produce the electricity in the Nordic countries in 2017. Figure 3 displays the shares produced from various sources in the Nordic countries. Evidently, hydropower dominates, followed by nuclear power production. There are also considerable shares of wind power and biomass. There was little production by means of fossil fuels, yet some hard coal and gas was combusted in Denmark and Finland. In Appendix 1 the data used to produce the charts is given.

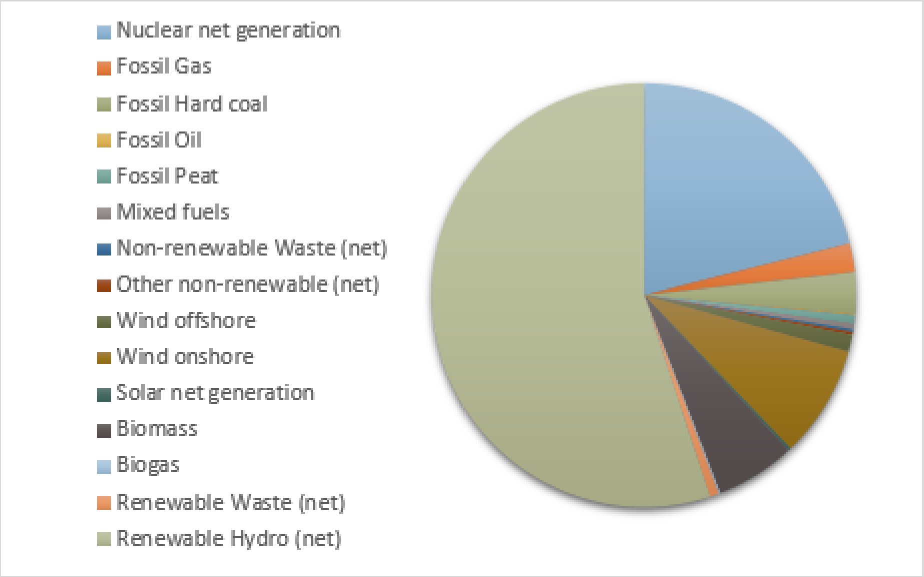

Figure 3. Sources of electricity in the Nordic countries. (ENTSO_E, u.d.)

The Nordic networks have alternating current and are interconnected (Svensk Energi, Svenska Kraftnät, 2014). The transmission grid in Sweden operates at two voltages, 400 kV and 220 kV (Svensk Energi, Svenska Kraftnät, 2014). The higher voltage lines have a strong north-south orientation, linking where the nations hydropower plants are located (Svensk Energi, Svenska Kraftnät, 2014) and where most of the population resides. The Swedish network is at lower voltages subdivided into regional and local networks with decreasing operational voltages and multiple owners (Svensk Energi, Svenska Kraftnät, 2014). The Swedish transmission lines are however state owned and managed by Svenska Kraftnät (Svensk Energi, Svenska Kraftnät, 2014). Most of the Norwegian network is located in the south of the country, where also most of the hydropower production is produced (Svensk Energi, Svenska Kraftnät, 2014).

The Finnish grid on the other hand is a wide mesh of lines with voltages of 400 kV or 220 kV in the southernmost part of the country, whilst a single 220 kV line tapers off to the north (Svensk Energi, Svenska Kraftnät, 2014). The transmission grid of Zealand can be seen as three 400 kV loops (one extending to Sweden) connecting some, but not all powerplants (Svensk Energi, Svenska Kraftnät, 2014). The Nordic countries are connected at around 20 locations (Svensk Energi, Svenska Kraftnät, 2014). In figure 4 below, the Nordic and Baltic electricity networks are depicted. In Appendix 2 an attempt to translate the text on the figure can be found.

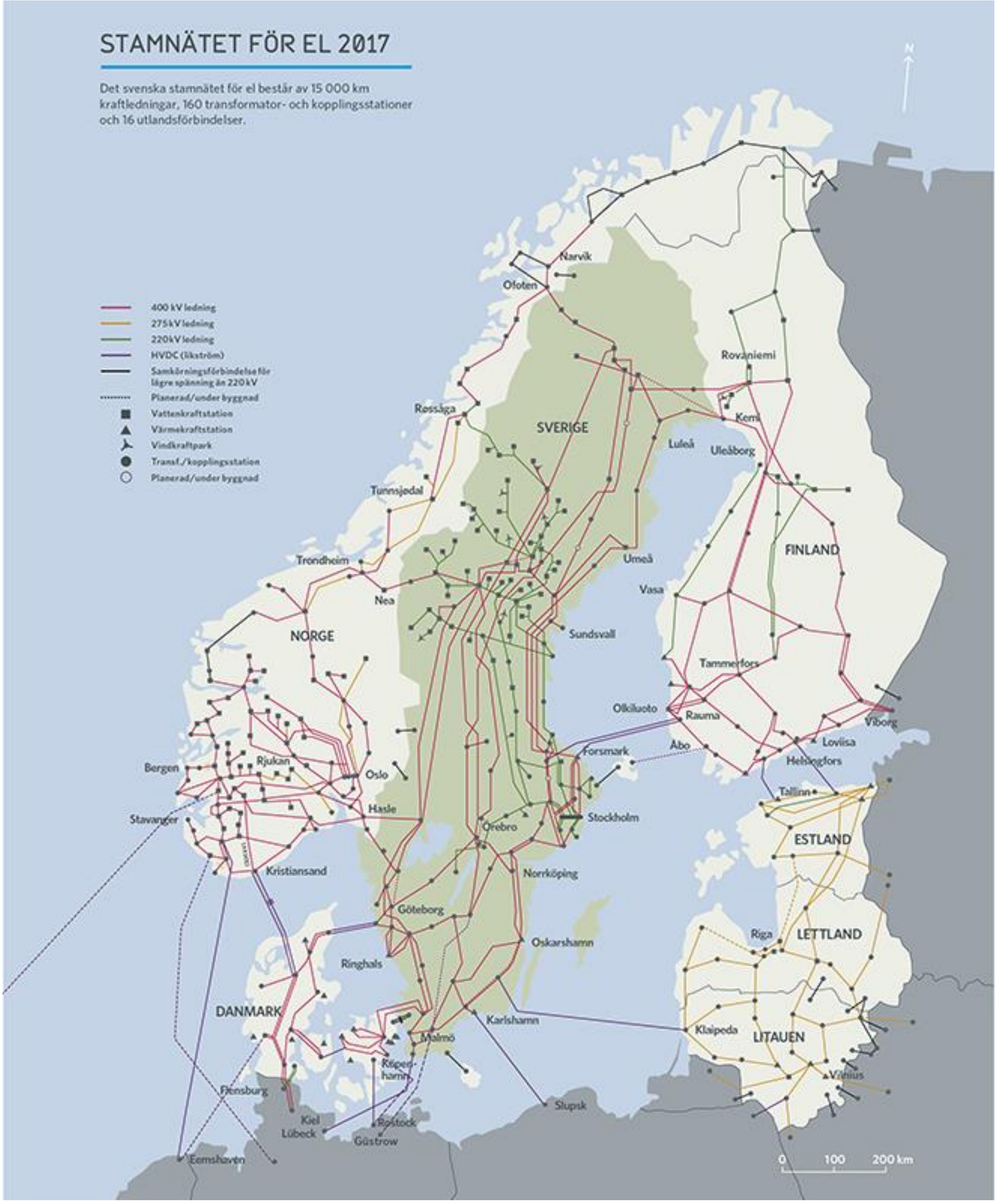

Figure 4. Map of the Nordic and Baltic electricity networks. Courtesy of Svenska Kraftnät: https://www.svk.se/drift-av-stamnatet/stamnatskarta/. Full translation of the text on the picture found in Appendix 2.

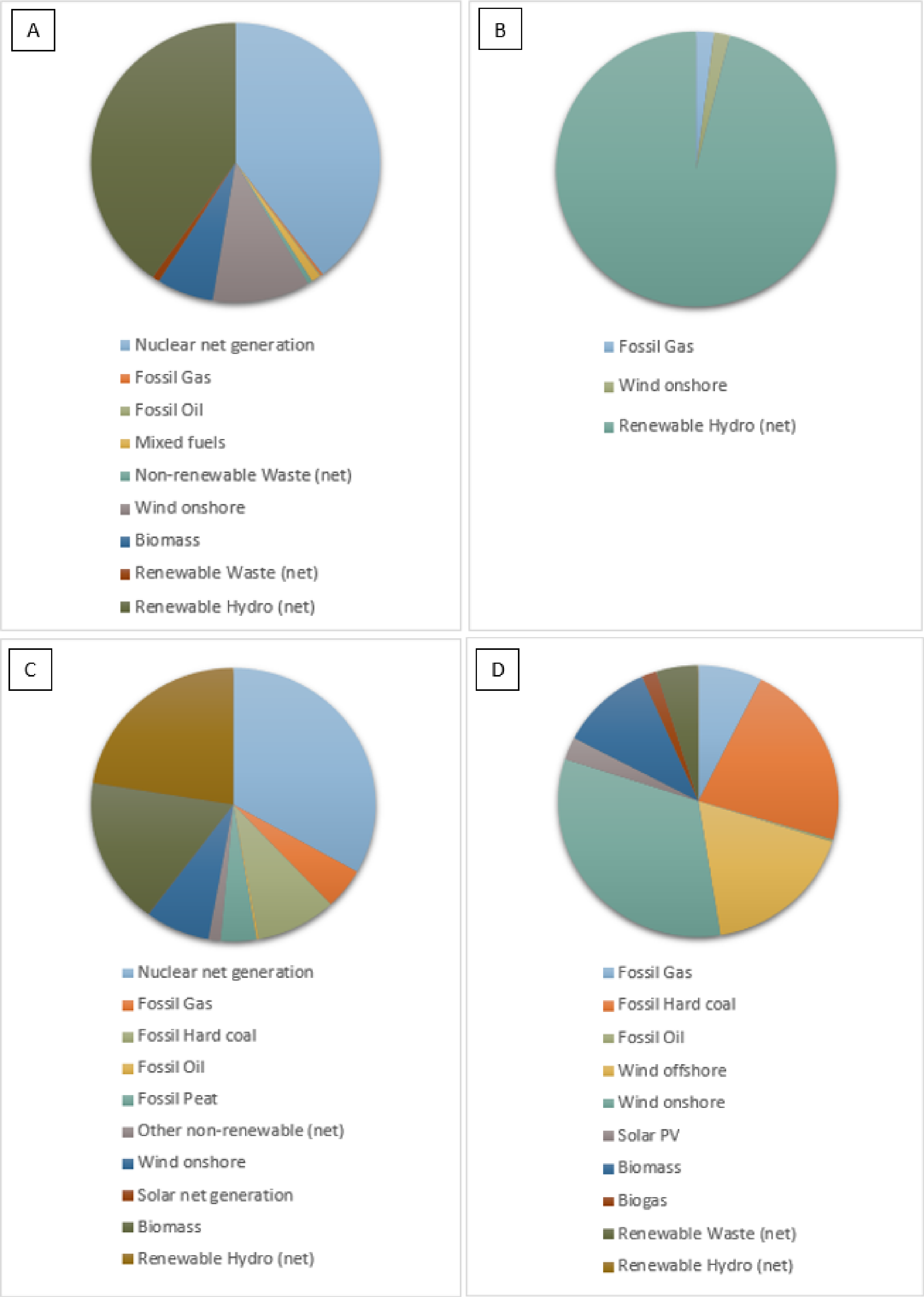

Figure 5. The energy mixes of the separate Nordic countries in 2017; A. Sweden, B. Norway, C. Finland and D. Denmark. Data from ENTSO-E: https://www.entsoe.eu/data/power-stats/monthly-domestic/

Finland have a rather diverse energy mix and produce most of their electricity from nuclear, hydro and biomass use, as seen in figure 5.C. The shares of the three largest production methods are similar, and the residual production was covered by many different sources. Next, it can be seen in figure 5.D that Denmark produced near half of all electricity by means of on- and offshore wind. The nation also stands for the largest solar production in the Nordics – 3 % of the electricity produced by Denmark 2017 was solar. The rest of the electricity production in Denmark was thermal (apart from a small share of hydro) and divided rather fairly between renewable and fossil sources.

The Norwegians produce by far most of their electricity by hydropower (around 96 %), visualised in figure 5.B. The residual production is shared by gas production and some onshore wind. Finally, as depicted in figure 5.A, Sweden produces the largest shares of electricity from hydro and nuclear. The rest of the production is mainly sourced from onshore wind and biomass. Generally notable is that the countries strongly base their power production on renewable sources, and that nuclear plays a large role in the countries that have such power plants.

Table 1. Total Consumption, production and capacity in the Nordic countries (ENTSO-E, 2018).

	Denmark	Sweden	Finland	Norway
Production [TWh]	29.4	159.1	65.1	148.6
Consumption [TWh]	34.1	139.9	85.5	133.7
Installed capacity [MW]	15 784	39 037	16 730	33 329

In table 1, a numerical overview with data provided from ENTSO_E is given, showing the difference in the production and consumption volumes of 2017, and the installed capacity the same year. Sweden and Norway produce similar amounts of electricity, whilst Finland and Denmark produce far less. Interesting is the similarity of the installed capacity between Denmark and Finland, even though Denmark produced less than half as much electricity as Finland did. A reason for this can be the high intermittency of the Danish wind production, evident in figure 6, which strongly affects the Danish production due to the large share it has in the electricity source mix.

Nord Pool operates the day ahead and intraday markets for the Nordic countries (Nord Pool, 2017). The company also collects data regarding total and wind production, consumption, exchange and water reserves. In figures 6 and 7, daily data from Nord Pool has been used, extracted for a period between the 1st of February 2018 to the 30th of January 2019 as there is limited access to historical data. Positive exchange indicates imported power. Figure 6 is a striking plot, where the large share of Danish wind from figure 5.D has a visible impact. Firstly, the consumption seems to have limited seasonal variation, yet a weekly cycle is evident, with lower demands during weekends and higher otherwise. Then one can identify that spikes in wind power production cause considerable spikes in total power production and if the wind is low, domestic production is strongly affected and imports are called for to make up for the demand. On the other hand, when the production passes the national demand, a large share of power is exported.

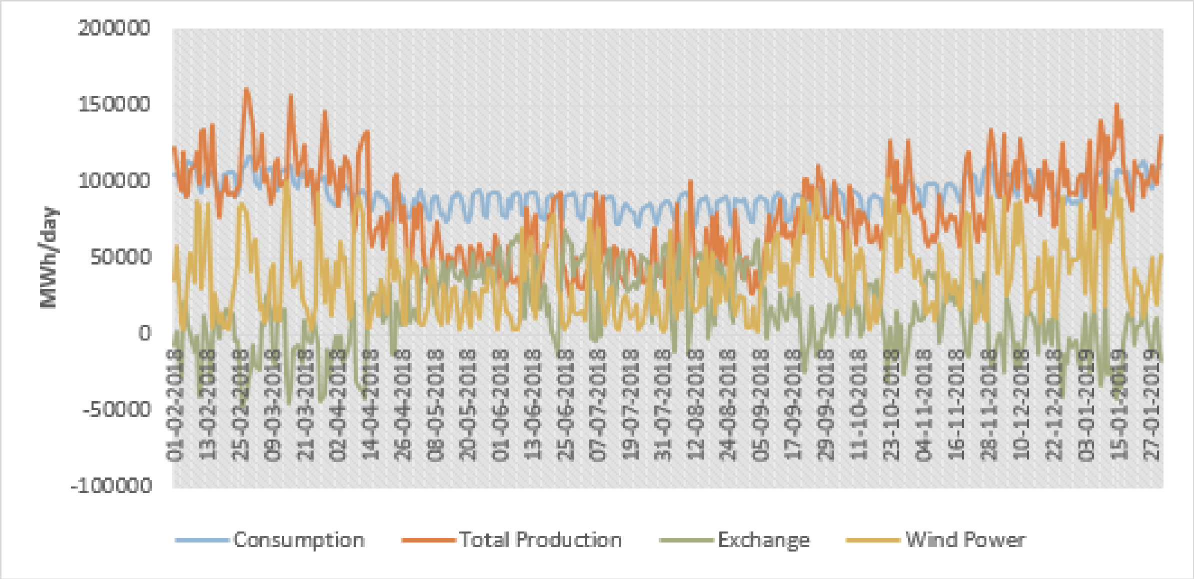

Figure 6. Danish trends. Wind power production correlates with exchange. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

In Sweden, the consumption during summer months follows a rather cyclic weekly trend, however compared to Denmark the seasonal variation is more pronounced. Also, consumption peaks occur during the winter season. The highest peak, on the 28th of February 2018 corresponds to an instance of very cold weather (Westin, 2018). In Denmark, at the same time, a peak in wind and consumption is discernible.

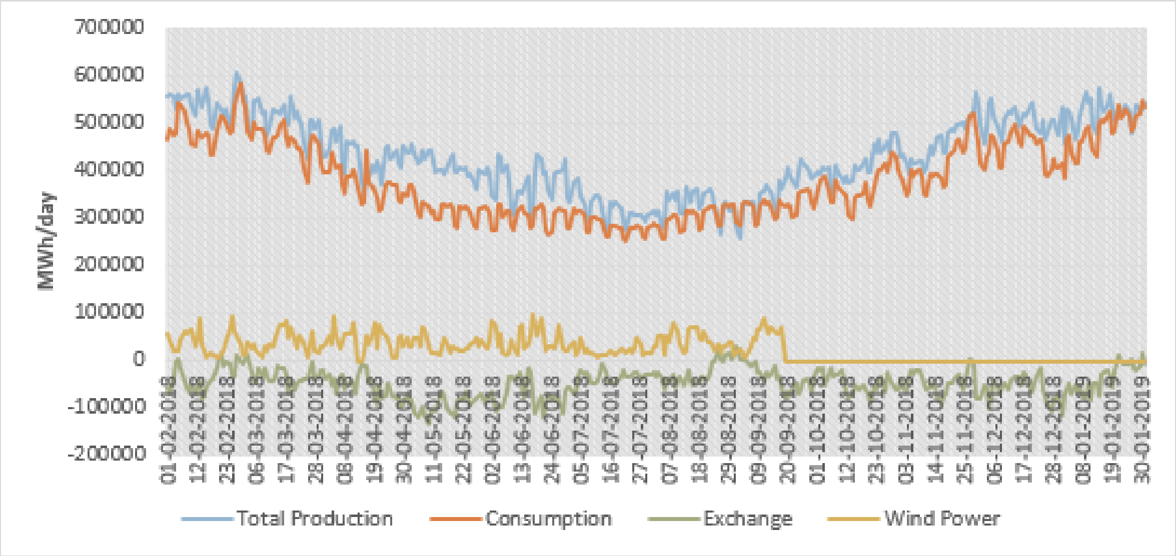

Figure 7. Swedish electricity trends. Sweden is a net exporter. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

From figure 7 one may also conclude that Sweden is a net exporter, and that this export, up until September is related to periods when the country has higher productions of wind power. When the wind is low (regarding January to September, wind data missing for the rest of the year) the exports decrease somewhat. The intermittency of the wind power production is also seen in the total production data, as it peaks when the wind power production peaks. One may also conclude that consumption and wind production during winter months are not entirely unrelated. For analysis of the trends in the other Nordic countries see Appendix 3.

3.2.2. The Baltic Electricity System

The Baltic countries have a transmission network of 275 kV, in a mesh that covers all three Baltic countries, as seen in figure 4. Estonia is connected through two HVDC cables to Finland, and also connects to Russia. Visible in figure 8, Estonian electricity generation is dominated by oil shale power. The remaining share is produced from renewables – mostly biomass and onshore wind.

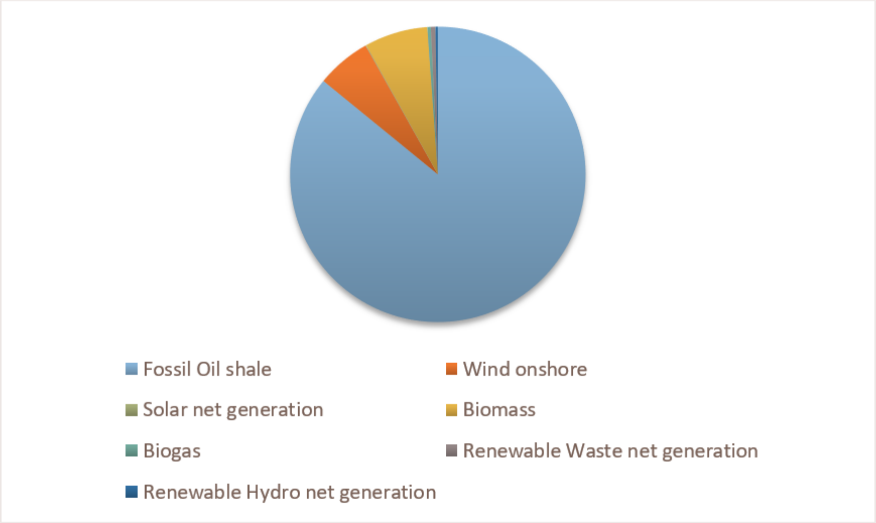

Figure 8. The Estonian power mix. Data from ENTSO-E: https://www.entsoe.eu/data/power-stats/monthly-domestic/

Latvia is connected to Estonia, Lithuania and Russia as figure 4 shows. Nationally it produces most electricity by hydropower. Shown in figure 9, most of the power is sourced from renewable sources, however a large share comes from gas.

