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Line Loss Prediction Model Design at Svenska kraftnät

Line Loss Prediction Based on Regression Analysis on Line Loss Rates and Optimisation Modelling on Nordic Exchange Flows

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Abstract

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Forecast and estimation on transmission line losses is a vital task in the daily operation and planning of the Swedish power system. The aim with this thesis is to design a new line loss prediction model at Svenska kraftnät (Svk), which provides a hourly forecast of the transmission line losses the next day for the Swedish bidding areas (SE1-SE4). The final goal is to reduce the additional cost related to inaccurate predictions. The developed model is based on regression analysis on historical line losses and estimated exchange flows between the adjacent bidding areas computed by linear programming. Simulation results for 2015 show that it is, with rather simple estimates and assumptions, possible to increase the prediction accuracy with up to 27% compared with the existing method and to reduce the related costs in a similar way. The study also shows that future modelling has potential to increase the precision even further and recommends a Neural Network approach as the next step.

Keywords: Line Loss Prediction, Linear Regression, Linear Programming, Nordic Exchange Flows, Net-position

Sammandrag

Design av förlustprognosverktyg hos Svenska kraftnät

Prognoser och estimering av stamnätsförluster är en central del i den dagliga driften av det svenska kraftsystemet. Den här uppsatsen har därför syftat till att utveckla en simuleringsmodell som ger en timvisprognos över morgondagens förluster i varje elområde (SE1-SE4). Detta verktyg är senare tänkt att precisera den dagliga upphandlingen av förluster och därmed minska kostnaden kopplad till osäkra prognoser. Den utvecklade modellen bygger på en regressionsanalys av tidigare uppmätta förluster och uppskattade transmissionsflöden mellan de närliggande elområdena beräknad med linjär programmering. Simulerignar för 2015 visar att, det med föhrhållandesvis enkla antaganden och uppskattningar av indata, går att precisera förlusterna med uppemot 27% jämfört med dagens prognos och därmed minska kostnaderna i liknande omfattning. Studien visar också att förbättringspotentialen är stor och rekommenderar fortsatta studier utifrån en Neurala Nätverk modell.

Nyckelord: Förlustprognoser, Linjär Regression, Linjär Programmering, Nordiska Transmissionsflöden, Netto-positioner

Executive Summary

Svenska kraftnät (Svk) is balance responsible player for the transmission line losses and obliged to cover these losses at the day-Ahead market. Svenska kraftnät is thus dependent on accurate predictions in order to reduce forecast errors and costs related to these errors. Today, these predictions are made by the Grid Supervisor (GS) but design of a new line loss prediction model would be favourable. The aim with this thesis has therefore been to design a model with increased precision which provides hourly forecasts on the transmission line losses the next day for each bidding area of Sweden.

The model is based on linear regression analysis of line loss rates and a separate optimisation model on exchange flows. The literature study recognised that line losses could be described as a linear combination of wind generation, supply, demand and exchange flows. These parameters relate to the losses through certain line loss rates which could be derived by linear regression and least-square estimates from historical data. The historical data was extracted from the official market database from Nord Pool and measured line losses from Svenska kraftnät. Nord Pool also provides forecasts on wind generation, supply and demand but exchange flows had to be estimated separately. These flows were predicted by an optimisation problem, based on estimates on future net-positions, assumptions on future electricity prices and given data on transmission line capacities, and solved by linear programming.

The designed model was evaluated against the GS predictions and actual losses for 2015. The model managed with own estimates on exchange flows reduce the total absolute prediction error with 27.2%. The method approach and designed model thus managed to increase the prediction precision as stated in the objective. If Svenska kraftnät would be allowed to trade and adjust their loss prediction at the intra-day market the GS would be able to apply forecast on exchange flows from Nord Pool instead. This approach reached a 42.2% reduction in total absolute prediction error which indicates that Elbas trading would be preferable in that sense. Moreover, the designed model has a potential to reduce the absolute prediction error with up to 57.2% providing that perfect forecasts on exchange flows would be given. Further simulation is though required in order to support these results and further modelling has also potential to increase the prediction precision even more.

Acknowledgement

This master thesis, conducted during the spring in 2016, is my last and final assignment after five years at KTH. This work concludes my engineering degree in Energy and Environment and master degree in Electrical Power Engineering at KTH. I have the deepest gratitude towards each and everyone who made this journey possible and I wish to direct my special appreciation to those who have guided me during my final work:

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Jakob Sahlin
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Contents

List of Symbols

KTH	Royal Institue of Technology
AC	Alternating Current
ATC	Avilable Transfer Capacity
BRP	Balance Responsible Party
DC	Direct Current
Elbas	Intra-Day Market
Elspot	Day-Ahead Market
EPX	European Power Exchange
EUPHEMIA	Pan-European Hybrid Electricity Market Integration Algorithm
FB	European Union
FB	Flow Based
GS	Grid Supervisor
LCD	Last Comparable Day
LP	Linear Programming
LRM	Linear Regression Method
MWh/h	Megawatthour per hour
ND	Net-demand (Demand - Wind power)
NTC	Net Transmission Capacity
SEK	Swedish Kronor (currency)
Svk	Svenska kraftnät
TSO	Transmission System Operator

Chapter 1

Introduction

This chapter begins with a brief background on line loss prediction models and related challenges. Thereafter, the problem is described together with the aim and objectives of this master thesis. The chapter ends with a short overview of the remaining succeeding chapters.

1.1 General Background

Transmission line losses have a considerable and growing influence on power systems around the world [1, 2]. Line losses overheat power lines, reduce the grids's available transmission capacity, and affect the agreed transaction of energy at the electricity markets. Certain market participants are therefore forced to account for these losses by purchase complementary energy. However, since the size of these line losses remain unknown before each operating hour, certain predictions are necessary. Any error between predicted and actual line loss has to be adjusted during each operating hour. This adjustment oppose an additional and unnecessary cost which highlights the requirement of accurate line loss prediction models. Transmission System Operators (TSOs) worldwide, who are economical responsible for line losses in the transmission grid, has thus a special interest towards adequate line loss prediction strategies.

However, even if line loss prediction have drawn more attention during the last years [1] they have also become more complex to perform [2, 3]. Increased market deregulation [1, 4] and shares of renewable and intermittent energy generation [5], which implies varying and changeable power flows, makes line loss prediction difficult [2, 3]. Line losses themselves are also influenced by a multitude of factors and non-linear correlations which makes predictions model even more complicated [2, 6]. Design of line loss prediction models have thus become a research priority [2] and several different models have been proposed across the world. However, a majority of these models are mainly designed for line loss allocation issues [4, 7, 8] for market applications as opposed to day-Ahead predictions for TSO purposes. The proposed models thus tend to focus more on line loss applications for distribution networks [5, 8, 9] than nationwide transmission grids [10]. Hence, further studies on line loss prediction models for these kind of applications would seem to be a valuable contribution to the overall research field.

Svenska kraftnät (Svk), the TSO in Sweden, has put forward a master thesis project with the aim to design a line loss prediction model. The task is to evaluate the existing line loss prediction method at Svk and develop a new approach with increased accuracy and precision. The project is meant to provide suggestions on new trading strategies and recommendations on how to trade line losses at the electricity market. The project proposal is thus aligned with the need of further studies on line loss prediction for TSO application. However, several challenges exist with TSO based line loss prediction models which require updated research, decision on plausible forecast strategies and identifications on appropriate simplifications.

1.2 Problem Description

Line loss prediction at Svenska kraftnät is made by the Grid Supervisor (GS) who is in charge of the power system operation. The GS at Svk reports line losses in MWh/hour for the upcoming day between 00:00-24:00 and for each bidding area in Sweden [1]. The GS provide a line loss approximation, based on previous experience and available prognosis data, for each hour and bidding area between 9-10am the day before. This approximation is then reported to the market division who trade the same amount at the Nord Pool day-Ahead Exchange Market. Any imbalance between reported and actual losses during each hour is regulated by the balance responsible and frequency control division [2]. More precise predictions would minimize the need of additional regulation power and thus reduce the overall costs.

However, precise predictions on total line losses for each hour and bidding area in the Swedish transmission system is a complicated matter. First of all, total line losses cannot be determined exactly due to natural fluctuations and uncertainties [11]. An obvious problem is that the future state of the system [3] is unknown at the time for day-Ahead line loss predictions. Another problem is that the line losses has to be traded before the day-Ahead market closes at noon. This means that the market turnout on energy transactions is unavailable which creates even more uncertainties.

Previous studies that show promising results [1, 8, 12, 13] are often dependent on accurate input data which for large operating transmission systems is not known

[1] Sweden has four bidding areas: SE1, SE2, SE3 and SE4 which are described in 2.1

[2] A brief description on Nord Pool, balance responsible and frequency control is given in 2.1

[3] The state of the power system concerns knowledge about voltages, currents, frequencies and active/reactive power flows within a given network topology.

the day before. Proper line loss prediction models are thus dependent on reliable forecasts on several different network parameters. Since it is well known that line losses depends on the amount of power being transmitted in the grid, separate prognosis on electrical demand, supply and exchange flows would be required. However, how these factors influence the total line loss for each Swedish bidding areas is not certain and probably affected by both time and weather variations. Line losses might also be affected by unknown factors not yet mentioned or identified. All of this highlights the fact that accurate predictions of line losses are difficult to achieve.

1.3 Aim and Objectives

The goal with this master thesis is to design a line loss prediction model at Svenska kraftnät which provides a forecast on transmission line losses in the Swedish transmission grid. The forecast shall include line loss estimates for each hour during the upcoming day, for all four bidding areas of Sweden and be provided in time before the day-Ahead market closes. Although, since line losses depends on the amount of supply, demand and exchange flows within each bidding area it is crucial to forecast these as well. Thus the goal is to design a model which derives the expected line losses from estimates on electrical supply, demand and exchange flows. The task is to increase the accuracy and precision of the existing line loss prediction method at Svk and reduce the existing error between actual and predicted line losses. The final objective is to provide recommendations on how to administer transmission line losses at Svk in the future. Thus, this thesis intends to complete the following aims:

Aim I: Provide total line loss predictions (in MWh/h) for SE1-SE4 for each hour the upcoming day.

Aim II: Provide forecasts on total electrical supply, demand and exchange flows (in MWh/h) within SE1-SE4 for each hour the upcoming day.

Aim III: Based on the achieved accuracy and precision determine how much the existing line loss error can be reduced.

The line loss prediction model is thus divided into two separate parts. The first part is designed to derive the line losses from given values on supply, demand and exchange flows. The second part is designed to forecast these input parameters for the next day. The envisioned model is meant to derive the future line losses through hourly predictions on regional net-positions and exchange flows and estimation of related line loss rates for each region. Net-positions are defined as the net difference between electrical supply and demand in one bidding area whereas the exchange power flows are the expected amount of power that is being transmitted to and from the same region. The line loss rates are defined as the correlation factors between the these parameters and the final line losses. An overview on detailed objectives required for this model approach follow below:

1. **Literature study**
    a) Study different prediction methods to estimate the line loss rate hourly for SE1, SE2, SE3 and SE4.
    b) Study different prediction method to estimate the net-position and power flows hourly from and within SE1, SE2, SE3 and SE4.

2. **Modelling**
    a) Extract historical data on net-positions, exchange flows and line losses from Nord Pool and Svk databases.
    b) Predict the future line loss rates for SE1-SE4 through a multi-variate linear regression model design in Matlab.
    c) Predict the future net-positions and exchange flows for SE1-SE4 through a linear programming model design in Matlab.