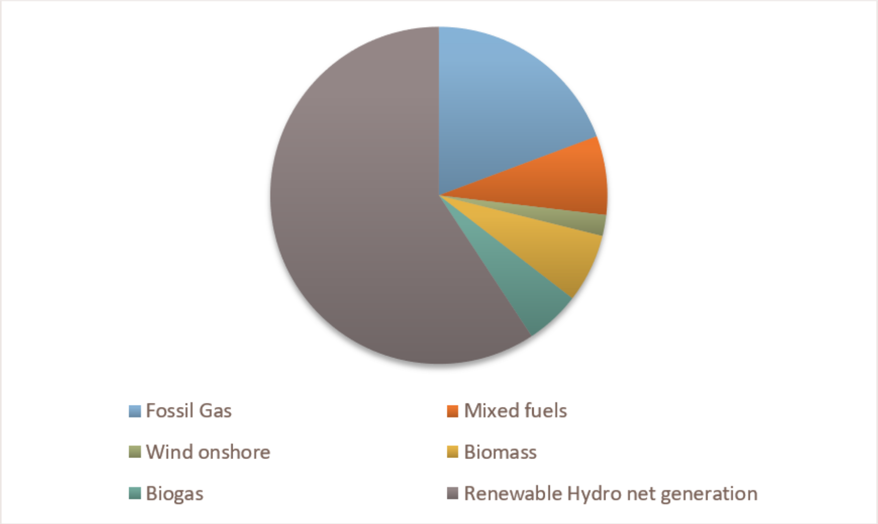

Figure 9. The Latvian power mix. Data from ENTSO-E: https://www.entsoe.eu/data/power-stats/monthly-domestic/

In turn, Lithuania is connected to Belarus, Poland, Kaliningrad and Sweden and has a diverse portfolio of electricity sources, visible in figure 10. The composition is dominated by renewable sources; onshore wind, hydropower and many more. A great deal of the power produced is provided from pumped storage.

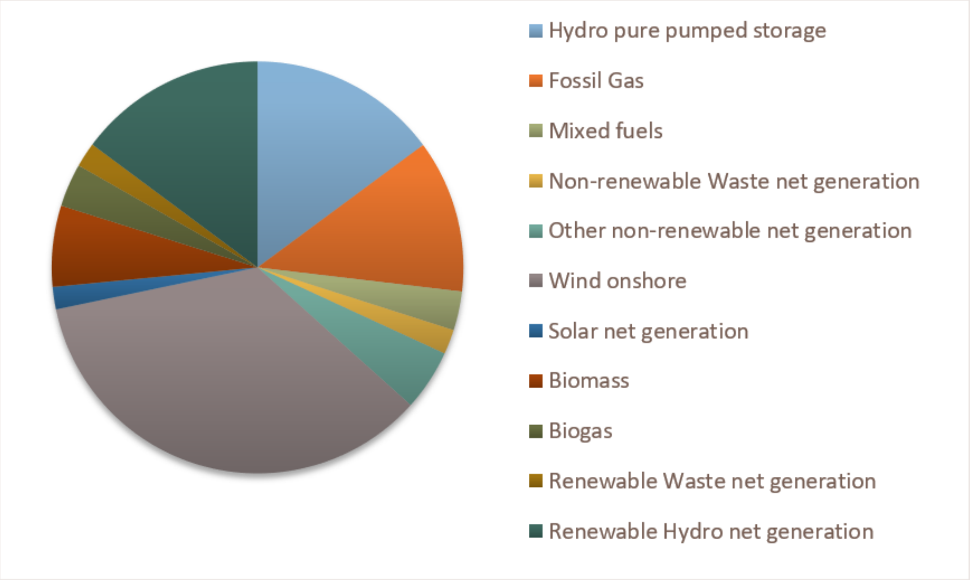

Figure 10. Sources of Lithuanian power. Data from ENTSO-E: https://www.entsoe.eu/data/power-stats/monthly-domestic/

Kaliningrad, the Russian region south of Lithuania, is also accounted to the Baltic area here. Electricity data is not readily accessible, however it is open that the capacity of the Kaliningrad area is around 1260 MW and should be able to cover peak demand, if the region were to be isolated (Office, Presidential Executive, 2018). Two new power plants, using gas and coal (Mayakovskaya and Primorskaya) were recently launched and together make up for an addition of around 300 MW for Kaliningrad. Most of the remaining capacity is covered by the 900 MW Kaliningradskaya TPP-2 which runs on natural gas (Inter RAO, 2019). So, in total, the Russian region is mainly powered by fossil fuels (50 MW of the total 1260 MW have here not been accounted for).

Table 2. Figures on the Baltic electricity production, consumption and capacity. (ENTSO-E, 2018)

	Estonia	Latvia	Lithuania
Production [TWh]	11.2	7.3	3.9
Consumption [TWh]	8.5	7.3	11.7
Capacity [MW]	2831	2929	3509

As seen in table 2, Estonia is a net exporter, while Latvia seems just to balance itself. Lithuania, despite having the region's largest capacity reserve, imports most of their power. The frequency of the Baltic electricity grid is currently synchronised with the Russian electricity grid, however recently an agreement was made to instead synchronise with the EU grid (de Carbonnel & Sytas, 2018).

Analysis of the regions consumption, production, exchange and wind power profiles can be found in Appendix 3.

3.2.3 The North-Western Electricity System

As seen in figure 1, the Nordic system has extensive ties with countries of North-Western Europe; Norway is connected to the Netherlands, Denmark and Sweden to Germany and Sweden to Poland. In table 3, one can conclude that Germany produces (and exports) almost 65 GWh more than it consumes. The Netherlands and Poland almost balance their consumptions.

Table 3. North-Western electricity production, consumption and demand (ENTSO-E, 2018).

	Germany	UK	Netherlands	Poland
Production [TWh]	602.3	312.3	111.5	157.7
Consumption [TWh]	538.7	324.8	115.4	159.3
Capacity [MW]	208 229	92 562	31 976	39 389

The German electricity comes from a very wide range of sources, as seen in figure 11, the largest single shares still being provided by (brown and hard) coal and gas. However, Germany uses many different types of renewables, most notably onshore wind provided as fair share of energy in 2017.

The Germans are phasing out nuclear power production in the south, however this may pose dire consequences for the energy intensive industry in the area. Between the north and south bottlenecks in transmission are present, posing problems for the industry and neighbouring countries alike - the German electricity is transmitted through neighbouring countries grids, hindering them from exchanging their own production. (Energiewende Team, 2018)

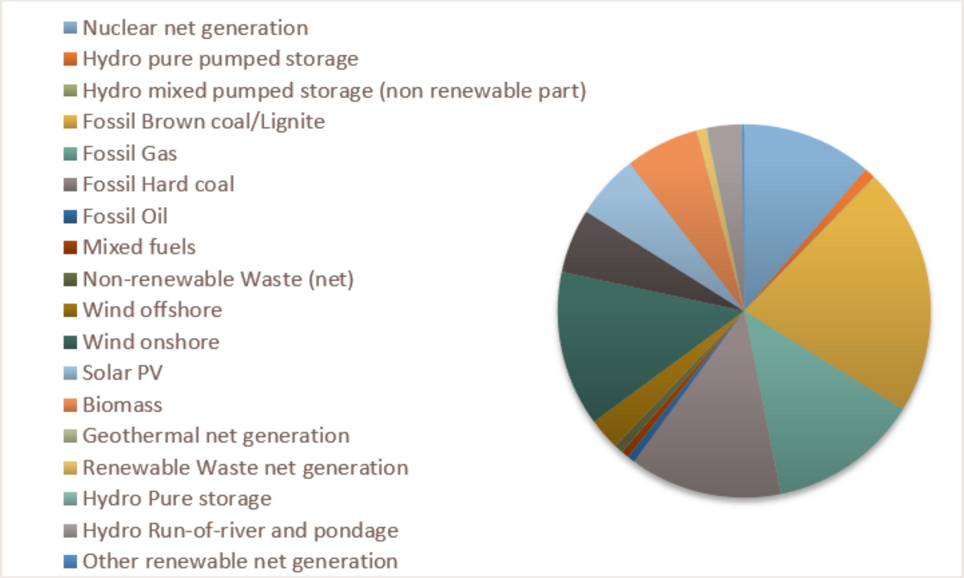

Figure 11. Sources of German electricity production.

As seen in figure 12, the UK produced the largest share of power with natural gas, holding deposits in the North Sea. Nuclear and renewables make up half; the Brits also use a vast range of different sources for renewable production. The relatively small share of coal has decreased further, and the renewables increased in 2017 (Department for Business, Energy & Industrial Strategy, 2018). The UK has hydro power plants concentrated in the north mainland and the western coast, fossil and biomass production mainly towards the south and all nuclear power plants along the nations different coasts (Department for Business, Energy & Industrial Strategy, 2018).

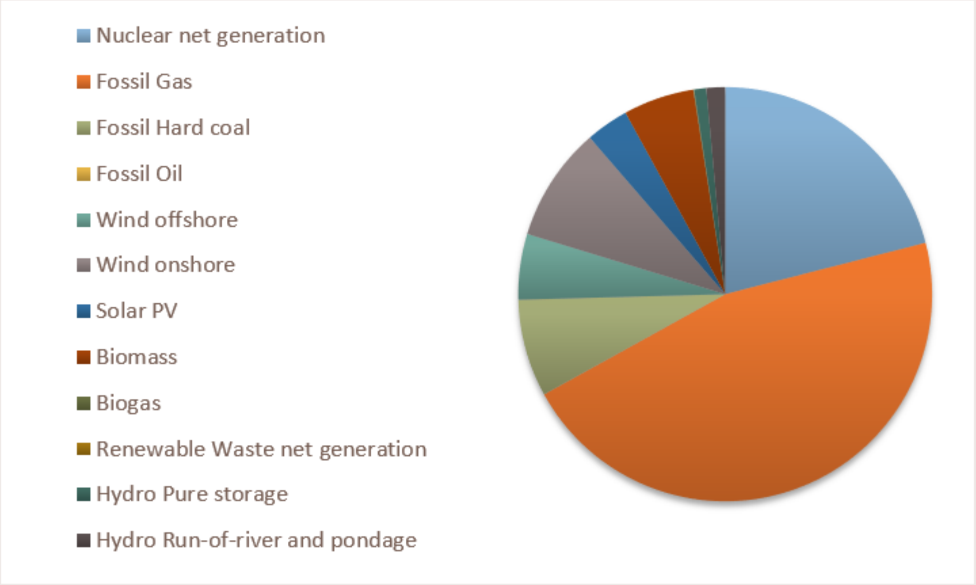

Figure 12. Sources of British power production (ENTSO_E, u.d.).

The Dutch produce by far most of their power from natural gas, holding large reservoirs in the North Sea. Their electricity production is strongly dominated by fossil fuels, with a large share coming from hard coal. Considering renewables, the largest share is from onshore wind. The nation does however have extensive and developed plans to extend production from offshore wind in the North Sea (Netherlands Enterprise Agency, u.d.). See figure 13 for the Dutch energy mix.

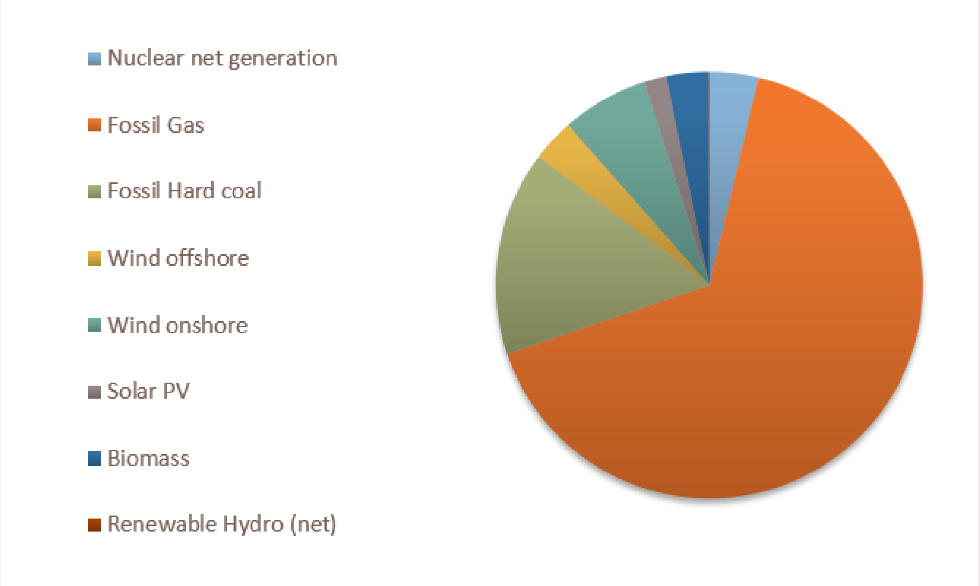

Figure 13. Sources of Dutch power production (ENTSO_E, u.d.).

Polish electricity is also dominated by fossil fuels, mainly hard coal which makes up almost half of the produced power. The largest lone amount of renewable energy came from onshore wind. The Polish energy mix can be found in figure 14.

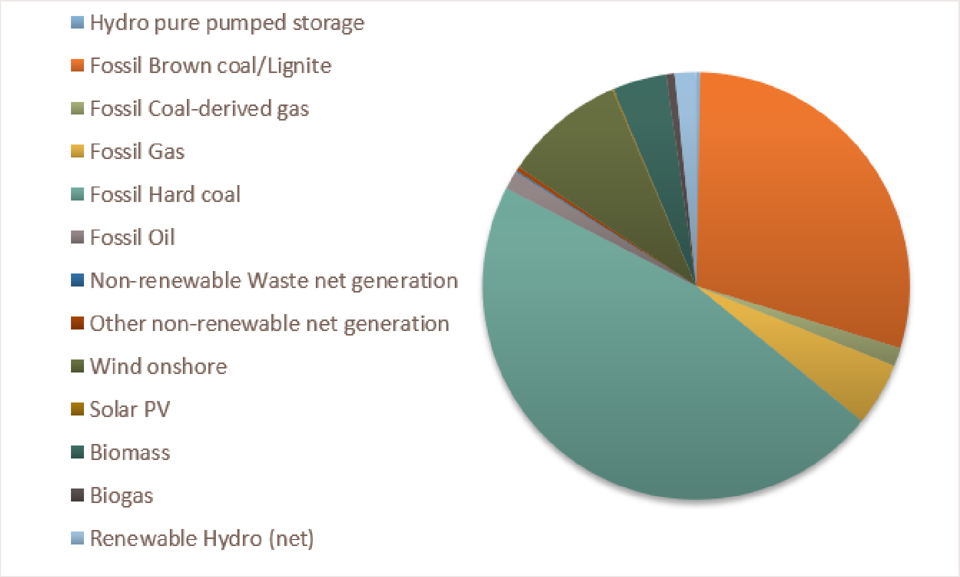

Figure 14. Sources of Polish power production (ENTSO_E, u.d.).

3.2.4. The Russian Electricity System

Recent data on the Russian electricity system is not as easily accessible as that of the EU. However, maps of the system dated 2002 imply that most of the network is located in the European part of Russia and that the network extends from west to east along the southern rim of the country (Global Energy Network Institute, 2017). Production follows an annual cycle, differing around 25 GWh between the winter month with most demand, and the summer month with least (CEIC, 2018). In total, Russia produces around 1091.5 TWh annually (CEIC, 2018).

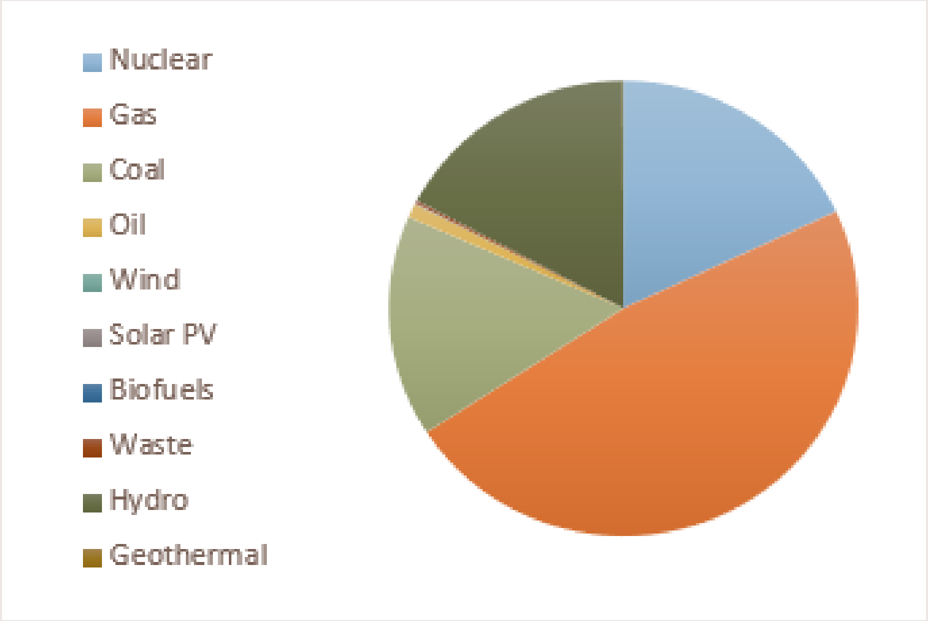

Figure 15. Sources of Russian electricity production 2016. (IEA, 2019)

As seen in figure 15, the production is heavily fossil, the largest share coming from natural gas, followed by coal. Shares of nuclear and hydro are similar to each other and together make up slightly over a third of the production. The shares of other renewables are negligible. A list is given in Appendix 6.

Since the 1990’s electricity consumption has increased in Russia, at the same time as the population has decreased and the economy (measured in GDP) has grown (IEA, 2019). Russia is a net exporter (and has been so since it was formed) exporting around 726 GWh in 2016 (IEA, 2019).

3.3 EVALUATING THE BENEFITS OF TRANSMISSION FOR REDUCING CARBON EMISSIONS

As mentioned in the introduction, the EU has set out that all the nations it comprises are to ensure that they have an interconnection capacity of minimally 10 % of their national production capacity by 2020 (European Commission, 2015). This is then intended to be raised to 15 % by 2030, if justified economically (European Commission, 2015). The Commission motivates this on the grounds that reliability will increase, capital can be saved by not needing to invest in new power plants, the cost for consumers will decrease with increased competition of supply and that higher level of intermittent renewables can be handled (European Commission, 2015). If a surplus of renewable electricity is produced in one country, such energy can be transmitted to another country where the demand is high (European Commission, u.d.). The Commission admits that to reach the goal of a fully decarbonised EU 2050 that well-functioning trans-European grids are vital, and that the network must evolve in the same track and pace as clean energy investments (European Commission, 2017). Until 2030 the Commission foresees circa € 180 billion in investments, which result in € 40-70 billion in savings annually (European Commission, 2017). Infrastructure projects found to be vital for well interconnected networks and the formation of the internal energy market have been selected, known as Projects of Common Interest (PCIs) (European Commission, 2017) and are in various stages of initiation, building or operation (European Commission, 2018).

This need for investments resound among Swedish authorities. Not only must the network be strengthened for safety of delivery and to support RES penetration, also as larger exchanges on both Nordic and European levels are expected (Svensk Energi, Svenska Kraftnät, 2014). However, some claim that even if the production from RES has been well considered by politicians, yet that the electricity network is not as prepared – a future scenario has not clearly been given, resulting in uncertainty for the network companies (Wolf & Andersson, 2018). Indeed, economic and population growth have resulted in some of the capacities in the Swedish network are maximally utilized, forcing network companies to decline new connections (Pöyry, 2018).

3.3.1 The Effects of Renewable Electricity Production

Up until now, electricity systems have been centrally planned, with a (relative) few, dispersed power plants producing all power (de la Poutre, 2018). When demand increased, the generation was ramped up – when demand decreased, generation was ramped down (de la Poutre, 2018). However, with the introduction of more renewables to the grid, this is no longer possible – renewable production such as wind and solar PV follows weather conditions and is inherently variable.

Solar power firstly varies with a daily cycle – determined by when the sun shines. There is also a certain seasonal variation, as there is more sunshine in the summer in the Northern Hemisphere. Further variability is introduced by local weather phenomena, most pronounced by clouds (Sayeef, et al., 2012). Sayeef et al. (2012) state that on a timescale of seconds solar power productivity can drop by more than half if insolation is hampered.

In turn, the power produced from a single wind power unit is neither a consistent source of electricity, as the yield is highly variable (Bach, 2010). Systematically, wind has a diurnal profile following from surface temperatures changing (heated by the sun) and a seasonal profile – winter wind speeds can be double those of the summer on northern latitudes (Mulder, 2014). However, in reality wind is affected by many different factors (Pidwirny, 2006) and the resulting wind profile usually irregular (see figure 6).