3. **Case studies**
    a) Derive the model's first achieved accuracy and precision through a yearly simulation with own estimates on future net-positions and exchange flows.
    b) Derive the model's second achieved accuracy and precision through a yearly simulation with estimates on future net-positions and exchange flows from Nord Pool.
    c) Derive the model's third achieved accuracy and precision through a yearly simulation with measured data on future net-positions and power flows from Nord Pool and Svk.

4. **Discussion and Analysis**
    a) Compare and evaluate the yielded model precision and accuracy with the existing method at Svk.
    b) Evaluate and suggest possible model improvements as recommendations for future work.
    c) Identify advantages and disadvantages with trading on the day-Ahead versus the intra-day market.

1.4 Report Overview

This thesis is structured in the same way as the aforementioned objectives in five chapters. The first chapter introduce the reader to the background and challenges related to aims and objectives in this thesis. The second chapter goes through the theoretical background to the research question at hand with a general description on the Swedish power system is given together with recent studies on transmission line loss equations and possible prediction strategies. This section also describes the three most common computational methods utilized in the following model design. The second chapter ends with a presentation of the existing line loss prediction approach at Svk today.

The third chapters goes over the method and model design approach applied in this study to predict the line losses in the Swedish transmission grid. This chapter provides both an overview and details of the developed model design together with general comments on applied data in the following case study scenarios. The model design follows in chapter four in which three separate case studies investigates the models achieved precision and accuracy regarding net-position, exchange flows and line loss predictions. The obtained results are then discussed and analysed according to the defined objectives. The fifth and final chapter presents the main conclusions drawn from the achieved results and provide recommendations and suggestions for future work.

Chapter 2

Theoretical Background

This chapter gives a background description of the Swedish power system and electricity market together with an overview on transmission line losses and common prediction strategies. The chapter ends by a general presentation of the line loss prediction approach applied at Svenska kraftnät today.

2.1 The Swedish Power System

The main goal with the Swedish power system is to deliver electrical energy from the generation points to the load points in the system. In 2015, Sweden had an annual demand of 135.7 TWh, a yearly generation of 158.3 TWh and a total net-export of 22.6 TWh to its neighbouring countries [14]. Svenska kraftnät is responsible to deliver the energy physically between energy suppliers and users while Nord Pool manage the economical transactions between the same actors. Thus, the delivery of energy in the power system follows both an economical and technical path as depicted in Figure 2.1. The technical path describes how the power gets transmitted between the available generation and load points but also oppose limits on how much that physically can be transmitted. The economical path determines the price on electricity and thus decides how large the supply, demand and export/import will be [15].

The Swedish power system is supplied by four types of generation: hydro power (16155 MW), nuclear power (9510 MW), conventional heat power (6614 MW) and wind power (5425 MW) [16]. The largest share of hydro power is located in the northern regions whereas the main load points are located in the southern regions. Hence, one of the main task of the Swedish power system is to transfer a large portion of hydro power in the north to the load in the south over a large distance. The main transmission of power takes part in the transmission grid which is operated by the transmission system operator, TSO.

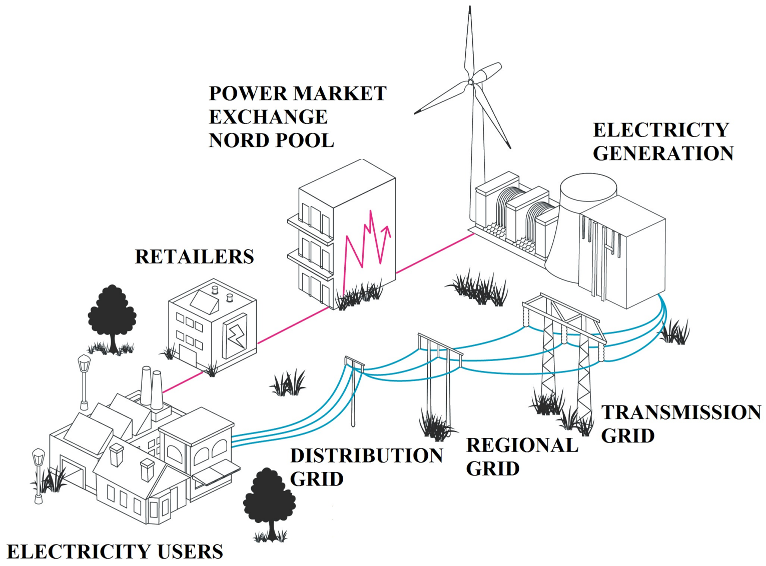

Figure 2.1: The technical and economical path of electrical energy. Source: Svenska kraftnät, 2016

2.1.1 Svenska kraftnät

Svenska kraftnät is the TSO for the Swedish power system and responsible to make sure that the transmission grid is able to deliver power in a secure and reliable way [17]. This means that Svk has to supervise and monitor the transmission system to guarantee the reliability and security of the grid. In practice this means that both voltage, frequency and power flows are operated and kept within their allowed boundaries. In Sweden, the transmission grid typically operates either at 220 kV or 400 kV to keep losses low and efficiency high [18].

National Grid Owner

Svenska krafnät is the national gird owner and thus in charge of 15 000 km overhead lines, 160 substations and 16 interconnections with adjacent regions as shown in figure 2.3. However, Svk is not responsible for the remaining parts of the power system which also includes the *the regional grid* and *the distribution grid*. The main task with the other two systems is to scale down the voltage level and delivers the electrical energy to the final users [18]. The regional and distribution grids are thus managed by separate regional grid owners [18]. Since Svenska kraftnät is the national grid owner they are responsible to cover the corresponding line losses. Back in 2015, the total line losses was around 10.7 TWh in the Swedish power system as a whole. A significant portion on 3.2 TWh took place in the transmission grid which correspond to about 2-3% of the total generation transmitted through the grid [19]. Consequently, the remaining line losses on 7.5 TWh, and also the largest share of the total line losses, took place in the regional and distribution grid [14].

Power Balance Responsible

Furthermore, Svenska kraftnät is also in charge to keep the power balance in the system which is defined as the balance between generation and load [15]. In the Swedish AC-based power system, this is done by keeping the frequency between 50$\pm$0.1 Hz. A surplus of electric supply in the system will increase the frequency whereas a deficit of electric supply will decrease it. The frequency is managed by automatic and manual frequency control and is operated by the TSO. The automatic frequency control is instructed to keep the frequency derivative equal to zero and is divided into two parts, normal and disturbance frequency control reserves. The normal reserve is activated to keep the frequency within 49.90-50.10 Hz while the disturbance reserve is activated when the frequency drops below 49.9 Hz [20].

The manual frequency control adjust the frequency after a disturbance back to its nominal value manually by either up- or down regulating the load and/or generation of certain actors [15]. These decisions are decided at regulating market where the TSO accept certain bids and offers of those actors who can change their scheduled amount of generation or load during that particular hour [18]. Thus, in order to keep these imbalances to a minimum, certain *Balance Responsible Parties* (BRPs) are instructed to keep the balance between market turnout and actual physical flow during each hour. The cost for any up- or down regulation is decided by the up- and down regulating prices and opposed to the BRPs with an power imbalance during each trading period[18].

2.1.2 Nord Pool

Nord Pool administrates the Nordic/Baltic power exchange market where the electricity trading takes place [15]. Nord Pool is a deregulated power pool market which allows different actors and participants from several countries and companies to buy and sell electricity under competition. The idea is basically to make sure that the energy suppliers are getting paid accordingly [18]. This can be done either during the day-Ahead market, the intra-day market or through financial and bilateral agreements.

The Electricity Market

The day-Ahead market (Elspot) lets different actors to place bids and offers per hour. The day-Ahead market, as the name suggest, is open between 36-12 hours before the first hour of delivery. These bids and offers state how much energy the actor wants to sell/buy and the smallest/highest price the same actor is willing to accept. When the day-Ahead market closes at noon, the bids and offers form an aggregated supply and demand curve which produces a system price for that specific hour [18]. Figure 2.2 shows an example on a fictive demand and supply curve which set the system price where the two curves meet.

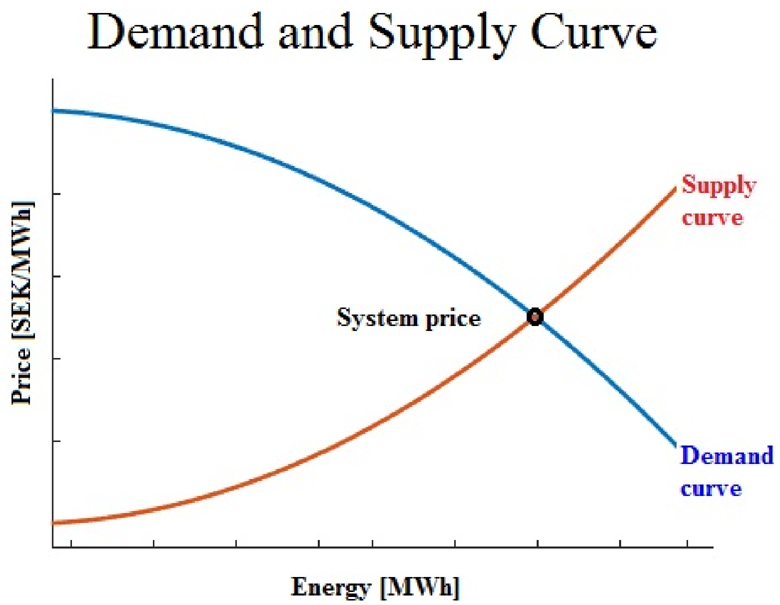

Figure 2.2: How the demand and supply curve derive the system price.

The intra-day market (Elbas) on the other hand allows participants to place new bids and offers at a separate price between 14:00 up to one hour before the hour of delivery. These bids and offers will be accepted at the given price and allows the different players to adjust the amount of energy which they have planned to buy and sell during that specific hour [18]. It is thus common the BRP tries to adjust their demand and supply obligation made at the Elspot market continuously at the intra-day market in order to reduce any imbalance that might occur during the operating hour. Furthermore, bilateral and financial trading take place between buyers and sellers directly and is described further in [18]. These energy volumes, as well as the energy volumes activated at the regulating market for frequency control, are therefore not handled by the Elspot and Elbas market.

Svenska kraftnät is BRP for the transmission line losses and obliged to cover for any mismatch between traded and actual line losses that occurred during each operating hour. However, unlike other BRPs, Svenska kraftnät are currently not allowed to trade at the Elbas market. The reason is that Svk would risk to impact the free market competition in a negative way due to its large insight in the daily operation and planning of the power system. This means that Svenska kraftnät cannot adjust there line loss predictions made at the Elspot market and thus not able to reduce their mismatch before the operating hour take place.