The variability effects the electricity system in several ways. As the production is not stable, it is more challenging to keep the system in equilibrium and the voltage stability can be compromised (Bayindir, et al., 2016). Bayindir (2016) however finds that more wind power in the system may have positive effects too, supporting the voltage stability. This owes to that reactive power increases with long lines, yet that this power may be absorbed by the induction that wind power production provides, thereby decreasing the voltage in the bus bars (Bayindir, et al., 2016). In other systems wind turbines may unwelcome precisely due to their consumption of reactive power[4] (von Meier, 2006).

The inertia of the system, the tendency of the system to remain at the same frequency, may decrease when much wind power is connected in the system as opposed to conventional, synchronous generation, especially in small islanded systems (Lalor, et al., 2005). With less system inertia, the system is more vulnerable frequency changes if supply and demand do not match (Lalor, et al., 2005). However, wind power may be used to support the frequency by controlling variable speed wind power plants (Krpan & Kuzle, 2019)

Photovoltaic solar power produces direct current, and if AC is required the power can be transformed by an inverter (NREL, u.d.). Historically, inverters have been a concern for utilities believing that power quality would decrease if high solar deployment mandated plenty of power to conditioned by inverters (Bravo, et al., 2014). However, inverters seem to be made more recently that actually improve power quality (Bravo, et al., 2014)

3.3.2 The Effects of Increasing Capacity

As seen in the introductive part of subchapter 3.3, there are many benefits to increasing transmission capacity – reliability, economic efficiency and that more renewables can be integrated. Considering both wind and solar, it is a common conception that the aggregated production of dispersed production units will smoothen the production profiles (Bach, 2010) (Sayeef, et al., 2012). However, it is still important not to neglect local effects regarding power quality for solar power (Sayeef, et al., 2012). The spatial separation can be rather large, as the Commission suggest excess production to be sent across national borders (European Commission, u.d.). Indeed Bach (2010) claims that as long as the demand profile of Denmark does not suit the wind production profile, the outcome is that the difference caused by the excess wind power is exported and replaces some (more expensive) electricity production elsewhere.

Daniels (2016) separates between *operational* and *embodied* emissions. Operational emissions cover the carbon emitted relating to the actual generation, whereas the embodied emissions consider the emissions from the assets that comprise the electricity network (Daniels, et al., 2016). Recently, the ratio of the embodied emissions of the transmission grid in Great Britain to the operational emissions were estimated to be around 4 % (Daniels, et al., 2016). However, with the decarbonisation of the operational electricity production, the embodied emissions of the same area may become nearly 25 % of the total in 2035 - if assuming that only these two types of emissions are considered, the embodied to operational ratio then becomes 1:3 (Daniels, et al., 2016).

Daniels (2016) notes that many studies consider the operational emissions - for instance Hawkes (2010) has calculated marginal emissions rates for several generators in Great Britain for 2008 - however that those relating to the repercussions of actually building the grid are limited.

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[4] To provide” space” for reactive power in a line one may need to increase the capacity of a line above what one may need for useful power.

Harrison (2010) has performed a life cycle assessment (LCA) of transmission assets in Great Britain. Life cycle assessments aim to quantify all the environmental effects that a product, process or service through production, use and retirement may cause (Harrison, et al., 2010). Closer to home, the Norwegian transmission grid has also been investigated using LCA, where it was found that the largest impacts were given by overhead lines, transformers and insulating gas (SF_6) (Jorge & Hertwich, 2013).

3.3.3 Methods to Increase Capacity

There are several different methods to increase the capacity of a given part of the transmission grid. Based on informal interviews with staff at Pöyry three methods have surfaced; increasing the (cross-sectional) conducting area of the cable, increase the voltage over the line or build an entirely new one (Sandblom, 2019). To *increase the cross-sectional area* of the line, one must entirely replace it and sometimes other artefacts such as poles if they cannot bear the new load (Västernäs, 2019). A wider diameter allows more current to flow and results in less losses compared to a leaner line. If planners have assumed that the capacity of a line may be required to increase over time, the line may be initially operated at a lower voltage than the cable is dimensioned for – however when a higher capacity is required, one may *increase the voltage* (Västernäs, 2019). Finally, one may increase the capacity between two regions by construction an entirely new line.

3.3.4 Concluding and Identifying Tool Components

In conclusion, many parameters must be considered when designing a tool to attempt to quantify the impacts of carbon equivalent emissions of extending the transmission grid. Seemingly the largest aspect is the operational emissions – the ability to displace the production of fossil power with renewables and to support the integration of renewables through balancing peaks and lulls in geographically dispersed locations. It is therefore important to consider quantities of power that may be displaced if an investment in the transmission grid is made, and how much the production of the power may emit.

Further, the embodied emissions may prove to play a large role in future systems. Extensive life cycle analyses are perhaps beyond the scope of this thesis; however, it should be possible to assess the greenhouse gas emissions based on values found in previous literature and the planned size (transfer distance) of the project. A related aspect is the time horizon. The technical lifetimes of network equipment may extend to 80 years (Daniels, et al., 2016). Hence, the result of a comparison from saved operational emissions and created embodied emissions may look very different if compared in the frame of one year compared to the lifetime of the investment.

Finally, one could include the need to maintain power quality at a high level. This is an important aspect, however as the aim of this tool is to be *complementary* for engineers and technical staff already ensuring the safety and quality of investments in the power grid it will not be covered to a great extent in this work.

In summary, when assessing the GHG emissions of increased transmission capacity one should consider:

- Operational emissions: how much emissions the actual power production gives rise to.
- Embodied emissions and time horizon: the emissions caused by the production and use of the assets, spanned over the time of use for a fair comparison.

4. MODEL DEVELOPMENT

4.1 DATA HANDLING

The model requires input data regarding wind power production, demand, capacities of both production facilities and transmission lines, alongside fair price data and carbon emissions per unit of energy produced. The handling of the wind power and demand data are explained in detail in the two following segments.

Data determining the capacity of transmission lines (in MW) was collected from the ENTSO_E (2018) except for the capacities between the Polish/German and Dutch/German areas. These were instead estimated as the highest recording of transferred power during 2017 and 2018, based on hourly data from the ENTSO-E Transparency Platform (ENTSO_E, u.d.). The aggregated production capacities for various power sources in the different areas were also collected from the ENTSO-E Transparency Platform (ENTSO_E, u.d.) for the year of 2018, apart from Denmark and Sweden. For the former, Transparency Platform values were taken for the year 2017 (the most recently available), and the latter case was handled separately as the Platform held no values for the separate Swedish market areas, see appendix 7. Finally, price data, in the form of average marginal costs per thermal power source and area was acquired from Pöyry Sweden AB. In the case of oil shale in Estonia, the price data was missing and set by iteration.

In cases where a small number of data points were missing from a ENTSO-E series for wind power or consumption, replacement was made to the average of the two neighbouring hourly values. In the cases of UK consumption data and wind data for Estonia, Latvia and Lithuania, data corresponding to several, often consecutive, days was missing. These entries were replaced by the average of all other non-zero values of the timeseries for the area. Further, the ENTSO-E data had double entries for the time interval 02:00-03:00 on the 28 October 2018, marking the change between summer and winter time. Values from one of the “double” hours were systematically removed.

4.1.1 Wind Power

The data used for the modelling of wind power production was collected from the ENTSO_E Transparency Platform (ENTSO_E, u.d.) and consisted of hourly values for all areas from the year of 2018. The hourly wind power production data is divided by the known capacity of wind power in a market area, yielding a capacity factor for each timestep, simplifying scaling up production at a later point. Data from different areas were compared, to investigate if the correlation between them may be modelled in a linear fashion.

For evaluating the linear dependence of two random variables, correlation coefficients are to be used (Centre for Mathematical Sciences, Lund University, 2012). The value of the correlation coefficient lays between 1 and -1, where values closer to 0 indicate there is little correlation (Centre for Mathematical Sciences, Lund University, 2012). When investigating the wind power production or consumption correlations between different areas Pearson’s correlation coefficient was calculated via MATLAB. It is defined as (Chee, 2015):

$$\rho(X,Y) = \frac{cov(X,Y)}{\sigma_X \sigma_Y}$$

Where ρ is the correlation coefficient, cov marks covariance, X and Y are the data series and σ_X and σ_Y are the standard deviations of X and Y respectively.

MATLAB uses the following to estimate Pearson's correlation coefficient:

$$r(X,Y) = \rho^*(X,Y) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{X_i - \mu_X^*}{\sigma_X^*}\right)\left(\frac{Y_i - \mu_Y^*}{\sigma_Y^*}\right)$$

where X and Y are the data series, N are the number of values in the data series, μ_X^* and μ_Y^* the calculated mean values of series X and Y and σ_X^* and σ_Y^* the calculated standard deviation of X and Y respectively (The MathWorks Inc, 2019).

Mukaka (2012) distinguishes between a low correlation for correlation coefficients between 0.30 and 0.50 and a moderate correlation for values ranging between 0.50 and 0.70 according to his "rules of thumb". If the correlation coefficient is above 0.5, the areas are here assumed to be correlated, and if below, the areas are perceived as if they are not. In the case of the UK/Netherlands the correlation coefficient is below the limit (0.44) yet the areas are exceptionally modelled as having a valid correlation.

The data sets from the areas were compared to sets from several different areas to find the best correlations and determine if it is possible to model all areas as dependent on a single data set or letting the determining data set *cascade*: that is, letting the calculated set of one area determine the next and so on.

The results indicated that it the correlation would be too low if all areas were to depend on any one area and the cascading approach was chosen. After developing several alternatives, it was chosen that SE4 would be the only predetermined series, which could then be used to calculate the values of SE3, DK2 and LT, which were in turn used to determine other areas as visualised in figure 16. Figure 17 displays a map with the geographic orientation of the dependencies.

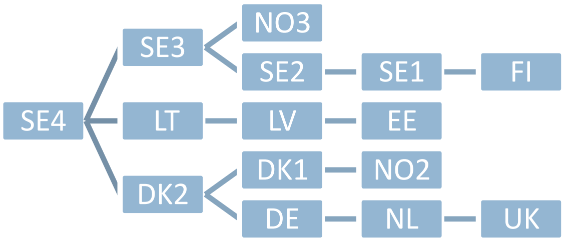

Figure 16. Time series dependency.

In figure 17, orange arrows indicate the direction of dependency; i.e. that the values of SE4 yield the values of SE3, which in turn are input for producing the values of SE2 etc. Yellow arrows indicate alternative and good correlations, which will however not be used for the model itself.

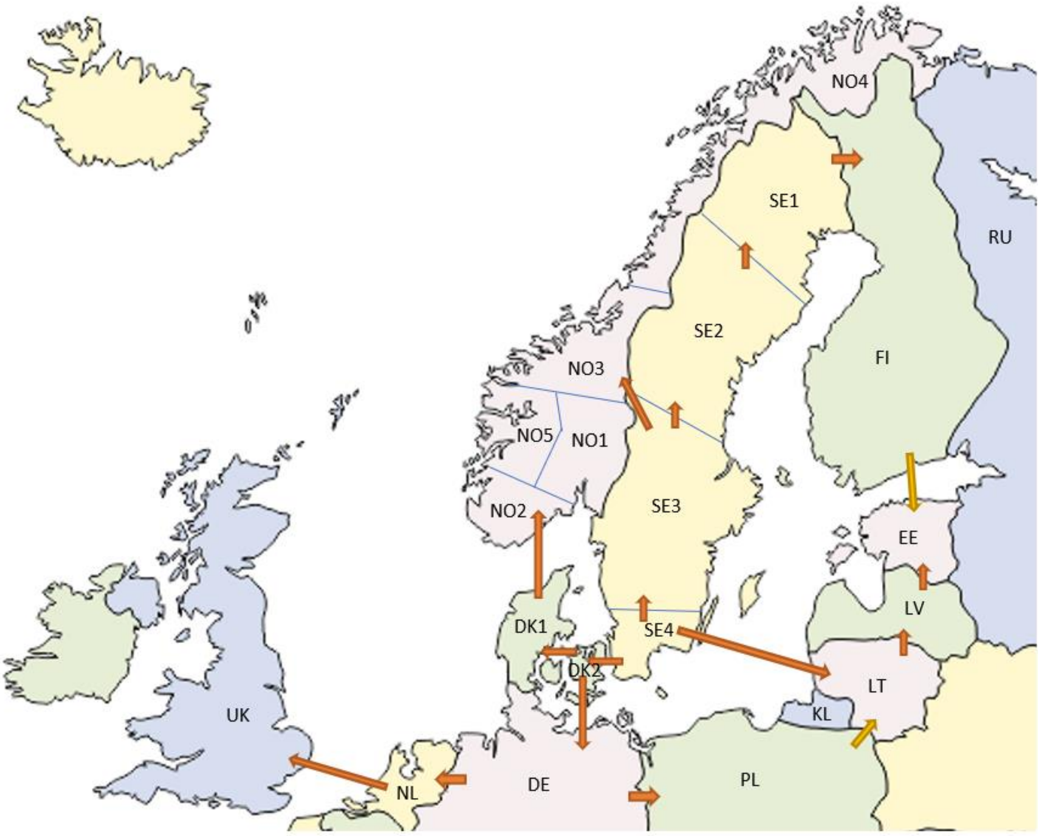

Figure 17. Wind power production dependencies, alternative 1. Map reproduced with courtesy from https://d-maps.com/carte.php?num_car=4579&lang=en

No area corresponded well to the series of NO4, therefore the areas wind production was modelled as a normal distribution. In table 4, the correlation coefficients between the areas, that also were used in the model are given.

Table 4. Correlation coefficients for used correlations.

Areas	Correlation Coefficient	Areas	Correlation Coefficient	Areas	Correlation Coefficient
SE1/SE2	0.760	**SE2/SE3**	0.554	**SE3/SE4**	0.723
SE1/FI	0.712	**SE4/DK2**	0.766	**DK1/DK2**	0.822
SE4/LT	0.583	**EE/LV**	0.718	**LV/LT**	0.768
DK2/DE	0.714	**NL/UK**	0.441	**NL/DE**	0.812
DE/PL	0.651	**SE3/NO3**	0.544	**DK1/NO2**	0.599

The wind correlation between different areas was modelled by linear functions, in a model similar to linear regression. Linear regression is best used when the data is unidirectionally dependent and there is only one set of data contain elements of stochasticity (Centre for Mathematical Sciences, Lund University, 2012). In this case neither requirement is true: the occurrences in one area may well affect the next and this dependence is also true in reverse, along with both data sets containing random elements. Still, linear modelling is simple, fast and likely to be sufficient for the purposes of this thesis.

If Y is the data set for an area that is to be modelled, and X is a previously known set, the linear model is given by:

$$Y = A \times X + B + \gamma_{rand}$$

The constants determined for each correlation, A and B, were determined by matching a first-degree equation to the wind power production values from two areas at the same timestep. Thereafter, the difference between the modelled Y values and the actual values corresponding to the same value of X (the residuals) are calculated and were tested to see if they seem normally distributed. As all residual distributions were found to be normal, a stochastic element, γ_{rand}, could be modelled as a random value from a normal distribution with the same mean value (0) and standard deviation as that of the residuals.

The starting series, that of SE4, will be prepared to correspond to 73 timesteps. If using this series as the source for all calculations, some areas may be subjected to a certain degree of distortion compared to reality, if many cascading calculations involving random variables are made. Such an example is the area FI, which in the model depends on the outcome of three previous calculations (SE4 to SE3, SE3 to SE2 and SE2 to SE1). However, in this case, the effects of this is assumed to be negligible: over 73 timesteps with normally distributed random variables taking part in determining the series of the areas, the aggregated results were observed to compare well to reality. Further, the choice of this method can be motivated by the fact that modelling congestion is key to this thesis, hence it is more important that adjacent countries have strong correlations in wind power production. Better still, many countries with high wind power production (DK1, DK2, DE) lay close to the region with the initial timeseries (SE4) whilst the distance to smaller producers at least is relatively equal.

There are several reasons for not using the historical data sets as inputs in the model, the most important being that number of timesteps can now be easily diminished – in the model 73 timesteps are used opposed to the 365 days or 8760 hours in a year – as they directly relate to the run-time of the model. Further, the reliability of the results increases if there are several cases with slightly different input data that indicate similar results. As there are random elements in the inputs, no results are expected to be exactly the same numerically.

4.1.2 Consumption

The data for demand was taken from the ENTSO-E Transparency Platform for the case of DE, UK, NL and PL (ENTSO_E, u.d.). Data from the rest of the areas was collected from Nord Pool (Nord Pool, u.d.). The correlation between hourly wind power production and consumption was investigated for the 17 areas with wind production data. The results showed low correlation factors; as seen in table 5 it is evident that a clear relationship is hard to discern in any area.

Table 5. Correlation coefficients between hourly wind power production and demand.

Area	Correlation Coefficient	Area	Correlation Coefficient
SE1	-0.019	**FI**	0.013
SE2	-0.086	**EE**	0.083
SE3	0.071	**LT**	-0.012
SE4	0.181	**LV**	0.036
DK1	0.165	**DE**	0.126
DK2	0.106	**UK**	0.122
NO2	0.237	**NL**	0.150
NO3	0.172	**PL**	-0.019
NO4	0		

These results give that for a fair interpretation of reality, a given level of demand and a given level wind power production must be randomly selected for any timestep in the model, and that the load should not be modelled as wind dependent (or vice versa). After examining the correlation coefficients for hourly demand data in different areas, it was evident that all the areas correlated rather well most of the time. Therefore, the method of selecting one single series to determine all other series (directly) was chosen.

After comparing multiple areas, it was found that SE3 and SE4 had a good relationship to most of the areas, as seen table 6. However, finally SE4 was selected as the single improvements of many correlation coefficients were high, with only a few percentage points disadvantage for those with better correlation values with SE3. The demand timeseries are determined in the same linear fashion as the wind power production, with a random element, with the only input being the SE4 timeseries for demand, adjusted to 73 timesteps.

Table 6. Correlation coefficients for the correlation of demand between different areas. Cells marked in grey hold higher values.

Area	Correlation to SE3	Correlation to SE4
SE1	0.825	0.799
SE2	0.899	0.876
SE3	1	0.980
SE4	0.979	1
DK1	0.720	0.776
DK2	0.847	0.877
NO1	0.967	0.930
NO2	0.968	0.940
NO3	0.953	0.925
NO4	0.934	0.900
NO5	0.927	0.900
FI	0.956	0.937
EE	0.911	0.931
LT	0.765	0.811
LV	0.740	0.787
DE	0.592	0.662
UK	0.697	0.707
NL	0.704	0.749
PL	0.680	0.734

4.1.3 Determining the Timestep

To determine how large representative timesteps can be made, both wind and demand data was analysed. Preferably, the timesteps are relatively few (increases speed), yet remain representative, preferably covering extreme situations rather well. To determine a fair timestep, both the hourly data was sorted in ascending order, a curve fitted to the ascent and comparisons made to ensure that the timesteps would make a fair representation generally.

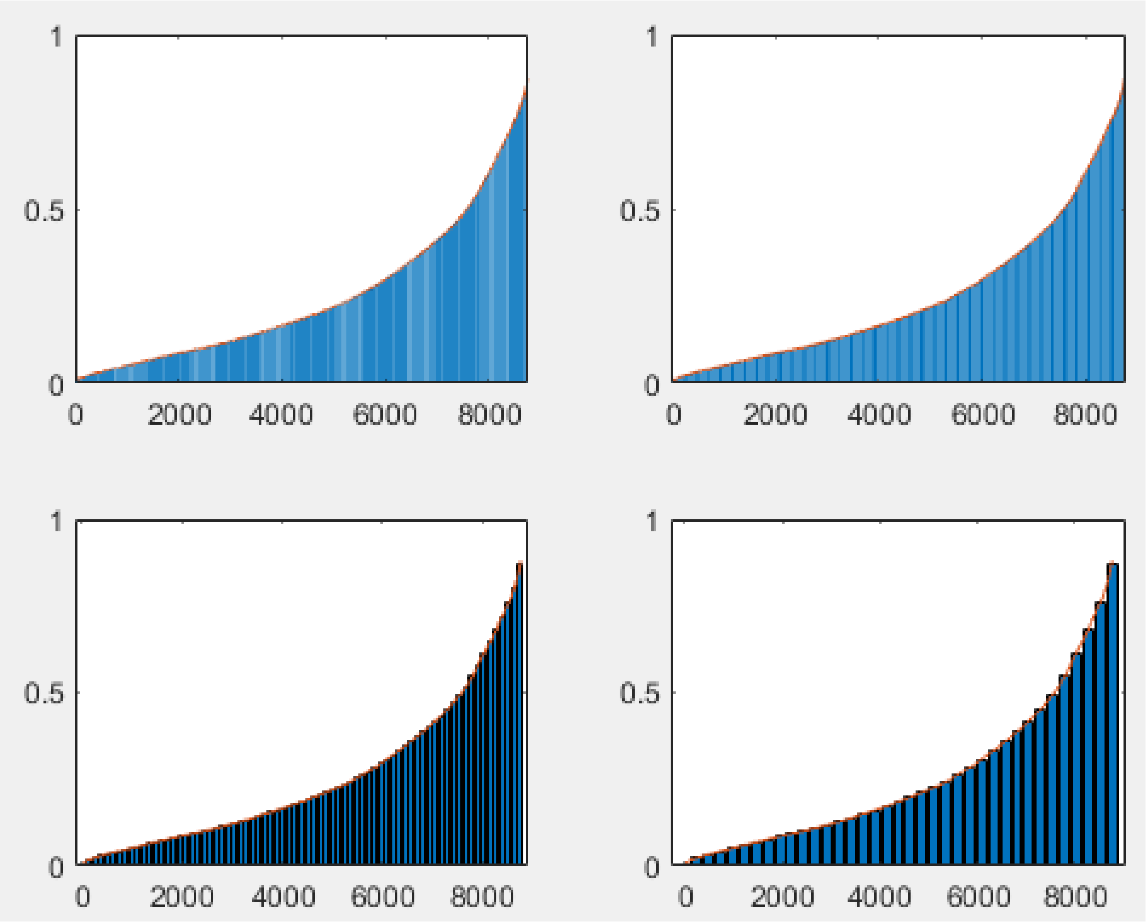

Figure 18. Timestep comparison for SE4. Top left figure orange line gives the fitted curve, in all other pictures the orange line corresponds to the original sorted data.