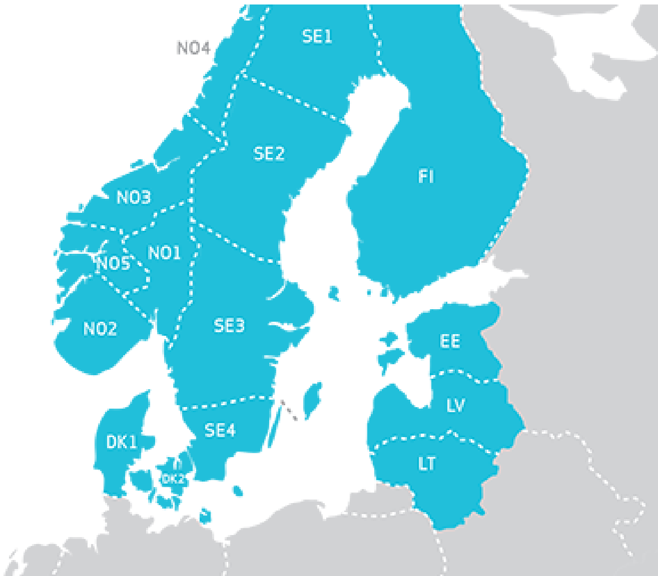

Figure 2.3: The Nordic and Baltic bidding areas of Nord Pool in 2016. Source: Nord Pool, 2016

Transfer Capacities & Bidding Areas

The amount of power that can be sold or purchased between two points in the grid during each trading period is limited by the Net Transmission Capacity (NTC on each inter-connector in the grid. Thus, the price will not only depend on the total available supply and demand but also on the physical transmission constraints. Whenever the capacity limit is reached between two specific regions the price between these may differ. Energy surplus in other areas will flow from low price areas to high price areas in order to receive as much revenue as possible for the sold energy [21]. The difference in price will thus work as an incentive to reduce the demand in high price areas in order to lower the pressure on the transmission inter-connectors to this area. However, it would not be strategic to allow price differences at every point in the power system. The power market is therefore divided into predefined bidding areas where transmission congestions between these areas will result in a price difference. Sweden is from 2011 divided into four different bidding regions which are illustrated in figure 2.3: SE1, SE2, SE3 and SE4 [15].

2.1.3 Grid Expansions

The Swedish bidding areas are connected to adjacent bidding areas in Norway, Denmark, Finland, Germany, Poland and from 2016 to Lithuania [22]. Sweden is thus highly influenced by export and import from other countries and their exist reasons to believe that this will be more prominent in the future [22, 23]. Svenska kraftnät development plan for 2016 to 2025 includes several new transmission links where both the NordBalt Cable to Lithuania and the SouthWestLink between SE3 and SE4 will be activated during 2016 and 2017 [22]. Another connection link between SE4 and Germany, Hansa Power Bridge, might also be in operation before 2025. Norway is also under-way to connect further transmission links to both Great Britain, North Sea Link, and to Germany, Nord Link[22].

The International Energy Agency, IEA, together with several Nordic Universities and Institutions, have recently published a future scenario on how the Nordic power system might develop to 2050, in which the Nordic countries reaches carbon neutrality in 2050, aligned with the political climate and environmental goals. Figure 2.4 shows the difference in energy transmission flows between 2015 and 2050 in which the specific scenario suggest that the total electricity trading between bidding regions and countries will gain in strength [23]. Both [22] and [23] believe that renewable energy will continue to increase its shares in the power system. This will introduce larger uncertainties and require a higher degree of flexibility in the daily power system operation and planning procedure [22, 23].

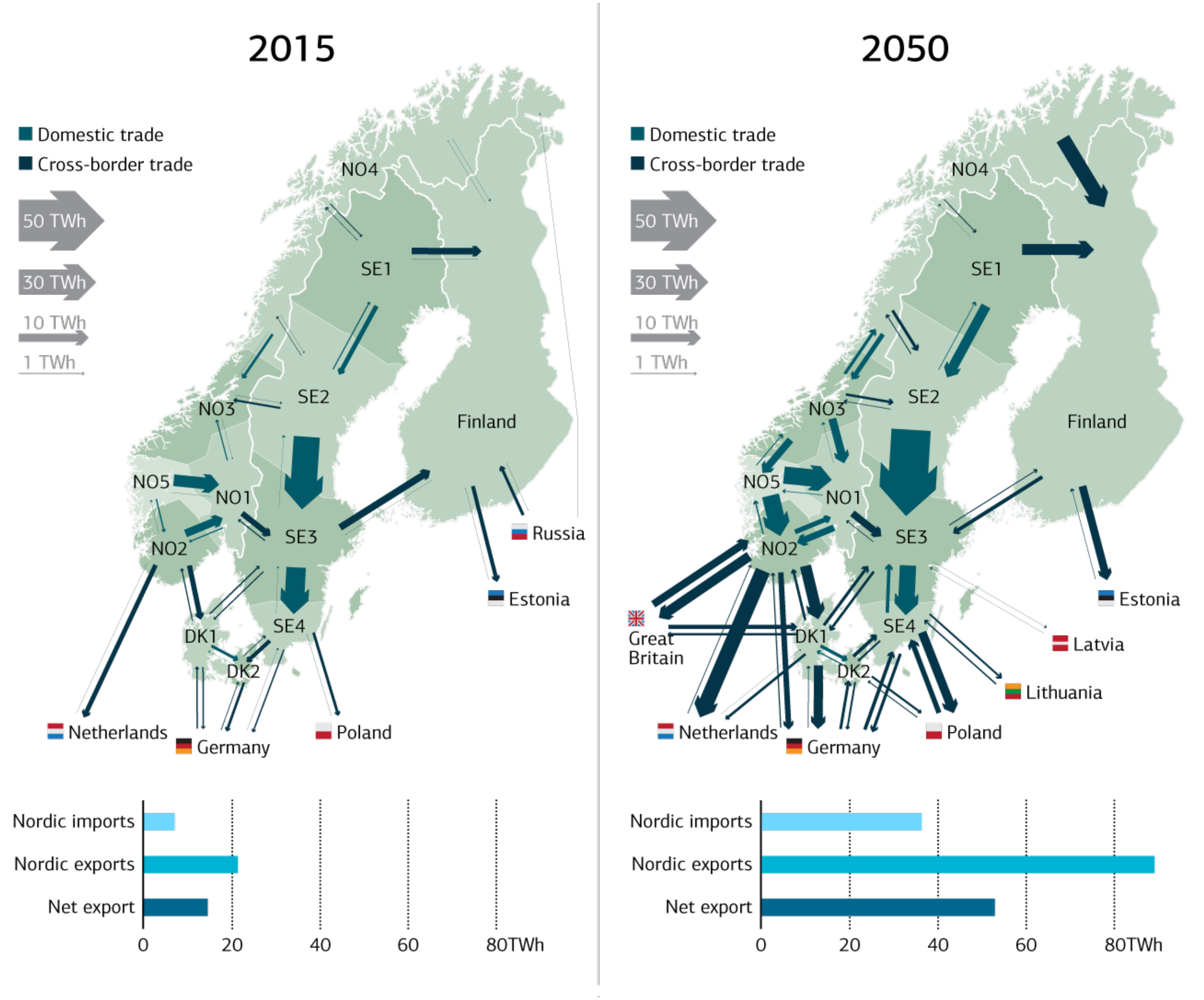

Figure 2.4: Exchange flow scenario 2015 and 2050. Source: Nordic Energy Technology Perspective 2016 [23]

2.2 Transmission Line Losses

Power line losses exist in every power system around the world. Whenever electrical power is transmitted between two points, through over-head lines, underground or sea-based cables, a certain portion of active power is transformed and lost along the way. This section will describe the basics behind transmission line losses and the related line loss rate within power systems.

2.2.1 Line Loss Equations

In general, five types of active power losses exist for AC transmission lines which convert electrical energy into heat during transmission: (1) Resistance heat loss (2) Leakage loss (3) Dielectric magnetizing loss (4) Dielectric polarization loss and (5) Corona loss. These five categorise of active line losses are either quadratic proportional to current and/or voltage levels and direct proportional to different impedance parameters and/or frequency at the time of measurement [11]. A common derivation of line losses (P_L) is however given by the resistance (R) times the current (I) passing through squared [11]:

$$P_L = R \cdot I^2 \tag{2.1}$$

The resulting electric energy line losses, ΔA (Wh), are thus derived by the integral of the total active power loss, ΔP_i ($Watt$), w.r.t the time period, T (h), of interest and bidding area i:

$$\Delta A_i = \int_0^T \Delta P_i(t)dt \quad \forall i = SE1 - SE4 \tag{2.2}$$

However, since the current, voltage, frequency and impedance[1] may vary with time it is quite difficult to provide accurate predictions and calculations on electric energy line losses according to (2.1)-(2.2) [11]. Therefore, another way to calculate the electrical energy line losses is by subtracting the total *power sales quantity* (p.s.q.) from the total *electric supply* (e.s.) [11]. The former is defined as the total amount of electricity power sold or utilized at the market during the corresponding hour-period and bidding region (i.e. measured by the electrical energy meters in the power system) whereas the latter is the total amount of electricity supplied to the market at the same hour-period and bidding region [11]. In other words, the electrical energy line loss is defined as:

$$\begin{gathered} \Delta A_{i,t} = A_{i,t}^{e.s.} - A_{i,t}^{p.s.q.} \\ \forall i = SE1 - SE4 \quad \& \quad \forall t = 1, ..., 24 \end{gathered} \tag{2.3}$$

where $A_{i,t}^{e.s.}$ is the *electrical supply* and $A_{i,t}^{p.s.q.}$ the *power sales quantity* [11] for each hour-period t. The *electrical supply* is defined in [11] as:

[1]Impedance is related to ambient temperature

$$A_{i,t}^{e.s.} = A_{i,t}^{e.p.} - A_{i,t}^{e.c.} - A_{i,t}^{out} + A_{i,t}^{in} \qquad \forall i = SE1 - SE4 \quad \& \quad \forall t = 1, ..., 24, , \tag{2.4}$$

where $A_{i,t}^{e.p.}$ is the total electrical energy generation of internal power plants, $A_{i,t}^{e.c.}$ the total electrical energy demand of these power plants, $A_{i,t}^{out}$ the total electrical export to adjacent bidding regions and $A_{i,t}^{in}$ is the electrical import form adjacent bidding regions [11] for each bidding region i and for each-hour period t. Thus, according to (2.4), the electrical energy transmission line loss would depend on the total amount of generation and demand in each bidding region and resulting transit power flows with adjacent regions.

However, the electrical line losses defined in (2.3) does not necessary cover the total electrical line loss. As mentioned previously, there exist other types of line loss such as corona loss and leakage loss which are not included in the above expression. Moreover, it is also possible to decompose transmission line losses between *no-load losses* and *load losses* which is a common practice for losses within electrical power appliances such as electrical machines and transformers [24]. *No-load loss* describes the losses caused when keeping voltages and appliances without an attached load in operation. *Load loss* on the other hand consequently stand for loss directly caused by the attached load. The no-load losses are often smaller than the load losses which the line loss expression in (2.3) refers to.

2.2.2 Line Loss Rates

There exist a direct relationship between the *electrical supply* and the *power sales quantity* with the resulting electrical line loss. This relationship is known as *line loss rate*, $\lambda(\%)$ which is defined in [11] as:

$$\lambda_{i,t} = \frac{A_{i,t}^{e.s.} - A_{i,t}^{p.s.q.}}{A_{i,t}^{e.s.}} \cdot 100\% \qquad \forall i = SE1 - SE4 \quad \& \quad \forall t = 1, ..., 24 \tag{2.5}$$

Hence, theoretically with the electrical energy line loss defined in (2.2) and corresponding line loss rate defined in (2.5) the line losses can be calculated directly from the following formula:

$$\Delta A_{i,t} = \lambda_{i,t} \cdot A_{i,t}^{e.s.} \qquad \forall i = SE1 - SE4 \quad \& \quad \forall t = 1, ..., 24 \tag{2.6}$$

The line loss rate makes it possible to construct a another formula for calculation the electrical line loss (2.7) where $B_{i,t}$ is the fixed no-load loss $[Wh]$ and $C_{i,t}$ the load loss rate $[\frac{1}{Wh}]$ which is related to the square of variable electrical supply $[Wh^2]$ [24]:

$$\begin{gathered}\Delta A_{i,t} = B_{i,t} + C_{i,t} \cdot A_{i,t}^{e.s.\,2} \\ \forall i = SE1 - SE4 \quad \& \quad t = 1, ..., 24,\end{gathered} \tag{2.7}$$

This approach is quite similar to the classical B-coefficient method which derives the line losses from second order function of the generated power transmitted in the lines (2.8). A complete explanation and derivation of the B-coefficient method is given in [25].

$$\begin{gathered}P_{L_{i,t}} = B_{0_{i,t}} + B_{1_{i,t}} \cdot P_{G_{i,t}} + B_{2_{i,t}} \cdot P_{G_{i,t}}^2 \\ \forall i \in SE1 - SE4 \quad \& \quad t = 1, ..., 24\end{gathered} \tag{2.8}$$

The line loss rate is a formidable factor when predicting line losses from given sets of electrical supply and demand. Three main parameters that affect the line loss rate are the expected *average power factor* , *load factor* and *minimum load rate* [11]. The *average power factor* $(p.f.)$ catch the ratio between active and reactive power flowing in the power system. According to [11] it is recommended to account for the reactive flows when determining the active power loss. The *load factor* $(l.f.)$ and *minimum load rate* $(m.l.r.)$ is the defined as the ratio between the average load to the maximum load and the minimum load to maximum load during the measuring period respectively. These two parameters reflects the utilization rate of the power system [11] which could affect the line loss rate and consequently the total line loss.

2.3 Common Prediction Strategies

Developed prediction strategies for power system application has gathered more and more interest the last few years. There exist several studies on line loss prediction models [1, 8, 12, 13] and the European Commission has recently charged the European TSOs to design and develop new prediction models on both net-positions and exchange flows [26]. The most common prediction strategies together with related mathematical theory are described in this section.

2.3.1 Prediction on Line Losses

Before, line losses were simply regarded as an extra load and suppliers were asked to increase their planned generation by a certain percentage to account for the total system loss [6, 7]. With the deregulation of electricity markets, it has become more important to know where the losses occur in the grid [6, 7] to be able to include these in the trading mechanism and ensure an economical efficient operation of power systems [4, 10]. The most common approaches has either been based on proportional techniques [4, 12], analytical load flow computations [6, 7, 8, 10] or statistical methods [1, 2, 13].

Research on line loss allocation problems have derived multitude of different models on how line losses depend on the power system topology and resulting power flows.

A common approach is to allocate line losses proportional to each generation and load bus depending on their amount of power transmitted or utilized [4, 7, 12]. This approach require predictions of the proportion rate connected to the amount of power that has been transmitted to/from each generation/load point. Different methods such as proportional sharing and incremental transmission loss techniques has been proposed and analysed further in [12]. These methods have though been criticized in later studies due to their linear approximation of line losses and simplification regarding network topology [6, 8]. Instead, other studies suggest that line losses should be derived from power flow equations and proven line loss computation formulas such as (2.1) and (2.8) [6, 8, 10]. Alternatively from defining losses by linear proportion constants researches in [6] suggest that the quadratic relationship between line losses and transmitted power proven in theory should be taken into account. Another study point out that DC-flow simplifications, such as applied in [7], should be avoided and replaced with AC power flow equations [10]. Furthermore, a recent study suggest that line loss allocation also should take loss composition such as no-load losses into consideration [8]. The accuracy of such methods seems to be coherent with the actual losses derived from succeeding measurements [6, 8, 10].

Although, another popular method is to derive line loss coefficients statistically rather than analytically from power flow equations and nodal computation. Studies from Malaysia [1] has shown that previous applied techniques, such as proportional sharing, could be improved by regression and least square methods. The idea is to regard the line loss rates as changeable learning coefficients which could be derived from historical data. The same study also suggests that different ranges of power flow should be applied in the sample selection to achieve a more accurate result [1]. Another study from 2013 even states that their strict multiple linear regression strategy achieves better result than comparable methods applied in industry [13]. Studies from China also propose multiple linear regression methods to derive line loss rates [2]. The authors also support the claim that previous research have paid to much attention on theoretical calculation of line losses and welcome further studies on short-term forecasts on line loss rates. Different research teams worldwide have recognised the value of line loss rates and started to apply Neural Network techniques to increase the accuracy in the aforementioned regression models [3, 9, 27]. The advantage with this approach is that the linear regression models depict the non-linear dependency of line losses without having to set up a complete set of load flow equations.

Linear Regression

The linear regression method is a common tool to study the relationship between different variables. The main idea is to construct a model which defines a linear relationship between a variable of interest and one or more possible covariates which the concerning variable may relate to [28]. The multiple linear regression model map several covariate variables to a single dependent variable:

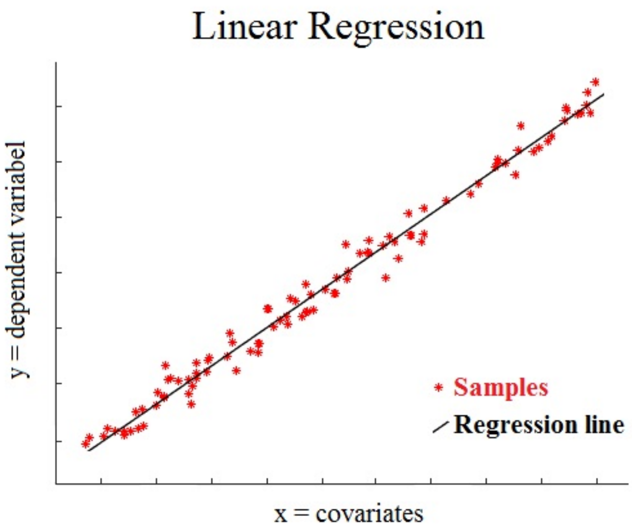

Figure 2.5: A graphical representation on how regression can fit a linear equation to a number of samples.

$$y = f(x_1, x_2, ..., x_K) + \epsilon = x_1\beta_1 + x_2\beta_2 + ... + x_K\beta_K + \epsilon, \tag{2.9}$$

where y is the dependent variable, x_1 to x_K the assumed covariates, β_1 to β_K the regression factors and ϵ random disturbances. The amount of covariates and related regression factors is determined by the designer. Although, the linear regression model is limited in its applications due to its assumption that a linear relationship exists between the dependent variable and the identified covariates. The covariates are in their turn assumed to be linearly independent among each other and the disturbance parameter (ϵ) [28].

After the regression model is designed, the goal is to determine the regression factors $\beta_1 - \beta_K$ in (2.9). With estimated values on these parameters a new equation is given which with other values on the covariates $x_1 - x_K$ could produce a mathematical prediction of the dependent variable, y. Figure 2.5 shows a single-variate example on a regression line is given from a selected sets of samples on covariates, x, and dependent variables, y.

The most common method to estimate these values is through least-square estimation [29]. The idea is simply to find combination of parameters that construct a line which fits a given set of N data points. Hence, this is the same as finding a line which has the smallest squared residual between the measured values (covariates) and model values (resulting data points) [29]. This action is the same by solving the least square normal equation:

$$\begin{aligned} XB &= Y, \\ X^T XB &= X^T Y, \\ B &= (X^T X)^{-1} X^T Y, \end{aligned} \tag{2.10}$$

where B is $N \times 1$ vector of estimates on the regression factors β in (2.9), X is a $N \times K$ matrix of explanatory variables (with X^T as the transpose matrix of X) and Y is the $N \times 1$ vector of dependent variables. Hence, with previous data samples of X and Y together with the condition that $(X^T X)$ is invertible the regression factors can be given which ensure the smallest sum of squared residuals [29].

2.3.2 Prediction on Net-position

Prediction on net-positions is generally about forecasting the electrical demand and supply which are decided by the actions at the electricity market. The market price in each bidding area derives a certain electrical demand which either is supplied by own generation and/or export from adjacent regions. This means that a certain non-zero net-position is derived in every bidding area. Thus, the electricity price determines where the generation will take place and how it is going to be distributed through the grid to cover the demand in every region. The main tool for these kind of computations are EUPHEMIA, Pan-European Hybrid Electricity Market Integration Algorithm, which are managed by the European Power Exchanges (EPXs) [30]. Hence, EUPHEMIA derives both net-positions for each bidding area as well as exchange flows between these areas. However, the data required for these simulations are unknown for prediction purposes and other methods are thus needed.

Some insights on the future electrical supply and demand are handed out by Nord Pool which already provides productions and consumption prognosis for each bidding area. These estimations is often derived from received production and consumption plans which the balance responsible parties have given to their respective TSOs. However, the actual turnout from these plans may vary during the day [31, 32] and the most recent plans are not always available for the TSO in time for certain calculations and analysis measures. A common approach to solve these situations today is the Last Comparable Day (LCD) method where hourly net-positions for a previous day is set as a reference value for the hourly net-positions for the forecasting day. This approach is however also imprecise since net-positions have been proved to vary notable from day to day [31]. There is an ongoing net-position project at the moment among the Nordic TSOs - on the basis on the aforementioned European Union (EU) regulation - with the aim to come up with a more developed net-position prediction strategy.

Last Comparable Day

The Last Comparable Day (LCD) method is a common estimation strategy within industry to gain a first idea on how a parameter will change depending on what type of day it is during the week. The method is generally applied as a base case estimation for further computations, for instance for NTC derivations [31]. Table 2.1 shows that the forecasting day "D" is assumed to have some connection to the conditions that happened on the day before yesterday "D-2". Mondays to Fridays are simulated as the most recent comparable weekday (D-2) whereas Saturdays and Sundays are simulated as the most recent weekend (D-7). Since data is only available for the day before yesterday it implies that Monday and Tuesdays have to be simulated as the last Friday (thus D-3 and D-4 respectively) [31].

Table 2.1: Last Comparable Day [31]

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
D-3	D-4	D-2	D-2	D-2	D-7	D-7

2.3.3 Prediction on Exchange Flows

Exchange flows are generally determined by the conditions of the electricity market which depends on network capacity limits and market price. The goal is to find the optimal flows which guarantee maximum social welfare (the total market value derived from the aggregated demand and supply curves) which fulfil the power balance in each area and capacity constraints on the inter-connections [30]. The strategy is to first establish and connect a limited number of bidding areas with inter-connectors with predetermined Available Transfer Capacities (ATCs).The ATCs decides how much power that can be transmitted on each line. The task is then to determine the amount of energy to be generated and allocate the resulting power flows which will cover the load in each area at a minimum cost. Thus, the electricity price will, in theory, determine how the power will flow on the inter-connectors. Thus, the objective is to solve an optimisation problem with predefined constraints which for instance could be solved by linear programming.[2]

The ATC-model or the increasingly more popular Flow Based (FB) model are two main methods which tries to allocate exchange flows [31, 32]. With given prices and net-positions for each area the ATC-model approach optimises the exchange flows to ensure that both the power balance is kept for each hour and that the energy flows from high price to low price. Thus, the ATC-model approach derives the exchange flows between different bidding areas from a given set of prices and power balance and transmission constraints. The FB-model approach has started to gain more attention compared to the ATC-model which is the most common method applied among TSOs [31, 32]. The FB-model approach takes certain network constraints and line characteristics into account which ensures that the power flow will follow

[2]The optimisation problem defined in EUPHEMIA is of course more complicated and applies more advanced computational methods. These, however, is outside the scope of this thesis and the interested reader is directed to [30].