In the top left of figure 18 the wind power daily average capacity factors of SE4 have been organised in ascending order, and a 15-degree polynomial has been fitted to suit the data. To investigate how finely the timesteps may be defined, bar graphs were then produced for optical comparison; timesteps corresponding to two, five and ten days are plotted as bar graphs together with the original data outline (orange) as an example for the reader. With a resolution of 365 timesteps, the fit is very good (top right). Setting ten days together (bottom right) may perhaps not provide a high enough resolution. Yet, a suitable compromise gives a time series 73 elements long (bottom left). This conclusion was reached for the entirety of the areas.[5]

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[5] The author gladly sends the images used to optically inspect timestep suitability for all areas upon request.

To ensure that 73 timesteps suit the known consumption as well, the same process was performed for the consumption data, whereby the conclusion was that a set of 73 timesteps would be a suitable number of timesteps.[6] The wind data, with a steeper curve after sorting, is more sensitive than the demand data to the length of the timestep – 37 timesteps seem to be a decent approximation for the latter. In figure 19, the comparison can be made for SE4. The hourly consumption was sorted and fitted with a 15-degree polynomial, as seen in the upper left corner. Applying the polynomial to 365 timesteps gives the graph in the top right corner, 73 timesteps in the bottom left corner and 37 timesteps in the bottom right corner.

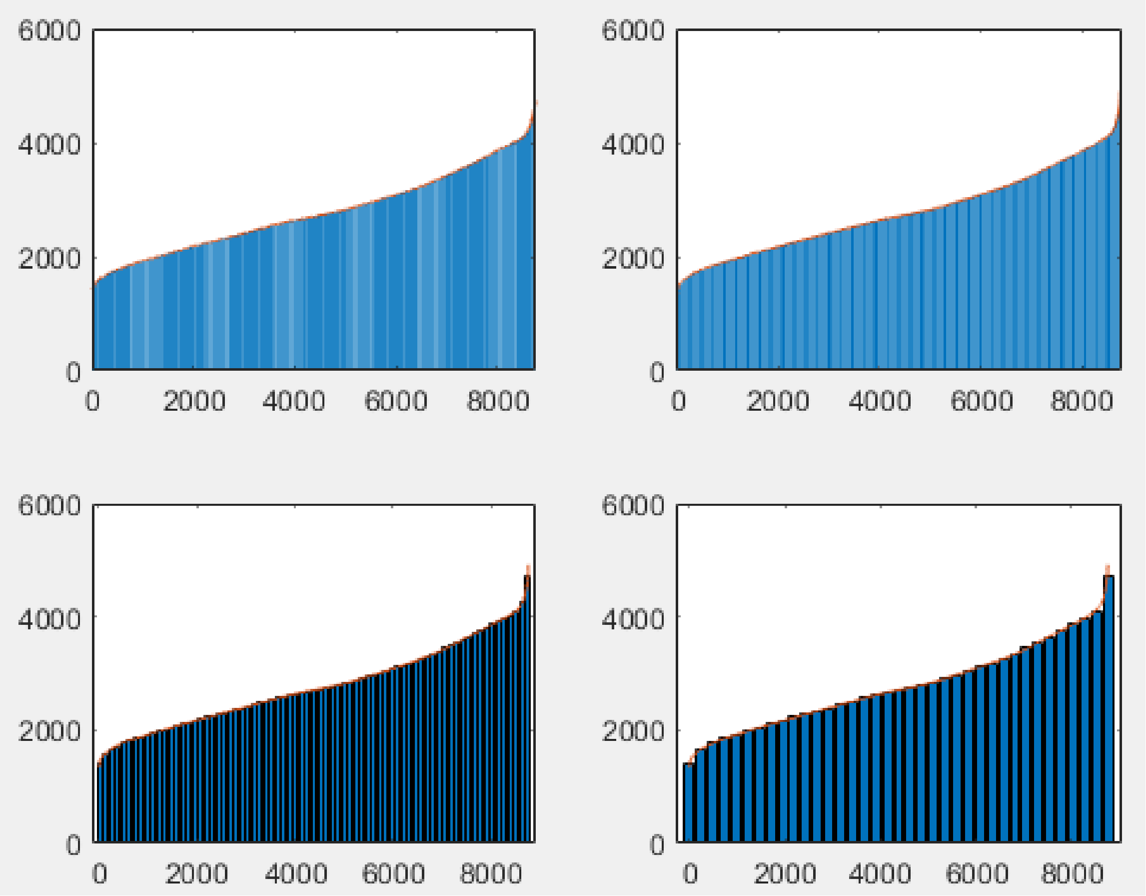

Figure 19. Fitted load duration curves for SE4. Top left figure orange line gives the fitted curve, in all other pictures the orange line corresponds to the original load duration curve.

4.1.4 Carbon Data

Values for calculation of the carbon emissions were taken from the IPCC’s book Climate Change 2014. The values were a result of a review the IPCC performed, resulting in ranges of values. In some cases, the range of an expected value was explicitly numerically specified, else they were read from a graph (in the latter case, the values recorded in table 7 below are marked “ca”). The reason for the size of some ranges were explained; for instance, the higher values of the wind power emissions are to come from smaller turbines, hydro power emissions are very largely dependent on the project itself and the negative impacts of biomass are yielded from increasing the albedo by changed land use (Bruckner, et al., 2014).

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[6] The author gladly sends the images used to optically inspect timestep suitability for all areas upon request.

Table 7. Carbon emissions values from the IPCC.

Electricity source	Lower Bound [gCO_2eq/kWh]	Higher Bound [gCO_2eq/kWh]	Median (ca) [gCO_2eq/kWh]
Coal	675	1689	1000
Oil	510	1170	n/a
Gas	290	930	475
Biomass (ca)	-700	325	30
Nuclear (ca)	4	200	10
Solar PV	18	180	30
Wind	7	56	10
Hydro (ca)	0	230	30
Geothermal	6	79	40
Ocean energy	2	23	7

However, the values that the IPCC provided are global and dated by five years. To ensure that the carbon values fed in to the model are sufficiently accurate locally and not obsolete, other sources were also considered. Vattenfall conducted a life cycle analysis of their power plants in the Nordic countries (Vattenfall, 2012), yielding results not too distant from the values given by the IPCC, as seen in table 8.

Table 8. Carbon emission values from Vattenfall (2012) for their Nordic power plants.

Electricity Source	Footprint [g CO_2 eq/kWh]	Electricity Source	Footprint [g CO_2 eq/kWh]
Nuclear	5	**Natural gas**	503
Hydro	9	**Peat**	636
Wind	15	**Coal**	781
Biomass wood	15	**Oil - Reserve**	933
Biomass straw	100	**Gas -Reserve**	1269

Thomson and Harrison (2015) differentiate between different settings in which a wind power plant is placed: offshore wind is estimated to emit 3-23 g CO_2 eq/kWh, and onshore wind 3-45 g CO_2 eq/kWh. If the onshore wind turbines are however placed on forested peatlands the emissions rise to 62-106 g CO_2 eq/kWh (Thomson & Harrison, 2015). Differentiation between hard coal and lignite is also possible: the former may emit 1000 g CO_2 eq/kWh for electricity production purposes, whilst for German lignite the value may range from 1088-1206 g CO_2 eq/kWh for a power plant with a conversion efficiency of 34 % (Quaschning, 2015). In table 9 an overview of the selected values and the reasoning behind why they were chosen is provided.

Table 9. Carbon emission values used as input for the model.

Power Source	Footprint [g CO_2 eq/kWh]	Source and Motivation
Hydro	9	Vattenfall's (2012) value is chosen here as most of the hydropower is located in the Nordic countries. The values for other power plant owners are assumed similar. The value lays within the range expected by the IPCC (2014).
Nuclear	10	The value interpreted from the IPCC (2014) is used here. The value Vattenfall (2012) found is similar (5).
Wind power	10	This value, as interpreted from the IPCC's (2014) graph lay between the value given for Vattenfall's (2012) wind power plants and what is expected by Thomson and Harrison (2015) for most types of surfaces.
Solar power	30	The interpreted median from the IPCC (2014).
Biomass	15	Almost half of the biomass capacity in the model resides in Sweden and Finland. Other power plants, not owned by Vattenfall, are assumed to perform similarly and wood is assumed to be the primary fuel. The value provided by Vattenfall (2012) is here used.
Other renew	40	This is assumed to be mainly geothermal and takes on the value from this power source from an approximation of the IPCC-value (2014).
Natural Gas	500	This value is chosen as it is near both the estimated IPCC (2014) value and the value provided by Vattenfall (2012). Reserve gas is neglected.
Fossil peat	636	Value taken from Vattenfall (2012).
Oil shale	636	According to Vreuls (2005) the emissions per unit energy in oil shale are near those of peat. Therefore, the Vattenfall (2012) value for peat is used also for oil shale.
Oil	933	Value taken from Vattenfall (2012). In the range expected by the IPCC (2014).
Hard coal	1000	Value calculated from Quaschning (2015), assuming 34 % conversion efficiency. Same as the estimated IPCC median (2014).
Brown coal	1150	Rounded mean value calculated from Quaschning (2015), assuming 34 % conversion efficiency. In the range expected by the IPCC (2014).
Fossil mixed fuels	636	This value is the median of the emission factors for the combusted fuels (biomass and fossil fuels).
Waste	0	Waste is assumed to have to be burned regardless of energy demands.
Other	636	For other sources, which are not considered as renewable, the median of the emission factors of the combusted fuels (biomass and fossil fuels) is used.

4.2 MODEL ALGORITHM

The model consists of four MATLAB scripts and an Excel workbook. Three of the scripts are preparational and extract the values required for the modelling of the consumption and wind power data alongside preparing the biomass and hydro input. More specifically, what the scripts for the consumption and wind data prepare are the coefficients required to calculate a linearly related data set for one area from another (see 4.1 Data Handling for more details) and the values required to generate the right distribution of residuals, which are then added to the linear model. These preparational scripts also produce an initiating timeseries: a representative timeseries with 73 steps, which aggregated would not differ much from the annual production. A third preparational script handles biomass and hydropower production. In order to avoid complicated hydro power modelling, the hydro power production of an area is initially made proportional to the demand of the area:

$$cf_{Area,hydro,t} = C_{Area,t} \cdot \frac{\sum_{t=1}^{73} P_{Area,Source=hydro,t}}{\sum_{t=1}^{73} C_{Area,t} \cdot P_{Area,hydro}^{max}}$$

Where $cf_{Area,hydro,t}$ is the hydro power capacity factor of a given timestep for a given area, $C_{Area,t}$ the consumption of the same area at the same timestep, $P_{Area,hydro}^{max}$ the maximum production capacity of the base year, $\sum_{t=1}^{73} P_{Area,Source=hydro,t}$ is the total expected production of hydro for the area and $\sum_{t=1}^{73} C_{Area,t}$ the total expected consumption of the modelled year, the latter two taken from the ENTSO-E Transparency Platform (ENTSO_E, u.d.). In the case of Sweden, the ENTSO_E did not hold separate values for hydro production in the different market areas, hence the country's total production was divided proportionally to the amount of capacity per area. After ensuring that the estimated hydro power profile for a timestep does not exceed the boundaries set by the production capacity, the initial hydro capacity factor time set was complete. The choice of capacity factors instead of actual power enable simple capacity scaling – assuming the capacity factors come from a representative year. If the capacity is to differ between different scenarios, the power production time series will result from multiplying the new capacity with the series of capacity factors. The same operations were performed for biomass, as the power production from this source is assumed to be much associated with CHP production, which in turn is assumed to have a certain weather dependence. Considering electric heating for instance, the electricity demand is also presumed to have a certain correlation with the weather. Therefore, the initial biopower production is simplified to following electricity demand:

$$cf_{Area,bio,t} = C_{Area,t} \cdot \frac{\sum_{t=1}^{73} P_{Area,Source=bio,t}}{\sum_{t=1}^{73} C_{Area,t} \cdot P_{Area,bio}^{max}}$$

Here, $cf_{Area,bio,t}$ is the capacity factor for biomass for a given timestep, and $\sum_{t=1}^{73} P_{Area,Source=bio,t}$ is the total expected biopower for 2018 collected from the ENTSO-E Transparency Platform (ENTSO_E, u.d.) and $P_{Area,bio}^{max}$ is the maximal level of production that biopower may have, limited by production capacity.

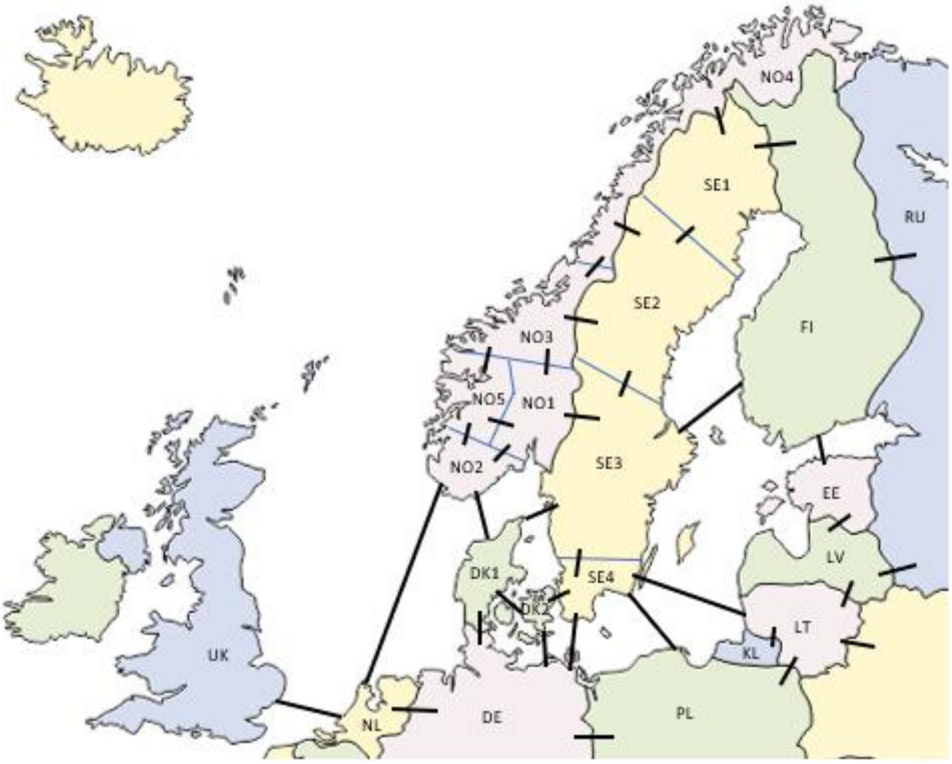

Figure 20. Map of the interconnections modelled, marked in black. Markings do not correspond to exact geographic positions. Map reproduced from https://d-maps.com/carte.php?num_car=4579&lang=en.

The Excel workbook functions as an interface. In the workbook, the transmission and production capacities, alongside marginal costs of production for two different scenarios are registered. The transmission capacities cover all extant interconnections between the areas in the model and some with the outer world, see figure 20. If several powerlines extend over one border they are aggregated into one. For the countries Sweden, Norway, Denmark, Finland, Estonia, Latvia, Lithuania, Germany, the United Kingdom, the Netherlands and Poland the production capacities of 15 different types of power sources per market area have been collected, mainly from the ENTSO_E Transparency Platform (ENTSO_E, u.d.) see Appendix 7 for details. The exercised power sources in the modelled areas are the following:

- Hydro
- Wind power (both on- and offshore)
- Biomass
- Natural Gas
- Brown coal
- Oil shale
- Fossil mixed fuels
- Other
- Nuclear
- Solar power
- Other renewables
- Hard coal
- Oil
- Fossil peat
- Waste

The main script collects the output of the preparational scripts and the data from the workbook. Then, based on the initiating timeseries and the imported values, the demand and wind power capacity factors are calculated for each area and timestep by means of:

$$P_Y(t) = A_{XY} \cdot P_X(t) + B_{XY} + \gamma_{rand,XY}(t)$$

Where $P_Y(t)$ stands for the production/consumption on a given timestep t in the area Y, A_{XY} and B_{XY} the coefficients for the linear equation relating area X to area Y, $P_X(t)$ the production/consumption in area X at timestep t and finally $\gamma_{rand,XY}(t)$ a randomly selected value from a normal distribution predetermined by the standard deviation of the residuals from the original data versus the linear model. In the case of wind power capacity factors, the calculation is cascading, as the set P_Y takes the place P_X when determining the series for the next area Z. For the consumption data, all countries depend on the same set – P_X directly yields P_Y, P_Z and so on. If the production or consumption values for a timestep becomes negative (if the random element was negative and larger than the linear value for the given timestep) the value was set to 0.

In the model, nuclear power plants are set to constantly run at 90 % of their nominal capacity, and solar power production at a constant value of 10 %. The algorithm then starts with a global optimisation; for one timestep at a time, dispatching the cheapest possible power plants in all the modelled areas together to cover the total missing power, without considering the limitations set forth by the interconnections between the areas, nor considering any losses[7]. Using linear programming the economic dispatch problem is solved in MATLAB for each timestep and scenario. Mathematically, the problem may be expressed:

Degrees of Freedom: $P_{Area,Source,t}$ where $Area = 1, 2, \dots ,19$, $Source = 1,2, \dots 15$ and $t = 1, 2, \dots ,73$.

Objective Function:

$$\min \sum_{Area=1}^{19} \sum_{Source=1}^{15} \lambda_{Area,Source} \cdot P_{Area,Source,t} \quad \forall t$$

Subject to the constraints:

$$\textstyle\sum_{Area=1}^{19} \sum_{Source=1}^{15} P_{Area,Source} = \sum_{Area=1}^{19} C_{Area,t} \qquad \forall t$$

$$0 \leq P_{Area,Source} \leq P_{Area,Source}^{max} \qquad \forall t$$

$$P_{Area,Source=nuc} = 0.9 * P_{Area,nuc}^{max} \qquad \forall t$$

$$P_{Area,Source=sol} = 0.1 * P_{Area,sol}^{max} \qquad \forall t$$

$$P_{Area,Source=wind,t} = cf_{Area,wind,t} * P_{Area,Source=wind}^{max}$$

$$P_{Area,Source=hydro,t} = cf_{Area,hydro,t} * P_{Area,Source=hydro}^{max}$$

$$P_{Area,Source=bio,t} = cf_{Area,bio,t} * P_{Area,Source=bio}^{max}$$

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[7] Losses are not at all considered in the model.

The determination of $P_{Area,Source,t}$ gives the amount of energy produced by a certain type of power source in a certain area during the timestep t, when the total production satisfies the total demand (all areas) at the cheapest overall electricity cost for that timestep. $C_{Area,t}$ is the load in an area at a given timestep. $P_{Area,Source}^{max}$ is the total installed capacity of a given power source in an area which remains the same for all timesteps. In the case of nuclear and solar, the production is predetermined at a given level for all timesteps in an area. When it comes to wind, an element for the timestep in question from the previously calculated capacity factor timeseries for wind, $cf_{Area,wind,t}$, determines the wind power level from the maximum capacity.

The results of this optimisation are collected and the difference between production and demand for each area is calculated for each timestep. In the next step of the algorithm, an attempt to balance over- and underproduction with each area's closest neighbours is deployed. This part of the algorithm aims to satisfy each nations balance for each timestep ($D_{Area,t}$) by providing or subtracting power from interconnections *and* local production/curtailment. It is mathematically described as:

Degrees of Freedom: $B_{Area,t}$ where $Area = 1, 2, \dots, 19$ and $t = 1, 2, \dots, 73$.