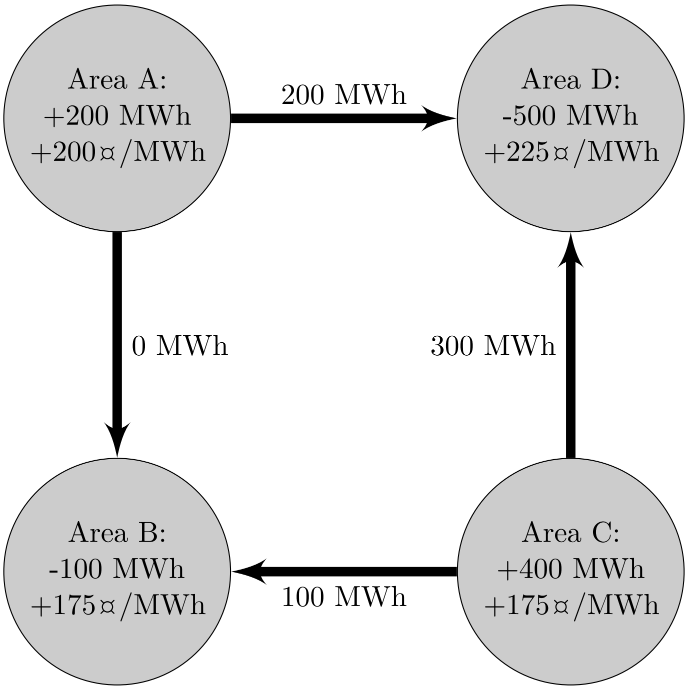

Figure 2.6: Schematic overview of the ATC-model.

the path with least resistance. The market turnout will thus be more likely to be allocated in concordance with real the physical flows [31, 32].[3]

Figure 2.6 shows an example on the ATC-model with four bidding areas (A,B,C,D). Each area has a predefined net-positions in which area D and B has a deficit of energy. The remaining areas have managed to increase their supply according to the figure and are able to supply the deficit areas with adequate energy. The four areas have also different electricity prices (¤/MWh). Financial, it is unprofitable for areas to sell energy to areas where the price (¤/MWh) is lower. Thus, area A only sell there excess energy to area D whereas area C sell there excess energy to both B and D.

Linear Programming

Linear Programming (LP) is about deriving an optimal solution to a given problem. The goal is to find the minimum or maximum turnout from a specified relation at a given sets of constraints and conditions. Linear Programming assumes that these objective functions, constraints and conditions are linear which will ease the

[3]The ATC-method and FB-method are two interesting computation methods which deserves a longer presentation than has been provided in this section. The basis behind both of these models, however, functions as an inspiration to the derived method applied in this thesis. The interested reader is nonetheless directed to [31, 32] for more details.

computation effort and design complexity. Although, even if power systems equations general are non-linear, LP has been proven to be accurate enough and thus frequently used for power system applications [33].

An optimisation problem is about deriving certain optimisation variables in order to minimize or maximize a given objective function with subject to certain constraints. A linear objective function with O number of optimisations variables and C number of constraints is general defined as:

$$\begin{aligned} \max_{z} \quad or \quad \min_{z} \quad & \sum_{o=1}^{O}(\xi_o \cdot z_o) \\ \text{subject to} \quad & \boldsymbol{A_{eq}} \boldsymbol{z} = \boldsymbol{B_{eq}} \\ & \underline{\boldsymbol{Z}} \leq \boldsymbol{z} \leq \overline{\boldsymbol{Z}}, \end{aligned} \tag{2.11}$$

where $\xi_{1,..,O}$ is objective function parameters related to the optimisation variables $z_{1,..,O}$. The $\boldsymbol{A_{eq}}$ is the coupling matrix $(O \times C)$ related to the optimisation variable vector $\boldsymbol{z}$ $(O \times 1)$ and equal constraint vector $\boldsymbol{B_{eq}}$. Additional inequality and/or boundary constraints can also be given where $\underline{\mathbf{Z}}$ $(O \times 1)$ and $\overline{\mathbf{Z}}$ $(O \times 1)$ states the minimum and maximum allowed boundaries [18].

2.4 Prediction Strategy at Svenska kraftnät

Line loss prediction at Svk is made by the Grid Supervisor (GS) who conducts a forecast based on previous experience. The GS starts by selection of one or several historical days - where the hourly losses for each bidding area are known - as reference. The task is then to adjust these values in order to match the following day. The GS selects certain parameters which is likely to influence the line losses and examines how these parameters vary between the reference and prognosis day. A different GS might make another approximation but each GS follows in general the same procedure and consider the following five aspects: Time variation, day of the week, weather condition, generation composition and expected network topology. Although, even if the GS is experienced it is still a challenge to foretell how much the line losses will vary from day to day with respect to these parameters.

2.4.1 The Grid Supervisor Approach

Time variation

The GS takes into account the fact that line losses will vary in the same way as demand and generation varies during the day. It is well known that the daily demand change throughout the day related to general activities in society. The demand usually follows an predictable demand curve with higher demand during morning and afternoon hours and lower demand during evening and night hours. Figure 2.7 shows a typical demand curve with 24 hour forecast and measured values

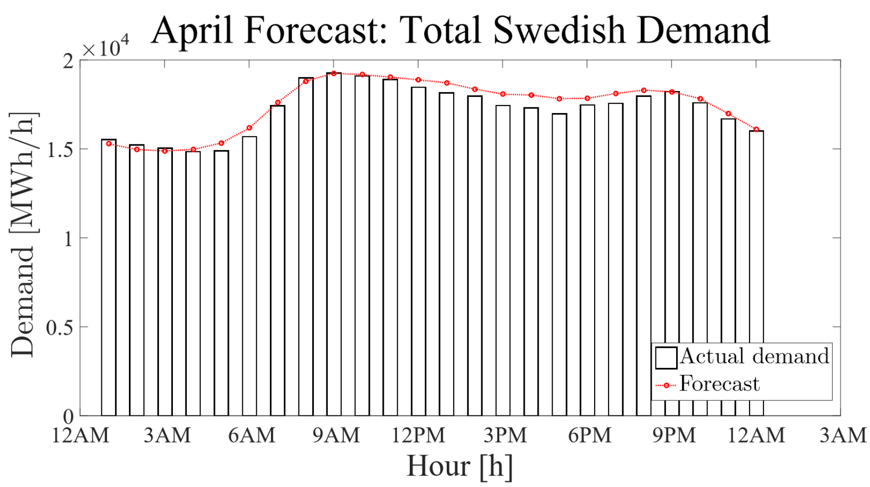

Figure 2.7: Forecast and actual values for total demand in Sweden for the 1^{st} of April, 2015. Data: Nord Pool

for the first of April, 2015. Other time variations such as seasons differences could also affect the line losses which the GS keep in mind.

Day of the week

The GS select reference days which is expected to have the most similar demand curve with the predicted one. The demand curve described above may vary in shape between weekdays and weekends where other social activities are more common. Holidays, vacation periods and special events might also inflict a distinct difference from the typical demand curve and thus affect the overall losses.

Weather condition

The demand curve is also highly related to the outside temperature since colder days require more energy and consequently induce higher losses than warmer ones. It is also known that the ambient temperature is related to power line characteristics, such as resistance, where higher temperature theoretically would increase the resistance and thus the line losses. Another weather dependent factor is the risk of dusts and storms which could increase the risk of line faults and consequently the resulting line losses.

Generation composition

Wind power prognosis and planned nuclear generation are important factor's which the GS takes into account. Where the generation takes place determines how far, and at what voltage level, the power will be transmitted in the power system. Since both farther distances (which is direct proportional to the line resistance) and lower voltage is equipped with larger losses this could be a vital parameter to take into consideration. Centralized power stations - such as large hydro and nuclear power - might have larger distances to the closest load points whereas distributed power sources such as wind power might be closer connected.

Network topology

The GS also have to predict line losses in an interchangeable network topology. Regular grid maintenance will inevitable put some overhead lines, power stations and load points out of operation from time to time. This alters the overall network topology which in some cases might cause power to be transmitted longer distances through the transmission grid (i.e. higher losses) to reach the awaiting end-users. The GS have to keep this in mind and also be aware that introduction of new lines, load and power stations could affect the final line losses.

2.4.2 Line Loss Measurements

Svenska kraftnät predicts the line losses against a certain reference value which is derived from different metering stations in the power system. This reference value is defined as measured value or actual value and is regarded by Svk to be the most accurate estimate on the actual line losses during each trading period. The measured values are typical derived by the line loss relation stated by (2.3)-(2.4) in 2.2.1. Data on required inputs are given by measured data on the hourly energy volume that is entering and leaving a predefined network area which each grid owner is committed to provide. This data is specific for certain network areas and is compared and corrected against the measured quantities in the adjacent network areas to guarantee that the exchange flows between these areas have been measured in the same way. If not, certain corrections are made to ensure that the provided results are as accurate and precise as possible. The line losses are computed by the simulation tools SPICA and GENERIS and uploaded at first in real-time and around one week after the operating day when corrections has been made. These are the final line loss values which the TSO are charged to predict and every prediction error relates to this data.

2.4.3 Line Loss Prediction Error

Certain mismatch between measured and predicted line losses is inevitable and occur for all hours and bidding areas. It is rare to achieve 100% correct predictions and each forecast is therefore either overestimated or underestimated in relation to the measured line losses. Table 2.2 shows the annual average between measured and predicted line losses from January 2013 to December 2015. During this period, the GS predicted line losses to 3 048 000 $\frac{MWh}{year}$ on average whereas the measured line losses computed to 3 033 000 $\frac{MWh}{year}$ on average. Although, the accumulative overestimations during the same period was 389 000 $\frac{MWh}{year}$ on average. During the same period, the GS underestimated the line losses with -373 000 $\frac{MWh}{year}$ on average. The total over- and underestimations almost cancel each other out which explains why the total total values between predicted and measured line losses match quite well. Around 25% of the annual predicted line losses had to be regulated either due to under- or overestimations which is a substantial amount. The annual average for each bidding area can be witnessed in table 2.2 as well[4].

Table 2.2: Average Historical Losses 2013-2015. Data: Svenska kraftnät, 2013-2015

	SE1 $[\frac{MWh}{year}]$	SE2 $[\frac{MWh}{year}]$	SE3 $[\frac{MWh}{year}]$	SE4 $[\frac{MWh}{year}]$	Tot $[\frac{MWh}{year}]$
Measured Losses	363 000	1 139 000	1 288 000	243 000	3 033 000
Predicted Losses	360 000	1 108 000	1 318 000	262 000	3 048 000
Overestimation	+61 000	+144 000	+132 000	+51 000	+389 000
Underestimation	-63 000	-175 000	-104 000	-31 000	-373 000
Absolute mismatch	124 000	319 000	236 000	82 000	762 000

The combined prediction error cause an additional cost on between 20-30 million SEK to the total line loss cost per year. This constitutes on around 1-2% of the total cost on around 1.5 billion SEK per year. The regulation of line losses contributes only a small portion to the total cost but would still be best avoided. The cost for these regulations is decided by the up- or down regulating prices at the balancing market. This is a rather complicated matter which requires an example to explain. If the TSO has overestimated the line losses the TSO has to sell the excess of energy either at the Elspot price or at a lower down-regulating price. In the opposite situation the TSO is forced to buy additional energy to cover for their deficit either at the Elspot price or at an even higher up-regulating price. Nonetheless, both situations will cause an additional expense which only could be reduced by lowering the amount of mismatch in each situation.[5] Thus, it is complicated to foretell exactly what the cost will be and which kind of mismatch (under- or overestimation) that implies the highest regulation costs. However, it is likely that the cost is proportional to the size of the prediction error and when lowered would reduce the cost in a similar way.