$I_{pos,t}$ where $pos = 1, 2, \dots 34$ and $t = 1, 2, \dots, 73$.

Objective function:

$$\min\left(\sum_{Area=1}^{19}\left(\alpha \cdot \left|B_{Area,t}\right|\right) + \sum_{Area=1}^{19}\left(\beta_{Area} \cdot I_{pos,t}\right)\right) \quad \forall t$$

where α=1 and β_{Area}=0 apart for the areas being RU, KAL or BEL where

$\beta_{Area} = 1$

Subject to the constraints: $\sum_{Area=1}^{19} B_{Area,t} = 0 \qquad \forall t$

$$B_{Area,t} + \sum_{pos \in POS_{Area}} (\omega_{pos,t} \cdot I_{pos,t}) = D_{Area,t} \qquad \forall t, \forall Area$$

And $\omega_{pos,t} \in \{-1,1\}$ *depending on the direction of power*

$$0 \leq I_{pos,t} \leq I_{pos}^{max,dir} \qquad \forall t, \textit{ where } dir \textit{ marks the direction of power}$$

$$0 \leq \left|B_{Area,t}\right| \leq \left|B_{Area,t}\right|^{max}$$

$$\sum_{pos \in POS_{Area}} I_{pos,t}^{import} \leq \left|D_{Area,t}\right| \qquad \forall t, \forall Area \textit{ for the relevant pos}$$

$$\sum_{pos \in POS_{Area}} I_{pos,t}^{export} \leq D_{Area,t} \qquad \forall t, \forall Area \textit{ for the relevant pos}$$

Here $B_{Area,t}$ is the curtailment or redispatch required for an area to balance the demand at a given timestep, and $I_{pos,t}$ is the power transmitted in an interconnector between two areas. For each interconnector, only one position exists. Depending on the known unbalances from the global optimisation ($D_{Area,t}$) the direction of the interconnector is determined: if two neighbouring areas are identified to have different signs on their unbalances, that is, if one is overproducing power and the other has a deficiency, $I_{pos,t}$ will represent the interconnector going from the overproducer to the deficient area. This is of importance, as this then defines what the maximum capacity, $I_{pos}^{max,dir}$, of the line is, as this may be different in different directions.

As the purpose of this part of the algorithm is to spread the produced power as evenly as possible, filling deficiencies by means of importing or exporting power is favoured by the objective function. The "price" for imports, β, is here set to 0 for all the modelled countries. However, the "price" to produce or curtail power, α, is set at 1. The values themselves are arbitrary, as long as α larger than β. In the case of the areas that are not modelled, yet connected to the modelled areas, such as Russia, Belarus and Kaliningrad the value of β is set to reflect that the import is not included in the global optimisation, rather it equals dispatching entirely new power plants in this simple model.

The balance of all the areas must remain as zero. Further, the balance of each individual country is to be modified with the help of the interconnectors. The new value for the balancing required after imports from neighbours are considered, $B_{Area,t}$, must therefore be equal to the difference resulting from the global optimisation, $D_{Area,t}$, with effects of "free" transmission ($\sum_{pos \in POS_{Area}}(\omega_{pos,t} \cdot I_{pos,t})$) subtracted. POS_{Area} is the subset of the interconnector positions related to the area and depending on the necessary direction of the power flow, $\omega_{pos,t} \cdot I_{pos,t}$ assumes a positive or negative value to mimic exports or imports in the areas balance. Maximally possible local balancing by redispatch or curtailment could be set at the yet unused production capacity, however, the local demand may be higher than what the areas total capacity can cover. Therefore, the boundaries of $B_{Area,t}$ are set merely for the sake to provide all the input for the MATLAB model to function and are set at an arbitrary value much higher than any value for demand, production or transmission. Finally, boundaries are set to ensure that the imports to an area are larger than the deficiency there, nor are the exports from an area larger than that areas overproduction.

When this optimisation is run, the results are the values of overproduction or deficiency in each area and the direction and value of the transmitted electricity.

In the next step of the algorithm, no optimisation algorithm is used, rather the order of the countries handled is sequential: meaning that the countries that come first on the list have better possibilities to get their deficiencies covered. The sequence is seen in table 10.

Table 10. Sequence of countries handled in the second, third, fourth and fifth degree neighbour transmission algorithm.

Number	Area	Number	Area	Number	Area
1	SE1	**8**	NO2	**15**	LV
2	SE2	**9**	NO3	**16**	DE
3	SE3	**10**	NO4	**17**	UK
4	SE4	**11**	NO5	**18**	NL
5	DK1	**12**	FI	**19**	PL
6	DK2	**13**	EE		
7	NO1	**14**	LT		

For each timestep, the algorithm checks for deficit areas in order of the list. When such an area is found, each of the neighbouring areas are investigated in turn: if there is still any transmission capacity remaining to reach a given neighbour, all the neighbours to the neighbour of the deficit area are checked. If any of these "second degree neighbours" are overproducers and have transmission capacity left to the initial neighbour power can be imported to the deficit country.

The value of the power imported is the smallest of the constraining values: the deficit, the transmission capacity between the deficit area and the first neighbour, the transmission capacity between the first neighbour and the second-degree neighbour, or the surplus of the second-degree neighbour. The direction of the transmission is flexible in each step: if power is sent in one direction, the capacity available to transmit power in the opposite direction is sum of the power sent and the rated capacity of the line.

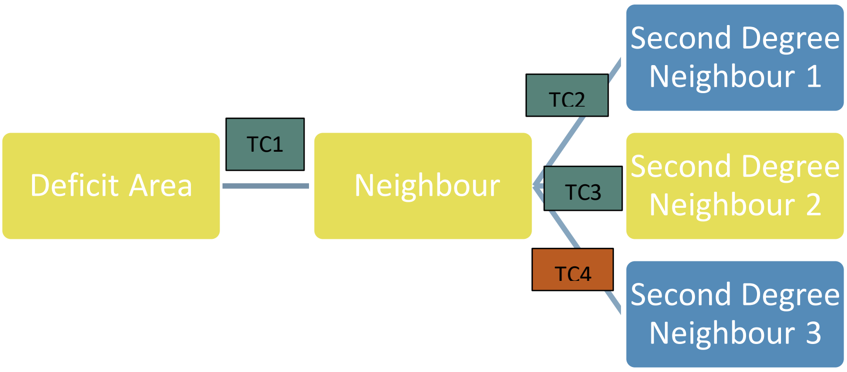

Figure 21. Checking the neighbour's neighbour for import possibilities. Yellow marks a deficit area, blue an area with overproduction. Green transmission capacities (TC) indicate that there some capacity is available in the direction of import to the first deficit area. In this situation, only "Second Degree Neighbour 1" is the only area that can export power to "Deficit Area" over "Neighbour", as it is the only overproducing area with sufficient transmission capacities connecting it to the "Deficit Area".

When all areas have been investigated, a similar process is initiated, however this time extending to the third-degree neighbour: if a deficit in a given area at a given timestep still exists, the transmission capacity to each neighbour, each of their neighbours and again each of their neighbours in turn are evaluated. If the third-degree neighbour has an excess of power, power is transmitted to the deficit area. The value of the power is determined by the smallest available area imbalance or transmission capacity. To ensure that most countries are covered, this process repeats, stretching to the third, fourth and fifth degree neighbours, balancing where possible. As a comparison, in the case of the UK transmitting power to SE1 or vice versa, the least number of boundaries the power must cross are six, however there are at least five ways of doing so without increasing the number of used interconnectors.

After this, a local redispatch or curtailment is performed. In the case of an area overproducing power, the most expensive electricity sources are removed until production corresponds to the sum of exports and demand. If hydropower is removed, the amount removed is "saved", and may be utilised at a later timestep, a rough salute to the fact that hydro power can be stored in reservoirs. All biomass capacity remains dispatchable, however the price of dispatching it is doubled compared to the global optimisation, attempting to model an assumed reluctance to increase electricity production for a CHP-plant when there is no further heat demand.

If there is too little power in the area, an economic dispatch is performed locally, considering an area and closest neighbours. If there is not enough power to cover the needs of an area, the availability of the transmission capacities to the nearest neighbours are assessed, and if neighbours then could help the deficit area to balance entirely, in the most economic manner. This does not give the best reflection of reality; however, it is better than only redispatching parts of the capacity available in the deficit area. Also, in a few cases, the areas may not at all be able to cover certain deficits alone. The local redispatching is an optimisation problem that may be described:

Degrees of Freedom: $P^{REDISP}_{Area,Source,t}$ where $Area$ is the deficit area,

$P^{REDISP}_{neigh,Source,t}$ where $neigh = 1, \dots N^{neigh}$ and N^{neigh} is the number of neighbours to $Area$, $Source = 1,2, \dots 15$ and $t \in T^{def}_{Area}$

Objective Function:

$$\min\left(\sum_{Source=1}^{15} \lambda_{Area,Source} \cdot P^{REDISP}_{Area,Source,t} + \sum_{neigh=1}^{N^{neigh}} \sum_{Source=1}^{15} \lambda_{neigh,Source} \cdot P^{REDISP}_{neigh,Source,t}\right) \qquad t \in T^{def}_{Area}$$

Subject to the constraints: $\sum_{Source=1}^{15} P^{REDISP}_{Area,Source,t} + \sum_{neigh=1}^{N^{neigh}} \sum_{Source=1}^{15} P^{REDISP}_{neigh,Source,t} = B^{REDISP}_{Area,t}$ $\quad t \in T^{def}_{Area}$

$$0 \le P^{REDISP}_{Area,Source,t} \le P^{REDISP,MAX}_{Area,Source,t} \qquad t \in T^{def}_{Area}$$

$$\sum_{Source=1}^{15} P^{REDISP}_{neigh,Source,t} \le I^{REDISP}_{neigh,area,t} \qquad t \in T^{def}_{Area}$$

For each timestep and area in turn, the algorithm searches for deficit areas ($Area$). When one is found the optimisation problem above is initiated. $P^{REDISP}_{Area,Source,t}$ is here are the capacities which are to be redispatched within the deficit area for the timestep when the deficit was found. T^{def}_{Area} are the collection of timesteps where $Area$ has too little supply. $P^{REDISP}_{neigh,Source,t}$ are the capacities of the neighbouring areas which may be dispatched to balance the area $Area$. Of course, the sum of all the dispatched capacities should equal the deficit in $Area$, $B^{REDISP}_{Area,t}$. To emulate a functioning market, the aim of the objective function is to minimise the cost. $\lambda_{Area,Source}$ and $\lambda_{neigh,Source}$ are the (assumed marginal) costs of each type of capacity in each area. Of course, the capacity dispatched in an area cannot be more than the difference between the total capacity and the capacity used in the global optimisation, here denoted as $P^{REDISP,MAX}_{Area,Source,t}$. A final constraint is that the sum of power redispatched in a neighbouring area is no higher than the transmission capacity between the areas allows to transmit.

The result of the algorithm should yield a balanced system. When all this is complete, the algorithm redoes all the steps from the global optimisation and forward for an alternate scenario. This allows a comparison between two years with the same wind and demand conditions, for varied transmission and/or production capacities.

For the different scenarios, annual production percentages are calculated for each area, and the carbon dioxide emissions calculated. The results are moved to an Excel workbook, where the usage of each transmission line, the carbon emissions, the power production of each source and production shares for both scenarios and every timestep are recorded.

5. DEVELOPED FUTURE SCENARIOS

In this thesis, two future scenarios were considered, to investigate the impacts of changed energy system configurations on carbon emissions from power production. Firstly, to contribute to the current discourse on the role of nuclear power in the future energy system, a scenario with the expected changes to nuclear and transmission capacities up until 2024 is produced. Thereafter the aim is to investigate whether a system with increased transmission capacity between areas indicates less carbon emissions.

5.1 NUCLEAR AND TRANSMISSION DEVELOPMENTS UNTIL 2024

Since the Fukushima accident, there has been an increased concern regarding nuclear power and an interest in replacing nuclear with renewables such as wind (van Kooten, et al., 2013). However, wind power production is of an intermittent nature, as opposed to nuclear, and leads to the need of backup generation (van Kooten, et al., 2013). Such production capacity is envisioned to be fast-ramping gas turbines or diesel power plants, which are significantly worse considering carbon emissions compared to nuclear: according to calculations made with the numbers of van Kooten et. al. (2013) the backup power should at most make up 1 % of the power produced in a wind/CCGT system if the emissions for the same amount of power produced from nuclear are not to be exceeded[8]. van Kooten et. al. (2013) also concede that the emissions from fast ramping units used for balancing are expected to be higher than if the operation were steady.

Germany reacted to the Fukushima accident by vowing to shut down all national nuclear power by 2022 (Tamma, 2018). The result has been that the Germans are forced to maintain use of their fossil power plants, for times when the renewable power production does not suffice (Wilkes, et al., 2018), increasing the expected emission levels. Other nations also intend on ending their nuclear production; the Swedish nuclear power production reactors in Oskarshamn and Ringhals will all finish their service in 2020 (Strålsäkerhetsmyndigheten, 2019). This leaves Forsmark (for now) with a production capacity of 3284 MW (Vattenfall, 2019). At the same time, the UK intends to shut down almost half of the country's nuclear capacity by 2024: a reduction to 4643 MW (World Nuclear Association, 2019). However, construction of Hinkley Point C2 is already underway with a gross capacity of 1720 MW and is to be utilised from 2027 (World Nuclear Association, 2019). Several other nuclear power plants have also been proposed in the UK (World Nuclear Association, 2019).

Finland are developing their nuclear power even sooner: Olkiluoto 3 (net production capacity 1600 MW) is to begin commercial operation in 2020, and the construction of Hanhikivi 1 (net production capacity 1200 MW) is to start in 2021 (World Nuclear Association, 2019). During the period 2020 to 2027 the production capacity in Finland is scheduled to be 4369 MW. The Dutch nuclear powerplant, Borssele, has a capacity of 485 MW and is planned to close in 2033 (World Nuclear Association, 2019). The same year, Poland intend to begin producing nuclear from a new 3000 MW facility (World Nuclear Association, 2019).

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[8] Van Kooten et al (2013) give the following values for carbon emissions; 0.02 tCO_2/MWh for nuclear, 0.015 tCO_2/MWh for wind power and 0.45 tCO_2/MWh for CCGT. The allowance for gas balancing before emitting the same amount as nuclear for the wind/gas system: 0.020-0.015=0.005 tCO_2/MWh. That equates to 0.005/0.45= 0.01111 MWh of gas power allowed per MWh of wind power in the system. The share of CCGT use in the wind-hydro system must therefore be maximally 0.01111/ (0.01111+1) = 1 % to not exceed the nuclear emissions per MWh.

A summary of the nuclear capacities used in the scenario is presented in table 11. The transmission capacities that are used in the scenario can be found in table 12, which are the TYNDP projects planned up until 2023. Apart from these two parameters, all parameters from the 2018 base case remain the same.

Table 11. Nuclear capacities used in the second scenario.

Country	Nuclear Capacity 2018 from ENTSO_E [MW]	Expected Nuclear Capacity 2024 [MW]
Sweden	8586	3284
Norway	0	0
Denmark	0	0
Finland	2782	4369
Estonia	0	0
Latvia	0	0
Lithuania	0	0
Germany	9516	0
United Kingdom	8974	4643
Netherlands	485	485
Poland	0	0

Table 12. Transmission projects included in the 2018 TYNDP, used for both scenarios.

Project	From	To	Capacity [MW]	Possible Commissioning	Distance [km]
GerPol Improvements	DE	PL	500	2018	25.7
	PL	DE	1500	2018	25.7
Doetinchem Niederrhein	NL	DE	1500	2018	57
	DE	NL	1500	2018	57
Kriegers Flak	DE	DK2	400	2019	24
	DK2	DE	400	2019	24
COBRA cable	NL	DK1	700	2019	325
	DK1	NL	700	2019	325
Upgrade Meeden - Diele	DE	NL	300	2019	27
	NL	DE	300	2019	27
NordLink	NO2	DE	1400	2020	514
	DE	NO2	1400	2020	514
DKW-DE, step 3	DK1	DE	720	2020	110
	DE	DK1	1000	2020	111
Estonia-Latvia 3rd IC	EE	LV	600	2020	205
	LV	EE	600	2020	205
Norway-Great Britain, North Sea Link	NO2	UK	1400	2021	720
	UK	NO2	1400	2021	720
NorthConnect	UK	NO5	1400	2022	655
	NO5	UK	1400	2022	655
NeuConnect	DE	UK	1400	2022	700
	UK	DE	1400	2022	700
LitPol Link Stage 2	PL	LT	500	2023	108
	LT	PL	1000	2023	108
Viking DKW-GB	DK1	UK	1400	2023	770
	UK	DK1	1400	2023	770
DKW-DE, Westcoast	DE	DK1	500	2023	92
	DK1	DE	500	2023	92

5.2 INCREASED TRANSMISSION CAPACITY UP TO 2035

The ENTSO-E update their Ten Year Network Development Plan (TYNDP) every second year, where they publish the long-term plans for the larger European network. Within the scope of the area covered by the model, 24 TYNDP projects were identified, with commissioning dates ranging from 2018 to 2030. Most of the projects discussed here offer improvements between nations already connected, however some are entirely new (for instance a direct connection between the UK and Germany). Some projects are under construction, whilst some are in the phase of planning, permitting or consideration (ENTSO_E, 2019).

The relevant projects from the TYNDP are collected in tables[9] 12 and 13, where the project names, relevant borders and capacities are clarified. The projects are ordered in their possible year of commissioning and projects mentioned up until 2021 are all under construction. Also included are the distances that the actual transmission lines will reach, which enables a rough calculation of the carbon emissions such an extension would give rise to. For this scenario, all power plant capacities, the demand, etcetera remains the same as in the 2018 base case.

Table 13. Transmission projects included in the 2018 TYNDP, exclusively used in the TYNDP Realisation scenario.

Project	From	To	Capacity [MW]	Possible Commissioning	Distance [km]
3rd AC Finland-Sweden North	SE1	FI	900	2025	200
	FI	SE1	800	2025	200
Hansa PowerBridge I	SE4	DE	700	2026	300
	DE	SE4	700	2026	300
Fenno-Skan 1 Renewal	SE2	FI	800	2029	200
	FI	SE2	800	2029	200
SE North-South Reinforcements	SE2	SE3	1500	2030	900
	SE3	SE2	1500	2030	900
Great Belt II	DK1	DK2	600	2030	120
	DK2	DK1	600	2030	120
DKE - DE (Kontek2)	DE	DK2	600	2030	170
	DK2	DE	600	2030	170
New Great Britain - Netherlands Interconnection	UK	NL	2000	2030	x
	NL	UK	2000	2030	x
Hansa PowerBridge II	SE4	DE	700	2030	300
	DE	SE4	700	2030	300
HVDC connection DKE-PL	PL	DK2	600	2033	330
	DK2	PL	600	2033	330
GerPol Power Bridge II	PL	DE	0	2035	20
	DE	PL	1500	2035	20

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[9] The values in table 12 are used for both scenarios.

6. RESULTS

All model runs are slightly different and, in this chapter, the output from one run constitutes the results for the validation of the model and the nuclear scenario, whilst the output from a second run is used for the TYNDP scenario.

6.1 GENERAL FUNCTIONING OF THE MODEL – BASE CASE ANALYSIS

To validate the model, the production output from the base case scenario is compared to the actual production values of 2018. Firstly, it is notable that the demand in most cases correspond quite well to the recorded data. In the Nordic countries, most of the results were in the same order of magnitude as the expected values, however there were many exceptions, as presented in table 14.

Considering hydro power, the annual production is near the value it should, apart from the case of Sweden, where the model output is 29 % less than expected. The modelled nuclear production in Sweden and Finland is slightly higher than expected. Considering wind power, the model produces higher values than expected for Sweden and Denmark, whilst much lower for the Norwegian areas.

Table 14. Comparison of ENTSO_E data and model output for the Nordic countries.

	SE		**NO**		**DK**		**FI**	
Production type	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**
Hydro	60977	44777	138040	134806	15	15	13145	13145
Nuclear	65801	67692	0	0	0	0	21889	21933
Wind power	16639	17102	3384	1633	13889	15633	5859	5803
Solar power	0	223	0	0	959	526	162	0
Biomass	9838	10268	0	0	3667	3629	12515	12515
Other renewables	0	0	0	0	0	649	0	2251
Natural gas	624	61	3170	0	2173	1065	3928	293
Hard coal	486	1782	0	0	6871	2877	5789	2006
Brown coal	0	0	0	0	0	0	0	0
Oil	187	5799	0	0	85	0	200	12141
Oil shale	0	0	0	0	0	0	0	0
Fossil peat	0	0	0	0	0	0	3048	0
Fossil mixed fuels	1539	0	0	0	0	0	0	0
Waste	2186	4237	0	0	1267	3155	0	1375
Other	0	95	1092	0	0	0	930	3171
Total Production	**158277**	**152035**	**145686**	**136439**	**28927**	**27549**	**67464**	**74635**
Demand	**138179**	**138664**	**135424**	**135743**	**33566**	**34079**	**85771**	**86624**

The values for solar are different: in Sweden, no solar production was reported to the ENTSO_E, however the installed capacity being reported yields a certain output. In Denmark the model results for the solar power are almost half of the recorded values. Finland does not have any installed solar capacity registered, hence the model output is naturally zero (0). For biomass, the output is very near the real data. For other renewable production in the case of Finland and Denmark, the results are expected as capacity has been reported, yet no production recorded.

Moving on to the fossil fuels in the Nordic countries, the Swedish electricity production is based far more on fossil fuels in the model: most striking is the oil power use being more than 30 times larger than expected. Some of the excess fossil production may be attributed to the "Fossil Mixed Fuels"-category not holding any capacity in the model. In the base case model output, the Norwegian fossil production is entirely removed. In the Danish case, the fossil power production is heavily reduced, however the production is in the same order of magnitude. In Finland, oil power production is very much increased by the model; whilst natural gas and coal are reduced.

Table 15. Comparison of ENTSO_E data and model output for the Baltic countries.

	EE		**LT**		**LV**	
Production type	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**
Hydro	121	0	121	121	2417	2417
Nuclear	0	0	0	0	0	0
Wind power	586	713	1140	1190	120	134
Solar power	17	1	81	72	0	0
Biomass	776	776	375	375	874	874
Other renewables	0	44	0	0	0	0
Natural gas	0	996	250	207	2628	2065
Hard coal	0	0	0	0	0	0
Brown coal	0	0	0	0	0	0
Oil	0	0	0	0	0	0
Oil shale	8769	7905	0	0	0	0
Fossil peat	0	0	0	0	0	0
Fossil mixed fuels	0	0	115	0	461	0
Waste	56	166	148	193	0	0
Other	0	745	166	0	0	0
Total Production	10325	11345	2396	2157	6500	5490
Demand	8426	8485	12149	12109	7344	7620

For the Baltic countries the results compare to reality in many cases: the expected hydro production is the same as the real data for Lithuania and Latvia and the wind power production output is similar to documented values in all areas, as displayed in table 15. Solar power production values are similar in Lithuania. The values for biomass are promising. Considering the fossil fuels, the values generally seem relatively adjusted, the main exception being Estonian natural gas.

In the modelled North Western countries, the values are usually rather close to the recorded data, as seen in table 16. In the Netherlands however, no hydropower is dispatched. Again, the nuclear values are a little too high, most notably in the Netherlands. Wind power, solar power and biopower for all countries match well. However, the category “other renewables” gives a very high production in the model.

For the fossil fuels, the model results for German gas (and oil) power are far too low, yet for coal and lignite the values do not differ too much. The total production is somewhat less in the model than expected. In the UK, the model output for natural gas is near the data, however the hard coal output is too low – this is the same in the Netherlands. Interesting in the Polish case is that hard coal and brown coal seem to have traded places when comparing reality to model results.

Table 16. Comparison of ENTSO_E data and model output for the countries in North-Western Europe.

	DE		**GB**		**NL**		**PL**	
Production type	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**	**ENTSO-E Data [GWh]**	**Model Output [GWh]**
Hydro	25113	24613	5964	5964	81	0	2349	2349
Nuclear	71861	75024	60654	70751	2810	3832	0	0
Wind power	107164	116963	42290	39340	10948	11679	12458	12847
Solar power	41157	37496	11803	10925	3117	2264	277	202
Biomass	40112	40842	17987	18211	3488	3488	5776	5252
Other renewables	1332	5405	0	27436	0	0	0	0
Natural gas	87333	0	129912	119631	71367	102020	12427	0
Hard coal	72948	49844	16756	1680	16742	0	75227	52226
Brown coal	134830	147200	0	0	0	0	44843	74480
Oil	3232	0	44	0	0	0	1602	3635
Oil shale	0	0	0	0	0	0	0	0
Fossil peat	0	0	0	0	0	0	0	0
Fossil mixed fuels	2588	0	0	0	0	0	0	0
Waste	9900	14761	374	0	0	5983	265	0
Other	0	12498	0	0	0	0	1861	1384
Total Production	**597571**	**524647**	**285784**	**293937**	**108553**	**129265**	**157086**	**152376**
Demand	**507804**	**492967**	**289278**	**302577**	**114711**	**116264**	**171069**	**172192**

Using the values for carbon emissions determined in 2.1.4, the total calculated emissions for the modelled base case is circa 530 Mton/year. Upon comparison it was evident that the modelled transmission did not balance well, differing with an amount of energy roughly equal to Polish demand. However, the energy balance of the system proved promising: as seen in table 17, the overproduction provided by the model was no more than 0.2 % of the annual demand.

Table 17. Output comparison.

Item	Model values [GWh]
Demand	1507324.71
Production	1509875.24
Outer Exchange	134
Difference	-2684.5279
Share	-0.001781

6.2 THE 2024 NUCLEAR SCENARIO

In Sweden, the reduction in Swedish nuclear is compensated by increases in hydropower, biomass and most notably, natural gas, as seen in table 18. The effects of the reduction are also seen in the Norwegian electricity system, as natural gas is dispatched when it was not in the base case and the hydropower production increases somewhat. Norway remains a net exporter, however Sweden must import to satisfy demand. In Denmark the required imports decrease, whilst increasing the usage of fossil fuels nationally. Finland, with new nuclear capacity is however set to change roles – from a net importer, to a net exporter. Markedly, the model output gives that Finnish power from hard coal also increases.

Table 18. Model output comparison for the Nordic countries. Scenario 1 is the base case, and scenario 2 is the nuclear scenario.

	SE		NO		DK		FI	
Production type	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**
Hydro	44777	47975	134806	138135	15	15	13145	13145
Nuclear	67692	25891	0	0	0	0	21933	34445
Wind power	17102	17102	1633	1633	15633	15633	5803	5803
Solar power	223	223	0	0	526	526	0	0
Biomass	10268	12441	0	0	3629	3613	12515	12461
Other renewables	0	0	0	0	649	657	2251	2251
Natural gas	61	2001	0	217	1065	3650	293	159
Hard coal	1782	1796	0	0	2877	4614	2006	3541
Brown coal	0	0	0	0	0	0	0	0
Oil	5799	5862	0	0	0	0	12141	12141
Oil shale	0	0	0	0	0	0	0	0
Fossil peat	0	0	0	0	0	0	0	0
Fossil mixed fuels	0	0	0	0	0	0	0	0
Waste	4237	4275	0	0	3155	3180	1375	1375
Other	95	97	0	0	0	0	3171	3171
Total Production	**152035**	**117663**	**136439**	**139984**	**27549**	**31888**	**74635**	**88493**
Demand	**138664**	**138664**	**135743**	**135743**	**34079**	**34079**	**86624**	**86624**

In the Baltic countries the results of the changed nuclear capacities manifest themselves by changing the magnitude of imports and exports, displayed in table 19. Estonian power production increases by ramping up oil shale combustion, Lithuania and Latvia on the other hand can reduce their power production from natural gas.

Table 19. Model output comparison for the Baltic countries. Scenario 1 is the base case, and scenario 2 is the nuclear scenario.

	EE		**LT**		**LV**	
Production type	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**
Hydro	0	0	121	121	2417	2417
Nuclear	0	0	0	0	0	0
Wind power	713	713	1190	1190	134	134
Solar power	1	1	72	72	0	0
Biomass	776	776	375	375	874	874
Other renewables	44	44	0	0	0	0
Natural gas	996	1042	207	0	2065	734
Hard coal	0	0	0	0	0	0
Brown coal	0	0	0	0	0	0
Oil	0	0	0	0	0	0
Oil shale	7905	10009	0	0	0	0
Fossil peat	0	0	0	0	0	0
Fossil mixed fuels	0	0	0	0	0	0
Waste	166	166	193	193	0	0
Other	745	745	0	0	0	0
Total Production	**11345**	**13496**	**2157**	**1950**	**5490**	**4159**
Demand	**8485**	**8485**	**12109**	**12109**	**7620**	**7620**

In Germany, even if the total capacity is reduced, the amount of power produced increases: to compensate for the loss of the nuclear power the German hard coal is almost tripled, and power production from lignite also rises. In the UK, the power production decreases in total when the nuclear power is taken off the grid, whilst in the Dutch and Polish cases, much stays the same, as can be seen in table 20.

Even with the increased transmission capacities up until 2024 included, the new configuration of nuclear power plants in Europe give rise to estimated carbon equivalent emissions of 650 Mton/year according to the model; an increase from the base case with around 24 % (120 Mton/year).

Table 20. Model output comparison for the North-Western European countries. Scenario 1 is the base case, and scenario 2 is the nuclear scenario.

	DE		GB		NL		PL	
Production type	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**
Hydro	24613	25113	5964	5964	0	0	2349	2349
Nuclear	75024	0	70751	36605	3832	3832	0	0
Wind power	116963	116963	39340	39340	11679	11679	12847	12847
Solar power	37496	37496	10925	10925	2264	2264	202	202
Biomass	40842	40573	18211	18267	3488	3488	5252	5210
Other renewables	5405	5405	27436	27436	0	0	0	0
Natural gas	0	8293	119631	109981	102020	109017	0	0
Hard coal	49844	130005	1680	1315	0	0	52226	53888
Brown coal	147200	177626	0	0	0	0	74480	74301
Oil	0	0	0	0	0	0	3635	3635
Oil shale	0	0	0	0	0	0	0	0
Fossil peat	0	0	0	0	0	0	0	0
Fossil mixed fuels	0	0	0	0	0	0	0	0
Waste	14761	14769	0	0	5983	5983	0	0
Other	12498	12755	0	0	0	0	1384	1384
Total Production	**524647**	**568997**	**293937**	**249834**	**129265**	**136262**	**152376**	**153817**
Demand	**492967**	**492967**	**302577**	**302577**	**116264**	**116264**	**172192**	**172192**

6.3 THE TYNDP REALISATION SCENARIO

In the case of all means of production remaining the same, whilst all projects in the ENTSO_E's Ten Year Network Development Plan up until 2035 are realised. In the Nordic countries, this causes an increase in the exports from Norway and Sweden, which can be directly acclaimed to more hydro power being used. Increased transmission enables the Danes and Finns to cut down on fossil power. These results are collected in table 21.

Table 21. Model output comparison for the Nordic countries. Scenario 1 is the base case, and scenario 2 is the TYNDP realisation scenario.

	SE		NO		DK		FI	
Production type	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**
Hydro	44810	46309	134892	137347	15	15	13145	13145
Nuclear	67692	67692	0	0	0	0	21933	21933
Wind power	17266	17266	1699	1699	15027	15027	5841	5841
Solar power	223	223	0	0	526	526	0	0
Biomass	10155	9734	0	0	3586	3640	12515	12515
Other renewables	0	0	0	0	648	648	2220	2220
Natural gas	24	0	0	33	1999	823	164	0
Hard coal	1771	1751	0	0	1985	1436	1323	590
Brown coal	0	0	0	0	0	0	0	0
Oil	5720	5720	0	0	0	0	11975	11975
Oil shale	0	0	0	0	0	0	0	0
Fossil peat	0	0	0	0	0	0	0	0
Fossil mixed fuels	0	0	0	0	0	0	0	0
Waste	4202	4176	0	0	3119	3120	1356	1356
Other	95	94	0	0	0	0	3128	3128
Total Production	**151957**	**152964**	**136591**	**139079**	**26905**	**25236**	**73601**	**72704**
Demand	**138541**	**138541**	**135502**	**135502**	**33582**	**33582**	**85248**	**85248**

In the Baltic countries, the fossil power is reduced in all countries, yet in a relatively low volume. The impacts on total production are also seemingly small yet do exist. The total saved fossil power in the region equates to around 1900 GWh, which is roughly the annual production of Lithuania. See table 22 for more details.

Table 22. Model output comparison for the Baltic countries. Scenario 1 is the base case, and scenario 2 is the TYNDP realisation scenario.

	EE		**LT**		**LV**	
Production type	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**
Hydro	0	0	121	121	2417	2417
Nuclear	0	0	0	0	0	0
Wind power	724	724	1289	1289	130	130
Solar power	1	1	72	72	0	0
Biomass	776	776	375	375	874	874
Other renewables	43	43	0	0	0	0
Natural gas	985	985	266	93	2131	967
Hard coal	0	0	0	0	0	0
Brown coal	0	0	0	0	0	0
Oil	0	0	0	0	0	0
Oil shale	7419	6840	0	0	0	0
Fossil peat	0	0	0	0	0	0
Fossil mixed fuels	0	0	0	0	0	0
Waste	164	164	193	193	0	0
Other	734	734	0	0	0	0
Total Production	**10848**	**10269**	**2315**	**2142**	**5553**	**4389**
Demand	**8414**	**8414**	**12256**	**12256**	**7083**	**7083**

In the rest of the North-Western countries, the effects of increased transmission capacity are more surprising; indeed, Germany and the Netherlands produce more fossil power, compensating for any reduction that the UK and Poland have made. Such results can be seen in table 23. The scenario has been run several times, with the same outcome: and the carbon impact from the changed power production is only slightly altered – according to the model, the carbon emissions *increase* with about 2 % from the base case.

Harrison et al (2010) performed a life cycle analysis of the British transmission grid. Using the value of 6300 tCO_2 eq/km and applying it to the combined distance of the TYNDP projects (listed in the segment "Scenarios"), an estimation for the carbon emissions produced from the lifecycle[10] of the infrastructure itself amounts to around 45 Mton of carbon dioxide equivalents.

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[10] In this LCA, the following stages of a product's life were included: raw materials, manufacturing, construction, O&M and retirement. For more information see Harrison et al (2010).

Table 23. Model output comparison for the North-Western countries. Scenario 1 is the base case, and scenario 2 is the TYNDP realisation scenario.

	DE		GB		NL		PL	
Production type	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**	**Scenario 1 [GWh]**	**Scenario 2 [GWh]**
Hydro	24591	25066	5964	5964	1	3	2349	2349
Nuclear	75024	75024	70751	70751	3832	3832	0	0
Wind power	116583	116583	39225	39225	11882	11882	13291	13291
Solar power	37496	37496	10925	10925	2264	2264	202	202
Biomass	40415	40112	18103	17852	3510	3488	5210	5210
Other renewables	5301	5331	27096	27264	0	0	0	0
Natural gas	1912	10389	110999	55232	100894	127109	0	0
Hard coal	65704	98570	1848	488	0	194	53973	34421
Brown coal	146111	157104	0	0	0	0	74268	70792
Oil	0	0	0	0	0	0	3635	3635
Oil shale	0	0	0	0	0	0	0	0
Fossil peat	0	0	0	0	0	0	0	0
Fossil mixed fuels	0	0	0	0	0	0	0	0
Waste	14381	14583	0	0	5983	5901	0	0
Other	12580	12755	90	0	0	0	1384	1384
Total Production	**540098**	**593013**	**285001**	**227701**	**128366**	**154672**	**154313**	**131285**
Demand	**508654**	**508654**	**293583**	**293583**	**115547**	**115547**	**174422**	**174422**

7. DISCUSSION

7.1 DELIBERATIONS ON THE RESEARCH SUB-QUESTIONS

The purpose of this thesis was to investigate the possibility of building a model of the Northern European energy system. This requires a certain degree of understanding, covering several topics. The purpose of researching the research sub-questions was to capture such comprehension. In chapter 3, attempts to answer the first three research questions are provided. These questions regarded the functions and effects of the transmission grid, the configuration of the electricity system(s) of Northern Europe and how to evaluate the climate impacts of changing transmission capacity. The answers of the two former matters are relatively fact-based, yet climate impact assessment has a more arguable character. In this thesis, a division was made between operational and embodied emissions, through attempting to calculate the carbon (dioxide equivalent) emissions from the power production and the emissions that any extensions would yield. This could be extended in several directions. Firstly, the values used could be subjected to a thorough assessment, to ensure that they are specific enough for the type of power generation or power line in a given area. The model is however based on a fair number of assumptions, and it is possible that such work to achieve accuracy may well be a wasted effort when combined with the other, broader estimations. Second, the “sunk” emissions of the grid are not considered at all. Yet as the tool is intended for assessing the impact of (new) investments, this perspective is perhaps not as interesting to endeavour. Finally, the analysis is based on what the current grid contains; perhaps future-proof grid sections have larger dimensions to handle the peaks of variable production, as well as power electronics to maintain power quality, altering the carbon footprint per unit length.

The outcome of the base case was that building the infrastructure of the TYNDP scenario gave rise to around 45 Mton carbon dioxide equivalents over the entire lifetime (see segment 6.3), which could be even 80 years. On the other hand, the operational emissions were around 530 Mton CO_2-eq/year (see segment 6.1 and 6.3). Taking the time horizon into consideration, these figures give that with the current production capacities, the embodied emissions of an extended network are negligible compared to the operational emissions. This comparative approach is truly interesting first when operational emissions savings are calculated by the model, giving a possibility to optimise the transmission development with regard to maximising the savings in GHG emissions.

The fourth research sub-question regards what scenarios are relevant to entertain. The scenarios were selected for dual purposes; they are both of current interest and they can be used to validate two different aspects of the model’s functioning. The nuclear perspective is interesting in the now due to the dilemma between the low greenhouse gas emissions nuclear power provides (see chapter 4.1.4) and the safety concerns raised in the wake of the Fukushima accident. In chapter 5, which considers the scenarios, the different standpoints of nations were recorded. Most polar are perhaps the German and Polish energy strategies: the Germans are in the midst of a full shutdown of their nuclear power plants, and despite their renowned “Energiewende” they will need to keep their fossil power online – the Polish, on the other hand, intend to start up nuclear power plants precisely to reduce greenhouse gas emissions (World Nuclear Association, 2019). The nuclear capacity built in Finland is far from offsetting the reductions made in Germany, Sweden and the UK. The scenario may be criticised however; is it a fair scenario when only nuclear and transmission up until 2024 are considered? Surely other developments, especially within renewable electricity, are set to evolve.

Perhaps with a fair renewable growth included in the model the results would become entirely different, as more renewables could compensate for the energy loss of the nuclear dismantling, and more transmission could, in theory, compensate for that the electricity production profile has shifted from stable to intermittent.

The most significant step in the model which defines which power plants shall be dispatched is the very first optimisation, where the entirety of the power plants in the system are included. The adjustments made (the redispatch), after attempting to balance the areas by means of transmission, is comparatively small (ca 10 % of the total) considering the volumes of energy in the global dispatch. This means, that even if the parts of the algorithm handling the transmission would be flawed, the outcome of the initial dispatch is likely to be rather sound: indeed, the balances of total supply and demand at the very end are close, even if the import and export balancing calculated from the modelled transmission certainly is not. It is therefore quite likely that the outcome of the nuclear scenario is a reasonable result considering the input data.

As the aim of the model is to evaluate the resulting emissions of future investments, it is interesting to examine what these investments may actually be. The TYNDP projects that were included in the second scenario should be the investments that are expected to materialise – indeed some are already being constructed. The results from increasing transmission capacities were expected to reduce the carbon emissions by displacing fossil power in other areas. Again, a fair argument would be that the exercise could be improved by also increasing the amount of power produced from renewables, so that one could see that parts of what elsewise would have been curtailed now could be transported to deficit areas. This may be part of the results for the TYNDP realisation scenario: instead of using the additional capacity for transporting increased volumes of renewable energy, the transmission capacity was instead used to balance the areas with the cheapest possible power available as it now could travel further, which could explain the redistribution of fossil power production, especially in the North-Western countries (see table 23).

During model development, great consideration was taken to that the energy balance (supply/demand) must be kept maintained. However, the testing to ensure that the balances calculated from the actual modelled transmission (that is, that the summation of all areas exchanges in a timestep renders zero (0)) commenced unduly, and when the problems concerning the matter surfaced there was no time to attempt identifying the cause. This malfunction may also play part in the unexpected results of the TYNDP realisation scenario (that the greenhouse gas emissions virtually do not change with respect to power production).

To summarise, the scenarios both are anchored in the development of the European electricity system, however to be able to obtain truly viable indications modelling of the renewable growth – particularly wind and solar power – should be included. It is reasonable to expect that the result of the future nuclear scenario may act as a functioning indicator, especially as the wind power production was continuously overproducing and that 2024 is relatively close in time (to 2018). The case of the TYNDP plan being realised, being in a more distant future and more prone to issues in transmission modelling should however probably not be used to draw any conclusions until the issues surrounding the unbalances have been resolved.