[4]The table values do not necessarily add up due to average computations.

[5]This procedure depends if a two price system or a single price system is applied at the balancing market. For a single price system the same price will be applied for both these cases decided by whether the power system as a whole find itself in either up- or down-regulation. Thus, if the system requires up-regulation, a higher price is awarded to participants with surplus of energy which consequently makes a profit on their own mismatch. On the other hand, the participants with deficit of energy would make an even bigger loss than with the two-price system case.

Chapter 3

Method Approach and Model Design

This chapter presents the suggested new line loss prediction approach which has been developed and evaluated in this thesis. This chapter also goes through the different stages required for the final line loss prediction.

3.1 Main Method Approach

The reason why it is difficult to achieve accurate predictions is directly related to the high level of uncertainties and versatility connected with line losses. There exist several factors, everything from power grid quantities and weather conditions to economical realities and random deviations, that in one way or another all influence the final line losses. Moreover, these parameters also depends on a multitude of variables connected to large scale systems and remains unknown for the GS and or predictor when the forecast on line losses has to be made. Thus, simplifications and limitations are vital in order to make any forecast even possible to commit.

Line losses could either be derived from strict physical relationships concerning voltage, current, impedance and frequency quantities or through a top-down perspective with focus on total electrical supply and line loss rates. The former approach derives the line losses from power flow equations and Newton-Raphson techniques whereas the latter approach applies linear regression methods and least square estimations and derives the line losses from statistical data. The losses could also be derived as the measured values are computed as the difference between in- and outgoing energy flows. However, all of these methods require forecast data on specific and detailed parameters which are complicated to predict. The in- and outgoing energy flows would be difficult to forecast for each specific connection line and the power flow equations approach requires detailed forecasts on a multitude of variables which together would inflict high uncertainties in the final results. The linear regression approach on the other hand requires a smaller quantity of input data which therefore has been evaluated to be a valid and reasonable approach in this thesis.

The goal with the chosen approach is thus to derive the resulting line losses from area specific demand, supply and exchange flows through a linear regression model design. The idea is in some parts similar to the approach applied by the GS and could therefore benefit from the existing experience at Svk. Furthermore, the method is intuitively a less complicated approach, than what a power flow equation strategy would be, which might save both time and effort while retrieving a similar result. The chosen approach has also shown promising results in other studies as mentioned in 2.3.1 which supports the application of the same method approach in this thesis as well.

However, the linear regression model was not the first design target but rather a result from several different model approaches on how to predict line losses. The first model targets were then analysed and evaluated continuously throughout the project concerning their performance which gave suggestions on adjustment to consider for the next version. Thus, the resulting model was designed following an iterative process where the flaws and strength from the preceding models were considered. This model approach gave a well-defined structure on how to practically come up with a suitable and applicable design.

3.1.1 Line Loss Prediction Model

The line losses have been defined through a linear regression model where the line losses are explained by covariates, linear regression factors and random deviations. With inspiration from (2.3)-(2.4) it is known that both the total electric generation, export/import with adjacent regions and final demand influence the losses. It is also known from the B-coefficient method and (2.8) that the transmitted energy has a squared relationship. Moreover, it is also valid to add a constant no-load factor to these parameters to mimic the general line loss composition stated in theory. This leads on to the following line loss regression model:

$$\begin{aligned} P_{L_{i,t}} = B_{No-load_{i,t}} + \sum_{g=1}^{G}(\beta_{i,t}^{s,g} \cdot S_{g,i,t}) + \sum_{l=1}^{L}(\beta_{i,t}^{d,l} \cdot D_{l,i,t}) + ... \\ \sum_{c=1}^{C}(\beta_{i,t}^{e,c} \cdot E_{c,i,t}^{2}) \quad \forall i = SE1 - SE4 \quad \& \quad \forall t = 1, ..., 24, \end{aligned} \tag{3.1}$$

where:

- $P_{L_{i,t}}$ - Active line loss for each bidding area (i) and hour (t)
- $B_{No-load}$ - Constant no-load coefficient for each bidding area (i) and hour (t)

- $S_{g,i,t}$ - Total supply of each generation source (g) [1] in each bidding area (i) and hour (t)
- $D_{l,i,t}$ - Total demand at each load point (l) in each bidding area (i) and hour (t)
- $E_{c,i,t}$ - Total exchange flow at each regional connection (c) in each bidding area (i) and hour (t)[2]
- $\beta^{s,g}_{i,t}, \beta^{d,l}_{i,t}, \beta^{e,c}_{i,t}$ - Regression factors for supply (s), demand (d) and exchange (e) parameters for each bidding area (i) and hour (t)

The model design in (3.1) states the general form where any number of generation sources (g), load points (l) and connections (c) are possible to include. In order to identify the best combination of covariates several case studies have been performed where different numbers and combinations of covariates are applied and tested. Thus, in order to derive the line losses on the left hand side in (3.1) one must forecast the parameters on the right hand side in (3.1). However, several of these variables are unknown for the GS at the time of prediction which require additional forecast data on these parameters. In this model this refers to forecasts on demand, supply and exchange flows and possible separated regarding type of load, energy source and inter-connector. Data on some of these forecasts are already available at Nord Pool which uploads forecasts on hourly total demand, total supply and wind generation the next day for each bidding area, SE1-SE4. However, since Svk has to report line losses before the market turnout has been decided at the day-Ahead market no forecasts on exchange flows between bidding areas are available. It is therefore necessary to develop an additional forecast model on exchange flows.

3.1.2 Exchange Flow Prediction Model

It is not a secret that predictions on exchange flows are a complicated task. A first forecast model has though been designed with inspiration from the principles behind the ATC-model described in 2.3.3. The ATC model shows that it is possible to extract future exchange flows between bidding areas if net-positions and electricity prices for each bidding area is given. The task is to optimise the exchange flows to achieve maximal social welfare (as described in 2.3.3) while the power balance in each area and transmission constraints on each connection link are met. The forecast model on exchange flows in this thesis has been designed to derive these estimates in a similar way. The optimisation problem focuses on the exchange flows related to and from the Swedish bidding areas but adjacent Nordic bidding areas have been included as well in order to increase the model similarity with reality.

[1] Sweden has general four different kind of generation sources: hydro, nuclear, conventional heat and wind power

[2] Line losses have shown squared-relationship with transmitted power

Additional export/import flows with the surrounding European continent are also included for the same reason. More information on this model are described in 3.3.3.

Linear programming is chosen as the main computational method since it is a common technique in solving these kinds of optimisation problems. The chosen model approach is motivated from its similarities with the ATC-method and the EUPHEMIA computations which are also based on an optimisation set up. The goal with the designed exchange flow model is also to identify how difficult it is to predict exchange flows at the moment and whether the suggested approach would be a valid computational strategy or not. Moreover, since the model requires forecasts on net-position and estimates/assumptions on the electricity prices the next day for each concerned bidding area, additional forecast on these parameters are also needed.

3.1.3 Net-position Prediction Model

The suggested exchange flow model is dependent on net-position data, i.e. demand and supply prognosis, for the neighbouring bidding areas in both Sweden, Norway, Denmark and Finland. Unfortunately, Nord Pool does not provide complete prognosis data on supply and/or demand data for the last three countries before the line loss prediction have to be made and thus cannot be applied in the exchange flow model. An additional forecast model on net-positions for Norway, Denmark and Finland is therefore required. A common forecast technique for certain demand and supply levels has been the Last Comparable Day (LCD) method in which the upcoming day is forecast from a similar reference day. The goal is thus to identify certain reference hours from past days that have a certain feature in common with the corresponding hour during the forecast day. Net-position forecasts in this thesis has been based on this method together with advice received from the ongoing net-position project among the Nordic TSOs. The same LCD method is also applied for a simple estimation on the electricity prices the next day which the exchange flow model also requires. A more advance price forecast model lies outside the scope of this thesis. More information on this model are described in 3.3.2.

3.2 Data and Scenarios

The above three models form together the complete line loss prediction model design proposed in this thesis. The exchange flow and net-position model are added since required input data are not known at the time of prediction. However, if these data could be extracted elsewhere or from other forecast models there would be no reason to go through these steps (unless the above developed models would provide more accurate forecasts). However, the above reasoning leads to the fact that different line loss predictions are dependent on the data quality that is supplied to the model. It is therefore possible to evaluate the model performance applying different sets of data. This would not always be a feasible case in reality since the data required are provided either before or after the time of prediction. Table 3.1 shows at what time Nord Pool provides forecast data on wind, supply, demand and exchange flows which in some cases could be utilized and in some cases not. However, in a research point of view, it would be interesting to analyse what level of accuracy is obtained if the quality of input data increases.

Table 3.1: Time schedule on when different type of data is available.

Time	**Type of Data**	**Forecast / Measurement**	**Bidding Area**	**Source**
The day-Ahead	**Elspot opens**			
	Wind	Forecast	SE1-SE4	Nord Pool
08:00-10:00	Supply	Forecast	SE1-SE4	Nord Pool
	Demand	Forecast	SEtot, NOtot, DK1-DK2	Nord Pool
09:00-10:00	Line Losses	Forecast	SE1-SE4	Svk
10:00	**Typical latest time of line loss prediction**			
11:00-12:00	Wind	Forecast	DK1-DK2	Nord Pool
	Demand	Forecast	FI	Nord Pool
12:00	**Elspot closes**			
13:30-14:00	Exchange Flows	Forecast	All Connections	Nord Pool
	Elspot Prices	Actual	All bidding areas	Nord Pool
14:00	**Elbas opens**			
17:00-20:00	Supply	Forecast	NO1-NO5,DK1-DK2,FI	Nord Pool
Operating day	**Time of operation**			
The Day-After	Wind	Measurement	All Nordic Areas	Nord Pool
	Supply	Measurement	All Nordic Areas	Nord Pool
	Demand	Measurement	All Nordic Areas	Nord Pool
	Line Losses	Measurement	SE1-SE4	Svk

3.2.1 Comments on Scenarios

The line loss model is tested applying three different sets of data, following the above discussion. The first dataset includes only the information given before the time of prediction which means that both Nordic net-positions and exchange flows has to be estimated by the corresponding models. The second dataset simulates a scenario in which Svk would be allowed to adjust their line loss prediction at Elbas. In this case the exchange flow prediction given by Nord Pool would be available which means that both the net-position and exchange flow model is bypassed. The third dataset evaluates the line loss prediction model if the forecast data would be equal to the actual measured quantity received the day after. This is of course non-realistic case but would foretell how much the line loss predictions would improve if the uncertainties in the input data is reduced. However, since this thesis has also examined possible model strategies to predict net-positions and exchange flows, these two models need to be evaluated separately as well. These models will be simulated with two different kind of input data and compared against the forecast data provided by Nord Pool. All of these datasets and scenarios will be presented in more detail in the succeeding case studies.

3.2.2 Comments on Data

The main sources of data applied in this project are retrieved from Svk and Nord Pool. However, it is known that all forecast and measured values are affected by stochastic variations and uncertainties. The line losses measured by Svk and the forecast and measured data on wind, supply, demand and exchange flows by Nord Pool are by no means an exception to this rule. The forecast data from Nord Pool is though judged to be the most reliable data source regarding market data for the Swedish and Nordic Power System. However, the reader should be aware that the data on exchange flows not necessarily correspond to the actual physical flow in the transmission grid. The reason to this is that Nord Pool only takes into account the derived flows at the Elspot and Elbas market. The physical flow however would also consist of bilateral trades outside the Nord Pool market and energy flows caused by frequency and power balance regulation at the balancing market. This type of additional exchange flows are not included in Nord Pool data which explains possible difference against the physical energy flow.

The measured line losses by Svk are also regarded to be the most accurate line loss data available. However, an alternative to this would be to compute the line losses separately by the given data from Nord Pool and the line loss relation given in (2.3)-(2.4) in 2.2.1. Since total supply, demand and exchange flows to adjacent areas are known from Nord Pool it would theoretically be possible to extract the line losses as the difference between in- and outgoing energy flows. The advantage with this alternative is that the same source of data is utilized for each parameter in the line loss model, in this case Nord Pool. However, this procedure is not possible to commit due to the fact that the Nord Pool data is not 100% accurate. Since Nord Pool does not include the exchange flows caused by frequency and power balance regulations the real physical flow within the grid are not measured. Moreover, it is also likely that the reported line losses from Svk are included in the Nord Pool data as extra demand (since Svk trade losses at the Nord Pool day-Ahead market) which definitely would affect the computation in (2.3). The line loss data from Svk is therefore the only reliable estimate on the actual line losses and has therefore been utilized in this report as well.

3.3 Main Model Design

The complete line loss prediction model includes several stages as described in figure 3.1. Each stage require specific forecast data which the model has to retrieve from

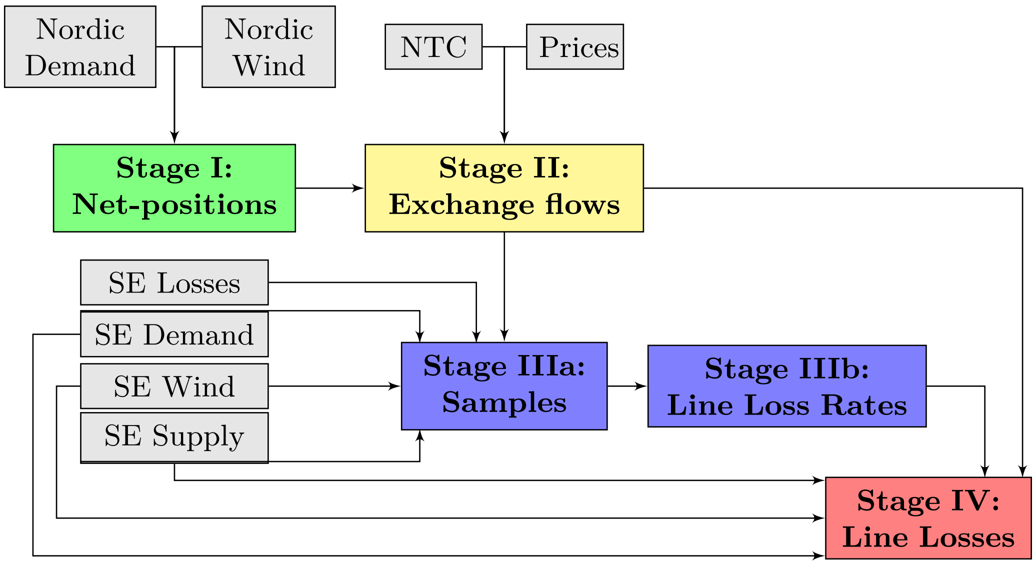

Figure 3.1: Model Overview: Stage I, II, III and IV.

external sources. The model starts by extracting available prognosis and measured data from 2013-2016 regarding supply, demand, wind and exchange flows. The data utilized in this paper is based on measured and predicted data from Nord Pool as well as statistics from Svenska kraftnät. Due to different data format between these sources some adjustment has been required in order to fill up missing data spots and adjust for daylight saving time. Moreover, the data is restructured per hour and type-of-day in order to catch relations between line losses and time variations. The model rearrange and acquire the required input data which either is available from the start or has to be estimated by the model itself.

The first stage of the model conduct net-positions forecasts for the Nordic areas which are required for the preceding optimisation model on exchange flows which is the second stage. These two stages require additional forecasts data on Nordic demand and wind generation together with NTC and assumptions on future prices. The resulting predictions, alongside extracted historical data from the Swedish areas, is sampled and added to the third stage of the model where the line loss rates computation through least square estimation takes place. The fourth and final stage of the model computes the resulting line losses with available forecasts on wind, demand, supply and exchange flows for the Swedish bidding areas. The model design has been conducted in *Matlab* with the extension package *Optimisation toolbox* to solve the LP problem.

- **Stage 1:** Estimate net-positions for NO, DK and FI for further computations on exchange flows to the Swedish bidding areas.
- **Stage 2:** Derive estimates on future exchange flows through linear program-

ming of a simple optimisation design.

- **Stage 3a:** The first step is selection of samples for further computations depending on different selections criteria.
- **Stage 3b:** Derive line loss rates, i.e. regression factors, for each bidding area and hour from historical samples.
- **Stage 4:** Compute the line loss prediction with the extracted line loss rates and available/estimated forecasts on required input data.

3.3.1 General Assumptions

The mindful reader notice that the prediction strategy put forward in this paper is a simplified model of how line losses technically occur and behave in power systems. First of all, all dynamic variations due to frequencies and time variations have been left out in order to reduce the model's complexity. Reactive line losses, which could influence the active line losses, are for the same reason not applied here. Furthermore, (3.1) derives the line losses as a whole and make no extinction between resistive heat, corona and/or leakage losses. The network topology for each bidding area have also been simplified and do not take into account different voltage levels nor differences between AC and HVDC techniques. Impacts in line losses from network topology changes due to regular maintenance are instead presented by variations in the line loss rates.

3.3.2 Stage I - Net-position Forecast

Net-positions for SE1-SE4 is required for the linear regression model which fortunately is available at Nord Pool at time of prediction. These forecasts are derived directly from consumption and production plans given from the TSOs. However, net-positions for the remaining Nordic area (which is needed for the exchange flows computation) is provided first after the line loss prediction has to be made. Thus, the goal with this stage of the model is not to estimate the net-positions for SE1 to SE4 but for the remaining Nordic areas to apply as input data to the preceding exchange flow model.

After guidance and advice from the ongoing net-position studies conducted by Svenska kraftnät, Energinet.dk, Statnett and Fingrid, a net-position forecast model has been designed based on the LCD method with respect to net-demand. Net-demand is defined as demand minus non-controllable energy generation such as weather dependent wind and run-to-the-river hydro plants.[3] In this model, the net-demand is defined as demand minus wind power according to (3.2). The idea is then to identify historical reference hours with a similar net-demand as the forecasting day

[3]Nuclear power stations could also be seen as determined energy source since they often will generate according to there scheduled production plans to ensure high generation efficiency.

which thus requires prognosis data on demand and wind power generation for the next day. Then the model estimates the future net-positions from the net-position that occurred during the chosen reference days.

$$\begin{aligned} ND_{i,t} =& D_{i,t} - WG_{i,t} \\ \forall \quad i =& NO1 - NO5, DK1, DK2 \quad \& \quad FI \\ and \quad t =& 1, ..., 24, \end{aligned} \tag{3.2}$$

where:

- $ND_{i,t}$ - Net-demand defined as the difference between demand and wind power generation for each area (i) and hour (t)
- $D_{i,t}$ - Demand for each area (i) and hour (t)
- $WG_{i,t}$ - Wind Generation for each area (i) and hour (t)

In this model, the appropriate reference hours for net-position comparison are derived by allocating up to ten samples form the last 30 days with the least residual error in net-demand for all areas combined. The computation process is given in (3.3) where each prediction hour (t) ($t \in 00:00 - 24:00$) is given ten similar reference hours ($s \in 00:00 - 24:00$).

$$\begin{aligned} \Delta ND_{i,t,s} =& \sum_i (ND_{i,t} - ND_{i,s})^2 \\ \forall \quad i =& NO1 - NO5, DK1, DK2 \quad \& \quad FI \\ and \quad t =& 1, ..., 24 \\ and \quad s =& (1, ..., 24)_{1,...,30}, \end{aligned} \tag{3.3}$$

where:

- $\Delta ND_{i,t,s}$ - Difference in net-demand between forecasting hour (t) and sample hour (s) for each area (i)
- $ND_{i,s}$ - Net-demand for each area (i) and sample hour (s) from the last 30 days.

The ten historical samples with the smallest $\Delta ND_{i,t,s}$ is chosen as the resulting reference hours for net-positions comparison. The final net-positions for hour (t) is thus set to be equal to the average of the net-positions for the reference hours (r_t) (3.4). The resulting net-position for each area is then possible to adjust according to maximum export and import capacities given in each area.

$$
\begin{aligned}
\Delta NP_{i,t} = & \frac{\sum_{r_t=1}^{10} NP_{i,r_t}}{10} \\
\forall \quad i = & NO1 - NO5, DK1, DK2 \quad \& \quad FI \\
and \quad t = & 1, ..., 24 \\
and \quad r_t = & (1, ..., 10)_{(1,...,24)},
\end{aligned}
\tag{3.4}
$$

where:

- $NP_{i,t}$ - Estimated Net-positions for each area (i) and hour (t)
- NP_{i,r_t} - Net-demand for each area (i) and reference hour (r_t) for each hour (t)

However, while demand prognosis is provided by Nord Pool for the Norwegian and Danish area neither demand for FI nor wind power prognosis for DK1 and DK2 is given in time. Additional estimation and assumptions is therefore required for these parameters.

3.3.3 Stage II - Exchange Flow Forecast

The first exchange flow forecasts for the Swedish connection lines is only available after the market price is set according to the EUPHEMIA algorithm. However, since the line loss regression model requires certain estimates on expected exchange flows before that, own predictions is required. As been witnessed in literature this is not an easy task, especially not when the market price is unknown, and could be considered as a task for a separate master thesis in itself. Nevertheless, a simple exchange flow estimation approach is presented in this model in order to create a complete line loss prediction model.

The exchange flow model is based on an optimisation problem solved through linear programming. The idea is to maximise the profit received from all exchange transaction based on the previously estimated net-positions for the Nordic areas.[4] If the exchange flows are set as optimisation variables x and the price in each area is given as λ, the task is then to keep the relative cost on each transmission line to a minimum. The price difference between two areas will either oppose an relative cost or relative profit for suppliers which will mandate the flow to a specific direction.[5]

[4]This approach has been derived through inspiration from the ATC-model discussed in previous sections. Even though the Flow Based model also mentioned in previous sections is seemingly a more accurate approach than the ATC-method the latter is chosen since it requires less input data and thus easier to implement in this project.

[5]If the price at the receiving area is lower than the price at the sending area, then the transmission of energy on that line will become more costly since the suppliers would have been paid more if the energy had been sold and utilized in the sending area instead. If the opposite is true then transmission on the line will become profitable (i.e. negative cost) since the suppliers in the sending area will gain more money per MWh by selling the energy to the receiving area.

The following objective function is given in (3.5).