7.2 THE FUNCTIONING OF THE MODEL

In the results (chapter 6) the output of the 2018 base case run are included for the purpose of validating the model. Most of the renewables, being rather predetermined by the model, are close to what they are expected to be. Hydro is modelled so that it can be less or equal to the 2018 hydro production. As any reduction made is saved in a “reservoir” so be used at a later timestep, and the wind power production on purpose made to be at its largest during the early timesteps so that the reservoir may be formed, many areas in the model produce up to what is maximally possible. This is however not true in the cases of Estonia, the Netherlands and most importantly, Sweden. The Dutch and Estonian reductions stem from pricing matters. The Swedish case is entirely more interesting, where almost all the reduction that occurs does so in SE2. A hypothesis why this may be so being that SE1 and SE3 are better connected to share their overproduction with other areas. SE2, wedged between these exporters and the exporting Norwegian area must therefore reduce the production. As there was no data of the hydro power production in the different areas on the ENTSO_E Transparency Platform, the annual production was simply divided between the Swedish areas based on the capacities installed in each. Possibly this is not a sound assumption.

Nuclear power production was kept constant, producing at a capacity factor of 90 % in all areas at all times. This is likely a too generous capacity factor, however the nuclear power production can easily be trimmed to perfection for this year. Solar production was also kept constant at 10 % of maximum capacity. This yields too low values in every country, yet is also easily adjusted. An improvement could also be made by distinguishing between the different climates in the modelled areas for solar power production.

The wind power production was too high in almost all cases. This is attributed to that the timestep fitting was re-adjusted towards the end of the process, skewing the output slightly (the wind power production was in early parts of the study correct). The 73 timesteps are now automatically equally distributed on the fitted production curve (not manually as before) which has led to that the outermost elements were counted as the double of what they should. This is a simple matter to adjust in a balanced way at a later stage. Demand was modelled in the same way, but owing to the slow ascent (or descent, depending on the illustration) of the load duration curve the effects of the outermost hours being weighted double of what any other hours are gives a small fault.

The modelling of biomass produced rather decent values, yet the simplistic way that it was modelled could be developed. The categories “other renewables”, “other” and “mixed fossil fuels” could also be improved as to how they were modelled – other renewables are likely to be weather dependent and could be adjusted with a capacity factor as a start. The miscellaneous fossil categories should be investigated as to what they contain and how best to model it. The “waste” category would also require deeper investigation as to what production profile power from waste may have.

The rest of the fossil fuels depend strongly on the set marginal costs. As these were averages for each area and power type, their relation to one another is not entirely perfect. For instance, in the model, reserve power and base power have the same price. In some cases, price data is accessible for both, however it may be complicated to deduce how large the reserve capacities are in the areas modelled. An improvement would nonetheless be to make a better differentiation between reserve and base load fossil capacities.

7.3 DESIRED IMPROVEMENTS

A sufficiently good model should mirror reality well enough for the model to be useful. Towards the end of the project, the lone developer did encounter several concepts that would possibly improve the trustworthiness of the model, or at least validate that the current functioning cannot be bettered.

Exchange Balancing

The most important flaw the model sports is that the power in the transmission lines is not balanced; that is, when considering all areas, the sum of exports do not equal the sum of imports, both on separate timesteps and in total. In fact, the total mismatch between imports and exports calculated from the transmission is roughly the size of the annual Polish demand, a considerable share. The source of this fault is unknown. A small part of the mismatch has been identified to appear directly after the global optimisation. Strangely, after each step of transmission investigations, the amounts required to be curtailed or redispatched required to balance the system have been reduced – and equal. During the encoding of the model, this was verified after each segment was completed. This makes this finding further curious – certain amounts of power have been withdrawn equally and correctly from the overproducing and underproducing (measured positively) areas in the model, considering the values limiting the transmission lines in between. The output regarding the transmission capacities also do behave seemingly correct. For instance, the powerlines between Finland and SE1 is often exporting from the Swedish area at full capacity, yet ever so rarely does power flow in the opposite direction. This mismatch only came into awareness when the data was to be extracted for the purpose of this report.

Modelling of Demand and Renewable Electricity

The model used for wind and demand does yield a relatively good result (when the timesteps are correctly adjusted). Yet, a suggested improvement could be mad by instead using the best linear predictor, as suggested by Lena Zetterqvist (Centre for Mathematical Sciences, Lund University). This would simplify the modelling yet may yield an improved result.

Further, as the model is to function when modelling several decades ahead, it would be of interest to consider the expected load growth. In Sweden this is particularly interesting as some areas are already beginning to experience a certain lack of supply (see chapter 3.3) and a functioning model would perhaps be able to help identify the measures to alleviate the situation effectively. Interesting would also be to see the impact of growing installed capacities of renewable electricity sources such as wind and solar. Also, as the expansion of wind power occurs, the windiest spots are taken first. With time this phenomenon may begin to reduce the capacity factors of wind. In the model, onshore and offshore wind are not separated, even though the capacity factors are not expected to be the same. With the growth of offshore wind, the model may be improved by distinguishing between these production types, so that future offshore wind power production is not reduced in the model by the lower onshore capacity factors.

Modelling of Hydro Power Production

Hydro power is notoriously difficult to model well: it is a combination of strategic profit-maximising behaviour, base power, peak power and furthermore it is weather dependent on a large-scale level with a long-time horizon. A good hydro model should include the strategy of the producing firms, model reservoirs and seasonal dependence - of course the aim is to empty the reserves enough before the spring floods to not miss out on an opportunity, yet still to keep enough to ensure security of supply if it is a dry year. In this model, the hydro power production simply follows the demand.

This was meant as to partially reflect on the strategy behind profit maximisation – indeed Kopsakangas-Savolainen and Svento (2013) show methods to emulate this based on a load duration curve, which is in essence also the basis here. There is also a rough function in this model that allows unused water to be stored for later, however this is far from any sophisticated modelling.

The modelled year, 2018, was also infamously dry in the Nordic countries. To build a sound model of hydro, one is likely to require a greater share of historical data, not only for a single year as here.

Thermal Power

A notable share of the power produced in the Nordic countries comes from CHP plants, where the power is sent to the electricity grid and the heat sent to district heating networks or used in an industrial setting. This implies, as an example, that when weather conditions cause an increased demand for domestic heating the power production will increase also and that it may at times possibly be unsynchronised with demand. It would therefore be a promising development to investigate what share of installed capacity that is CHP and to what extent electricity demand follows temperature spells to possibly be able to model it better.

Also, an improvement would be distinguishing between base load, reserve and peak power in the model, as this gives a merit order that is more nuanced and is likely to improve the results of the base case when compared to the real data.

8. CONCLUSION

As a reminder, the main research question of this thesis is:

> *"(How) can a model be designed and used for evaluating climate implications of investments in transmission capacity in the long and short term?"*

This model is built to be very flexible yet easily handled: if the model is improved to function correctly the upshot would be the opportunity to run any desired scenario at any point in the future as long as the categories of power production are expected to remain similar (and if not, they may actually be extended quite easily) and the number of interconnectors between areas do not increase (even though this is rather easily done as well), one has the correct input data and one assumes the assumptions that the model relies on to remain valid.

The worth of the extant model is not negligible – indeed interesting results have already surfaced. However, indicative model is perhaps not even indicative in its own right yet – the outcome must be thoroughly analysed before conclusions can be drawn. If all results are possible to explain, and valid arguments can be made for neglecting any flaws in the outcome, it is not entirely unthinkable that this model could swiftly be in functional use if several minor adjustments were to be made. However, the results of the modelling should certainly not be used as any basis for decision making without deeper contemplation as to why such results arose. This is nonetheless the author's views on any modelling results.

The contents of this thesis, especially referring to chapter 4 (Model Development) and the improvements suggested in the discussion, may comprehend a fair share of the prerequisites of a model able to fulfil the tasks requested in the research question - even if the model itself does not entirely (yet). The basic modelling performed for the purpose of this thesis is deemed likely a good foundation for further development of the tool.

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Appendix 1. 2017 Production Data from ENTSO_E, Nordics

Table 24. Collected ENTSO_E data in GWh.

Generation Sources	DK [GWh]	FI [GWh]	NO [GWh]	SE [GWh]	TOTAL [GWh]
Non-Renewable Net generation	8794	34321	3079	66528	112722
Nuclear net generation	0	21574	0	63008	84582
Non-renewable hydro net generation	0	0	0	0	0
Fossil fuels net generation	8794	11859	3079	2659	26391
Fossil Gas	2171	3129	3079	401	8780
Fossil Hard coal	6534	5927	0	0	12461
Fossil Oil	90	168	0	177	434
Fossil Peat	0	2634	0	0	2634
Mixed fuels	0	0	0	1623	1623
Non-renewable Waste net generation	0	0	0	861	861
Other non-renewable net generation	0	888	0	0	888
Renewable net generation	20641	30680	144846	92552	288719
Wind net generation	14754	4795	2727	17269	39545
Wind offshore	5180	0	0	0	5180
Wind onshore	9575	4795	2727	17269	34365
Solar net generation	789	21	0	0	810
Solar PV	789	0	0	0	789
Bio net generation	3670	11254	0	10088	25011
Biomass	3159	11254	0	10088	24500
Biogas	511	0	0	0	511
Renewable Waste (net)	1410	0	0	1295	2705
Renewable Hydro (net)	18	14610	142119	63900	220647
Of which Hydro Pure storage	0	0	142119	63900	206019
Of which Hydro Run-of-river and pondage	18	14610	0	0	14628
Total Hydro net generation	18	14610	142119	63900	220647
Total net generation	29435	65000	148634	159080	402149
Transmission losses, mainly 380kV & 220kV	1020	1074	1845	3343	7282
Exchange balance	4690	20426	-15177	-18993	-9055
Imports	15310	22204	5889	14221	57623
Exports	10620	1778	21066	33214	66678
National electrical consumption	34125	85426	133456	140087	393094

Data collected for figures 3 and 5.A-D for year 2017 from ENTSO_E. Monthly data has been aggregated. For further information see https://www.entsoe.eu/data/power-stats/monthly-domestic/

APPENDIX 2: TRANSLATION OF FIGURE 1.

The image has been used for this purpose with the consent of Svenska Kraftnät.

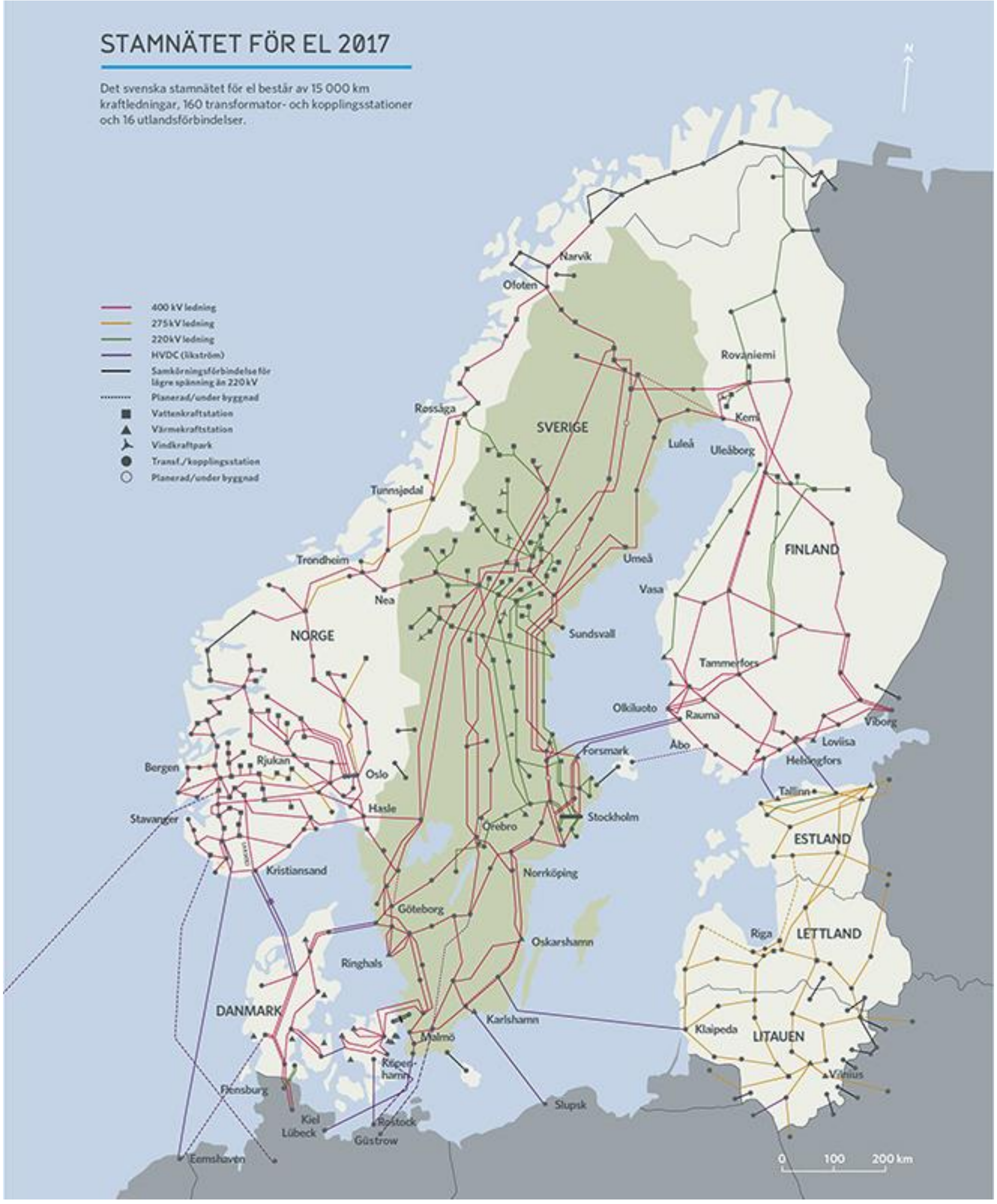

Figure 22. Map of the Nordic and Baltic electricity networks. Courtesy of Svenska Kraftnät: https://www.svk.se/drift-av-stamnatet/stamnatskarta/.

Rough translation of the text on figure 1 (here 22):
"The transmission network for electricity 2017. The Swedish transmission network consists of 15 000 km power lines, 160 transformer- and switching stations and 16 cross-border interconnections"

Translated legend:
Red: 400 kV line
Yellow: 275 kV line
Green: 220 kV line
Purple: HVDC line
Grey: <220 kV interconnector line
Dashed line: Planned or under construction

Square: Hydropower plant
Triangle: Thermal power plant
Triple blade turbine: Wind power park
Filled circle: transformer-/switching station
Empty circle: Planned/under construction

APPENDIX 3. PROFILE ANALYSIS

This appendix considers the profiles of consumption, exchange, wind and total power production in Sweden, Finland, Denmark, Norway, Estonia Latvia and Lithuania. It begins with an excerpt from the thesis for context purposes.

Nord Pool operates the day ahead and intraday markets for the Nordic countries (Nord Pool, 2017). The company also collects data regarding total and wind production, consumption, exchange and water reserves. In figures 23 to 29, daily data from Nord Pool has been used, extracted for a period between the 1st of February 2018 to the 30th of January 2019 as there is limited access to historical data. Positive exchange indicates imported power. The most striking plot is given in figure 23, where the large share of Danish wind from figure 4 has a visible impact. Firstly, the consumption seems to have limited seasonal variation, yet a weekly cycle is evident, with lower demands during weekends and higher otherwise. Then one can identify that spikes in wind power production cause considerable spikes in total power production and if the wind is low, domestic production is strongly affected and imports are called for to make up for the demand. On the other hand, when the production passes the national demand, a large share of power is exported.

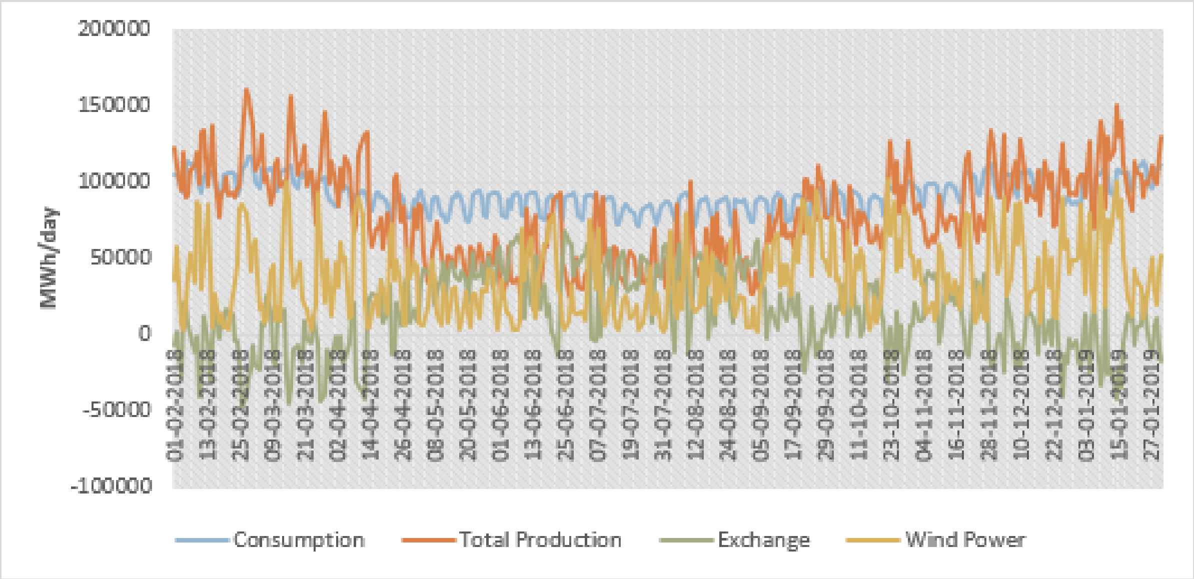

Figure 23. Danish trends. Wind power production correlates with exchange. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

In Sweden, the consumption during summer months follows a rather cyclic weekly trend, however compared to Denmark the seasonal variation is more pronounced. Also, consumption peaks occur during the winter season. The highest peak, on the 28th of February 2018 corresponds to an instance of very cold weather (Westin, 2018). In Denmark, at the same time, a peak in wind and consumption is discernible.

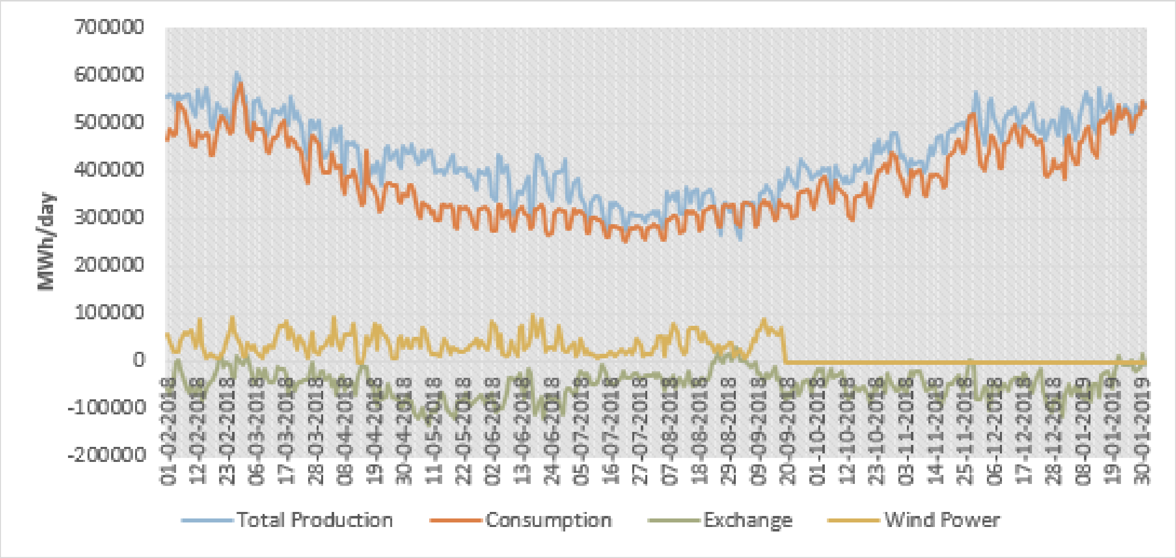

Figure 24. Swedish electricity trends. Sweden is a net exporter. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

From figure 24 one may also conclude that Sweden is a net exporter, and that this export, up until September is related to periods when the country has higher productions of wind power. When the wind is low (regarding January to September, wind data missing for the rest of the year) the exports decrease somewhat. The intermittency of the wind power production is also seen in the total production data, as it peaks when the wind power production peaks. One may also conclude that consumption and wind production during winter months are not entirely unrelated.

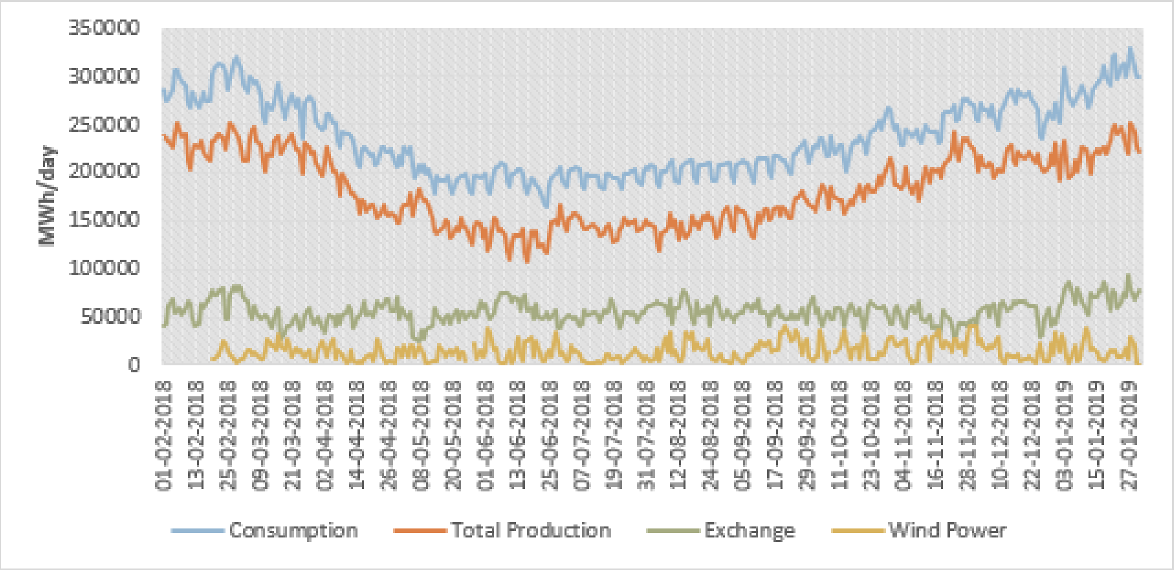

Figure 25. Finnish electricity trends. Finland is a net importer. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

In figure 25, consumption is again quite cyclic during the summer months and more distorted on a seasonal basis. The production follows demand, yet remains below it at all times, yielding the need for an import to balance the demand. The small amount of wind power the country has an inverse correlation to the imported power – when the Finnish wind blows harder, less power is needs to be imported.

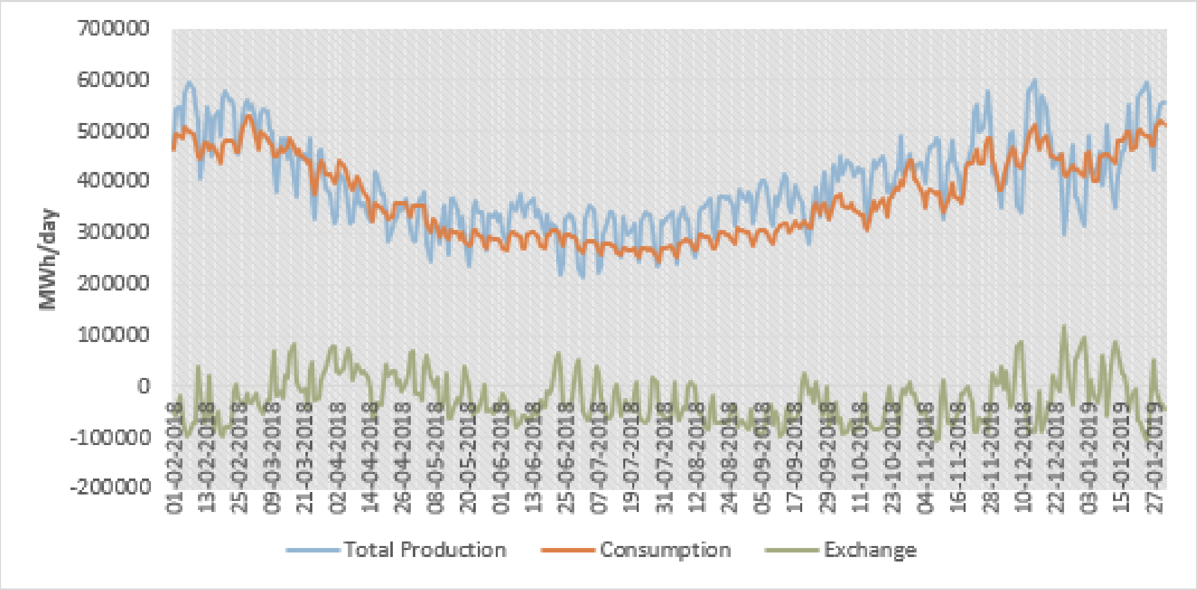

Figure 26. Power trends of Norway. An economically induced production trend? Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

In figure 26, the Norwegians also have visible weekly summertime trends and a larger seasonal variability, yet evidently their (hydro) power production swings more than consumption does, with elements of a weekly trend. When production goes down during the weekends, the Norwegian power supply is compensated by imports. The Norwegians probably could sustain their domestic demand alone (a gross oversimplification not taking into consideration that hydro reserves are sensitive to weather conditions, however there was around 7 % more production than demand over a year). If so, their dynamic behaviour may be the result of economic factors. At times with high demand, such as weekdays, the market price of electricity is likely to be higher, resulting in more hydro to be dispatched. With a lower price, hydro power producers gain less profits and behaving strategically, may opt not to produce. This causes other types of power to enter the market, and power may be imported to Norway.

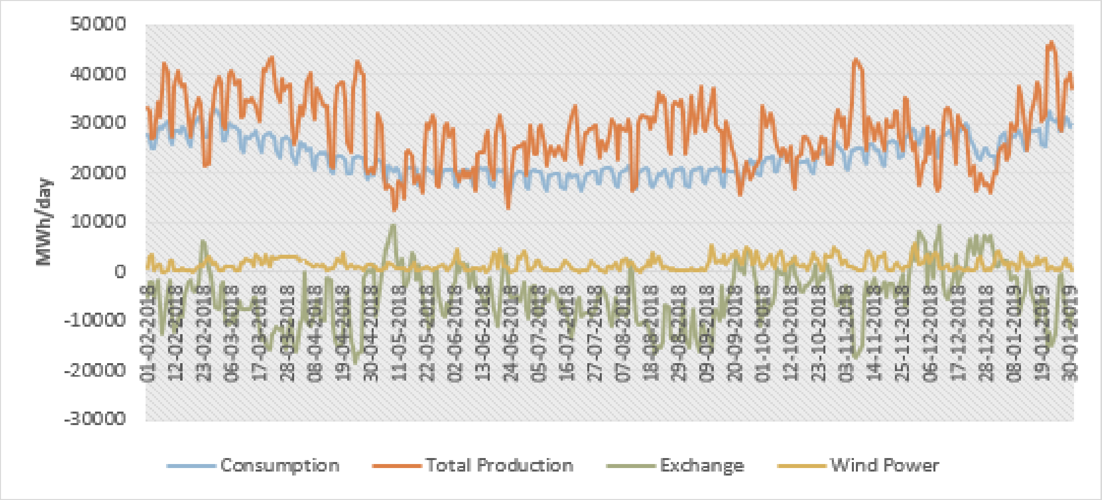

Figure 27. The Estonian power trends. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

In figures 27 to 29 the production, demand and exchange of Estonia, Lithuania and Latvia are depicted. In figure 27 one can see that Estonia has an even and cyclic demand, yet that production (and thereby exchange to make up the difference) varies strongly. The variation does not seem to correlate with the wind power production.

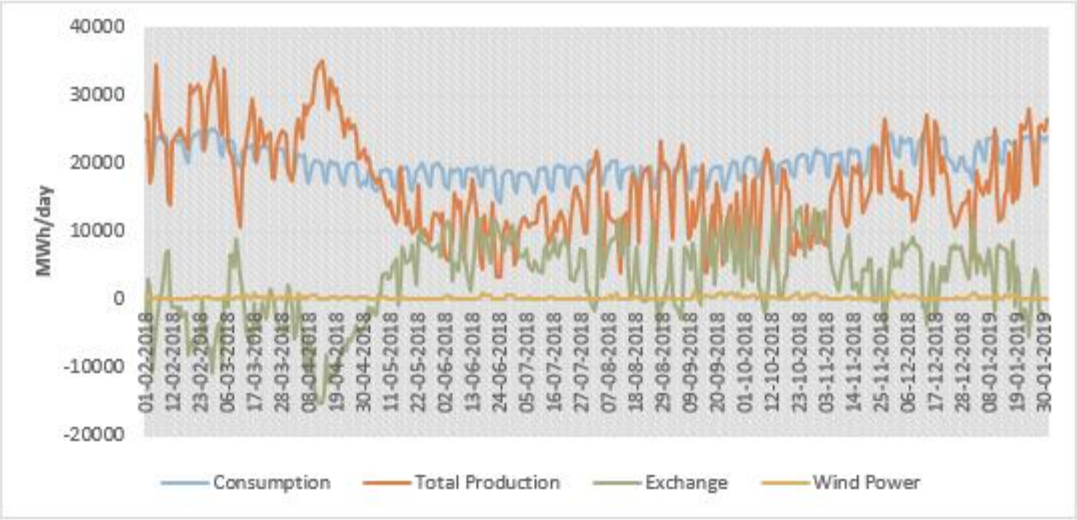

Figure 28. Latvian power trends. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

Recalling that Latvia produces most power by means of hydro and other renewable sources that one can stock (biomass) one notes a large variability despite the little intermittent sources in figure 28. The consumption remains even and cyclic. Lithuania are clearly net importers, importing a very large share of the power they use over a year, as seen in figure 29. The profile of the little power they produce is strongly moulded by wind power production. Their many interconnectors make sense in the light of the shares of imported power.

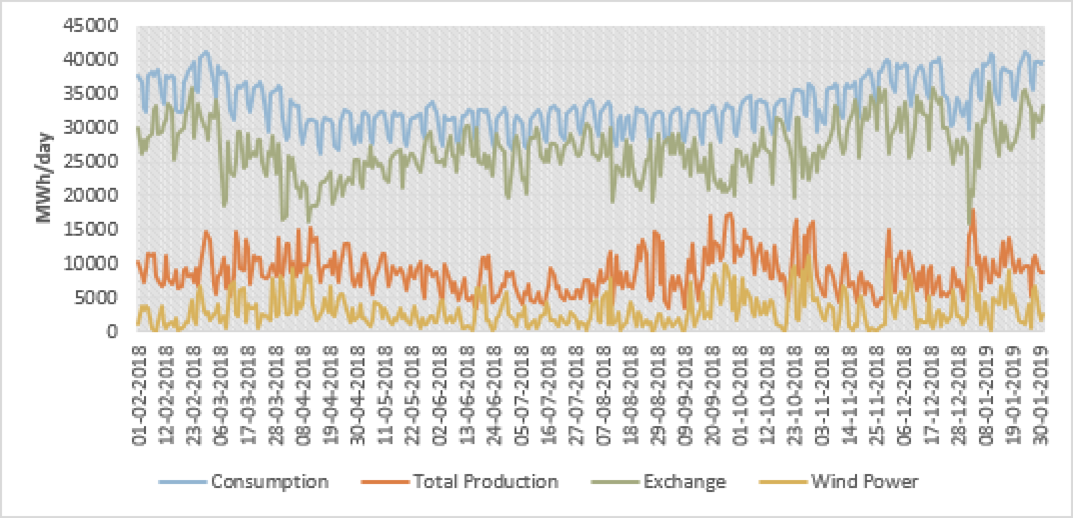

Figure 29. Lithuanian power trends. Data from Nord Pool: https://www.nordpoolgroup.com/Market-data1/Power-system-data/Production1/Production1/ALL1/Hourly2/?view=table

APPENDIX 4. 2017 PRODUCTION DATA FROM ENTSO_E, BALTICS

Table 25. Baltic electricity sources in GWh.

Sources of Generation 2017	Estonia [GWh]	Lithuania [GWh]	Latvia [GWh]
Non-Renewable Net generation	9654.2	1417	1973.3
Nuclear net generation			
Non-renewable hydro net generation	0	575	0
Hydro pure pumped storage		575	
Hydro mixed pumped storage (non-renewable part)			
Fossil fuels net generation	9654.2	582	1973.3
Fossil Brown coal/Lignite			
Fossil Gas		464	1417.32
Fossil Oil shale	9654.2		
Mixed fuels		118	555.98
Non-renewable Waste net generation		75	
Other non-renewable net generation		185	
Renewable net generation	1584	2449	5370.62
Wind net generation	669.5	1356	147.73
Wind offshore			
Wind onshore	669.5	1356	147.73
Solar net generation	8.1	68	0
Solar PV		68	
Solar Thermal			
Bio net generation	821.2	377	869.43
Biomass	778.9	246	482.74
Biogas	42.3	131	386.69
Renewable Waste net generation	55.9	75	
Renewable Hydro net generation	29.3	573	4353.46
Of which Hydro Pure storage			
Of which Hydro Run-of-river and pondage	29.3	573	4353.46
Non-identified net generation			
Total Hydro net generation	29.3	1148	4353.46
Total net generation	11238.2	3866	7343.92
Consumption of pumps		815	
Transmission losses, mainly 380kV & 220kV	432.7	353	226.53
Exchange balance	-2734.3	8677	-64.7
Imports	2313	11926	4073.7
Exports	5047.3	3249	4138.4
National electrical consumption	8503.9	11728	7279.22

Data collected for figures 8-10 for year 2017 from ENTSO_E. Monthly data has been aggregated. For further information see https://www.entsoe.eu/data/power-stats/monthly-domestic/

Appendix 5. 2017 Production Data from ENTSO_E, NW Europe

Table 26. Electricity production from different sources in North-Western Europe. In GWh.

Sources of Generation 2017	Germany [GWh]	UK [GWh]	Netherlands [GWh]	Poland [GWh]
Non-Renewable Net generation	396429.8	232934	95083	133126.7
Nuclear net generation	72154.98	65620	4161	
Non-renewable hydro net generation	6378.64	0	0	473.21
Hydro pure pumped storage	5909.66			471.3
Hydro mixed pumped storage (non-renewable part)	468.98			
Fossil fuels net generation	312912.2	167314	90922	131978.5
Fossil Brown coal/Lignite	137323.2			46366.36
Fossil Coal-derived gas				2214.75
Fossil Gas	82926.01	143554	73646	7533.02
Fossil Hard coal	84154.09	23719	17276	73631.84
Fossil Oil	4280.92	41		2232.48
Mixed fuels	4227.99			
Non-renewable Waste net generation	4983.97			176.99
Other non-renewable net generation				498.05
Renewable net generation	205862.8	79413	16431	24604.96
Wind net generation	103378.1	43970	10952	14447.46
Wind offshore	17413.73	16026	3619	
Wind onshore	85964.39	27944	7333	14447.46
Solar net generation	35518.42	10450	1858	163.12
Solar PV	35518.42	10450	1858	163.12
Bio net generation	40606.5	17416	3559	7439.82
Biomass	40606.5	17289	3559	6440.62
Biogas		127		999.2
Geothermal net generation	160.5			
Renewable Waste net generation	5374.81	68		
Renewable Hydro net generation	19491.78	7509	62	2554.56
Of which Hydro Pure storage	621.87	2941		538.53
Of which Hydro Run-of-river and pondage	18869.91	4568	62	1781.04
Of which Hydro mixed pumped storage (renewable part)				234.99
Other renewable net generation	1332.63			
Total Hydro net generation	25870.42	7509	62	3027.77
Total net generation	602292.5	312347	111514	157731.7
Consumption of pumps	8252.38	3924		690.02
Transmission losses, mainly 380kV & 220kV	9978.68	5393	928	1669.05
Exchange balance	-55357.4	16417	3508	2286.72
Imports	28083.56	20162	22459	13270.76
Exports	83440.92	3745	18951	10984.04
National electrical consumption	538682.8	324840	115022	159328.4

Data collected for figures 11-14 for year 2017 from ENTSO_E. Monthly data has been aggregated. For further information see https://www.entsoe.eu/data/power-stats/monthly-domestic/

APPENDIX 6. 2016 PRODUCTION DATA FROM IEA, RUSSIA

Table 27. The Russian sources of electricity (IEA, 2019).

Source	TWh 2016
Nuclear	2286.62
Gas	6068.39
Coal	1993.88
Oil	127.56
Wind	1.72
Solar PV	5.37
Biofuels	0.37
Waste	28.28
Hydro	2170.62
Geothermal	5.19

Data collected for figure 15 for year 2016 from the International Energy Agency. For further information see https://www.iea.org/statistics/?country=RUSSIA&year=2016&category=Electricity&indicator=ElecGenByFuel&mode=chart&dataTable=ELECTRICITYANDHEAT

APPENDIX 7: CAPACITIES IN THE MARKET AREAS

The capacities within the Finnish, Estonian, Latvian, Lithuanian, German, British, Dutch, Polish and five Norwegian and two Danish bidding zones were collected from the ENTSO_E Transparency Platform (ENTSO_E, u.d.). The data was taken from the most recent available year. If the ENTSO-E categories did not fit into the categories defined here, the (neglectable) sources were grouped under “Other” or “Other Renewable”.

As data on the Swedish bidding zones was missing, the report “Elproduktion” from the series “Energiåret” (Energiföretagen, 2018) was used to define the capacities of hydro, nuclear, gas, wind and solar power. The report also provided lumpsums of thermal power production from various plant types; “electricity only” and combined heat and power (CHP) for both industrial needs and district heating. Nevertheless, the plant type is insufficient for the purposes of the data collection. The map published by Bioenergi “Biokraft I Sverige 2018” displays the capacities of power plants using biofuels, peat and waste indistinguishably, yet does separate industrial from non-industrial production. The power plants as displayed on the map, apart from biogas (as the power produced from such gas was comparatively very small), were manually divided into the different Swedish bidding zones and compared with the size of the industrial and non-industrial thermal production as given by Energiföretagen (2018).

Table 28. Comparison between Energiföretagen’s thermal capacity data and Bioenergi and other sources in MW.

	SE1		SE2		SE3		SE4	
	Energiåret	Bioenergi & others	Energiåret	Bioenergi & others	Energiåret	Bioenergi & others	Energiåret	Bioenergi & others
CHP and condensing power	142		207		2500		1142	
whereof condensing power					*243*		*670*	
CHP Ind	122		325		604		400	
Biomass, waste & peat		71.9		270.4		1833.36		378.1
Biokraft Ind		129		408.17		741.315		105.9
Hard coal						205[11]		
Brown coal								
Oil						740[12]		662[13]
SUM	264	200.9	532	678.57	3104	3520	1542	1146

In table 28, for each area the total thermal power capacities from Energiföretagen (yellow) is compared to that of the map published by Bioenergi (green) and other external sources (orange). Apart from in SE4 the industrial capacity determined by Bioenergi is higher than by Energiföretagen, indicating that the industrial production is largely bio based, as confirmed by the Swedish Energy Commission (Energikommissionen, 2016). In the case of other power production, there is more power produced from biomass etc. in SE2 that the total CHP and condensing power expected from Energiföretagen.

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[11] Sourced from (Gad, 2017) and (ENTSO-E, 2018)

[12] Sourced from (MälarEnergi, 2011) and (Vattenfall AB, 2014)

[13] Sourced from (Uniper, 2019)

When reviewing the fossil power plants in Sweden, it was found that all coal plants existed in SE3 (Gad, 2017). According to ENTSO-E data, this should be a capacity of 205 MW (ENTSO-E, 2018). In SE4, the recorded oil burning capacity is assumed to come from the Karlshamn power plant, which recently shut down a block (Uniper, 2019). The size of the block corresponds rather well to the discrepancy between the numbers between Energiföretagen and Bioenergi with the others. SE1 also has a deficit when comparing the aggregation of different sources, however comparing it to the 5315 MW hydropower Energiföretagen declares, the difference is negligible. In SE2 and SE3 the production facilities from Bioenergi and others are larger than those of Energiföretagen. According the ENTSO-E (2018), Sweden should have had 2695 MW of installed oil capacity in 2017, however only 1402 MW is covered here.

As the translation of thermal power for condensing power and CHP for DH and industrial use is required for the functioning of the model, the data from Bioenergi and other sources is accepted cautiously. It is worrying that the difference in power production capacity is +416 MW in SE3 and -396 in SE4, yet the deficit in SE4 may be explained by the recent closure of a block in Karlshamnsverket. The data is therefore deemed to be used until better data is made available and may be revisited as a source of errors.

Further, Bioenergi lumps the data from biomass, waste and peat. The shares of peat are assumed to be negligible yet comparing numbers from the ENTSO-E (2018) the waste should make up around 12 % of the total biomass and waste category.

The results of these considerations are displayed in the final version of the used data in table 2 below. The difference with ENTSO_E mainly comes from the difference in oil power production facilities.

Table 29. Results and comparison to ENTSO_E data in MW.

Power source	SE1	SE2	SE3	SE4	TOTAL	ENTSO_E TOTAL
Biomass	176	594	2256	424	3450	3145
Hard coal			205		205	205
Brown coal					0	0
Oil			740	662	1402	2695
Fossil peat					0	0
Fossil mixed fuels					0	120
Waste	25	84	319	60	488	445
Other					0	0
SUMMA	201	679	3520	1146	5545	6610

The data with regard to Kaliningrad was collected from (Inter RAO, 2019) and (Presidential Executive Office, 2018), more details can be found under segment 3.2.4. Considering continental Russia, data are difficult to find, hence any import from Russia will be modelled as a power inflow with the same shares of sources for 2016 as IEA (2019) suggest.