The idea behind this setting is that the model will optimise the exchange flow to the bidding areas with the largest price while keeping power balance in each area and obeying the capacity boundaries. However, since the net-positions is set in this problem it might happened that it is not possible to fulfil all the power balance constraints in every area. Hence, two more optimisation variable is set as the excess of energy per hour and deficit of energy per hour in each area to ensure a feasible solution to the problem. The optimisation variables brings an extra cost to the objective function which will keep the excess and deficit energy per hour variables to a minimum.

$$
\begin{aligned}
\min \quad & \sum_{c=1}^{C}((\lambda_{c,t,1} - \lambda_{c,t,2}) \cdot (x_{c,t}) + \lambda_{EE} \cdot EE_{i,t} + \lambda_{DE} \cdot DE_{i,t}) \\
\text{s.t.} \quad & A_{eq} \cdot X_t - EE_t + DE_t = -B_{eq,t} \\
& \underline{NTC_t} \leq X_t \leq \overline{NTC}_t
\end{aligned}
\tag{3.5}
$$

$$
\begin{aligned}
\forall i = \quad & SE1 - SE4, NO1 - NO5, DK1, DK2 \quad \& FI \\
c = \quad & 1, ..., 29 \qquad \text{and} \qquad t = \quad 1, ..., 24,
\end{aligned}
$$

where:

- $x_{c,t}$ - Exchange flows at connection (c) for every hour (t)
- $\lambda_{c,t,1}$ - The price in the default set sending bidding area for every connection (c) and hour (t)
- $\lambda_{c,t,2}$ - The price in the default set retrieving bidding area for every connection (c) and hour (t)
- λ_{EE} - A fictive penalty cost for any excess of energy in one area
- $EE_{i,t}$ - The amount of excess energy per hour for each area (i) and hour (t)
- λ_{DE} - A fictive penalty cost for any deficit of energy in one area
- $DE_{i,t}$ - The amount of deficit energy per hour for each area (i) and hour (t)
- A_{eq} - Coupling matrix (12×29) assigning which connections that are included in each bidding area.
- X_t - Exchange Flow vector $(29 \times t)$ for all connections for each hour (t)
- $B_{eq,t}$ - Net-position vector $(12 \times t)$ for all bidding areas for each hour (t)

- EE_t - The amount of excess energy not delivered $(12 \times t)$ for all bidding areas for each hour (t)
- DE_t - The amount of deficit energy not received $(12 \times t)$ for all bidding areas for each hour (t)
- $\underline{NTC_t}$ - The negative flow net transmission capacity limit $(29 \times t)$ for each connection line for each hour(t)
- $\overline{NTC_t}$ - The positive flow net transmission capacity limit $(29 \times t)$ for each connection line for each hour(t)

Figure 3.2 shows how the model is about to function on principle. The exchange flows to and from Sweden, Norway, Denmark and Finland are considered but also the biggest international exchange flows from these countries to the surrounding European continent. NO2 has one connection line to the Netherlands and Russia respectively whereas DK1 & DK2 have one connection line each to Germany. SE4 has in total three lines to Germany, Poland and Lithuania while FI is connected to Estonia and Russia. These six additional bidding areas are not included in the power balance constrains and would thus be able to transmit or receive as mush energy on each line as the capacity limit on each line allow for. The dedicated reader might note that the electricity prices for the additional European countries is unknown. The reason to this is that data historical data from neighbouring TSOs and EPXs has been hard to come by. For simplicity reasons these have been assumed to behave similar as the historical prices in the closet adjacent Nordic or Baltic areas.

The dedicated reader might notice that the a firm definition of exchange flow direction as either positive or negative is vital in order for the optimisation problem to function properly. Each derived exchange flow parameter can be either positive or negative. The direction of each exchange flow has been set as positive if sent from SE areas and negative if sent into these areas. Thus, as soon as the capacity limits and net-positions is given alongside assumptions on the future electricity price in each area the optimisation problem is set and ready to be solved.

3.3.4 Stage III - Line Loss Rates and Sample Selection

The line loss rates, (i.e. the regression factors) are the final parameter needed to estimated before the line losses can be derived. These factors are derived through least square estimations from historical data received from Nord Pool and Svk as well as own estimates derived from the previous model stages. However, the linear regression model as stated in (3.1) has been modified to be compatible with the available data and after separated test simulations. These simulations show that the no-load factor included in (3.1) and suggested in theory leads to less accurate predictions than without the same parameter. Keeping the squared relationship on the exchange flow parameters on the other hand seems to improve the results.

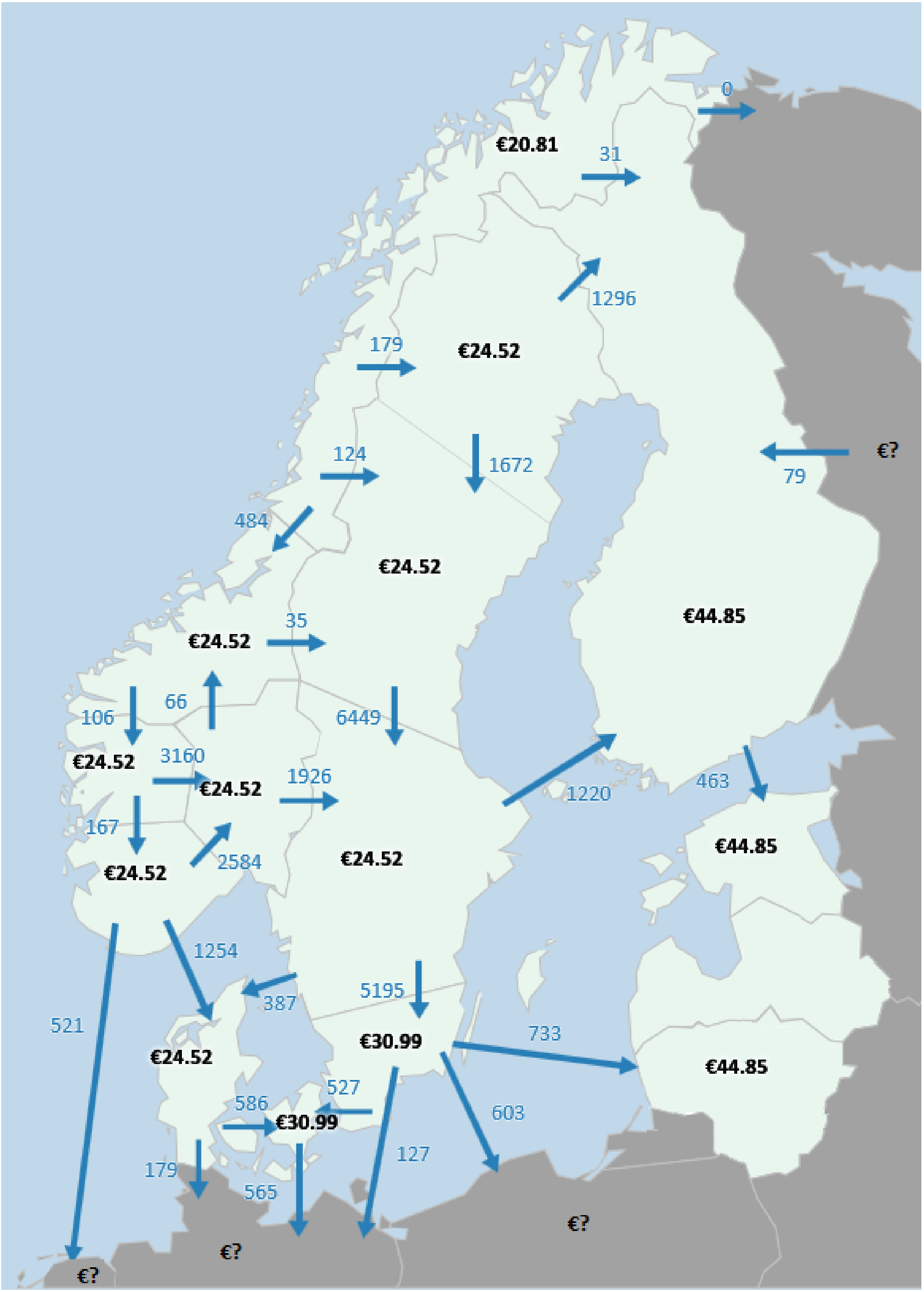

Figure 3.2: The LP model provides forecast on the exchange flows depicted above. Due to limited data on electricity prices in Netherlands, Germany, Poland and Russia certain assumptions on these prices had to be made. Source: Figure material from Svk, 2016

Moreover, due to limited prognosis data on the decompositions of supply and demand, just the total demand and supply level is included in the modified regression model together with wind generation forecasts given from the Nord Pool data base. Thus, the modified linear regression model concerning line loss is presented as:

$$\begin{aligned} P_{L_{i,t}} =& \beta^w_{i,t} \cdot W_{i,t} + \beta^s_{i,t} \cdot S_{i,t} + \beta^d_{i,t} \cdot D_{i,t} + \sum_{c=1}^{C} (\beta^e_{c,i,t} \cdot E^2_{c,i,t}) \\ \forall i =& SE1 - SE4 \qquad \text{and} \qquad \forall t = 1, ..., 24, \end{aligned} \tag{3.6}$$

where:

- $P_{L_{i,t}}$ - Active line loss for each bidding area (i) and hour (t)
- $W_{i,t}$ - Expected wind generation for each bidding area (i) and hour (t)
- $S_{i,t}$ - Expected total supply for each bidding area (i) and hour (t)
- $D_{i,t}$ - Expected total demand for each bidding area (i) and hour (t)
- $E_{c,i,t}$ - Expected exchange flow from each regional connection (c) to/from each bidding area (i) and hour (t)
- $\beta^w_{i,t}, \beta^s_{i,t}, \beta^d_{i,t}, \beta^e_{c,i,t}$ - Regression factors for wind (w), supply (s), demand (d) and exchange (e) parameters for each bidding area (i) and hour (t)

With the linear regression model design set, it is time to decide on how many and which kind of data points to apply in the preceding simulations. It is likely that a high number of samples would provide less biased line loss rates but might also reduce impacts caused by specific conditions. The total number of samples is also limited to the number of data points that are available which also motivates a strategic sample selection. The selection methods extract samples for the forecast day "D" which means that samples have to be withdrawn from the day before "D-1" going back one year. The latest samples available is given first at "D-7" where the measured line losses from Svk can be confirmed. Thus, each selection method can start to withdraw samples from "D-7". In this thesis, three different kinds of selections methods are taken into account: Weekday selection, season selection and prognosis selection.

- **Weekday selection:** Figure 3.3 shows how the selection method extracts samples which match the forecasting day. A Monday is thus simulated by samples from previously Mondays while a Saturday is simulated with samples from recent Saturdays.

- **Season selection:** Figure 3.4 shows that samples which are closest related in time to the forecasting date is selected in this case. Forecast dates in January are thus simulated with the most recent data points from the current and previous months.

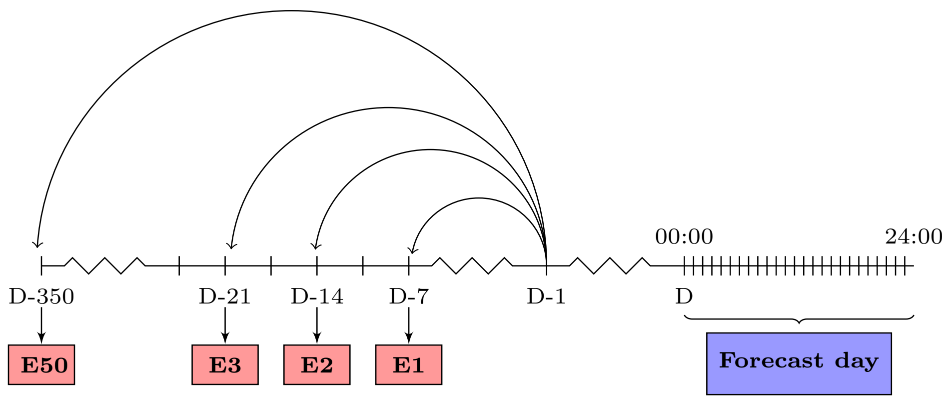

Figure 3.3: How 50 samples are retrieved by weekday selection.

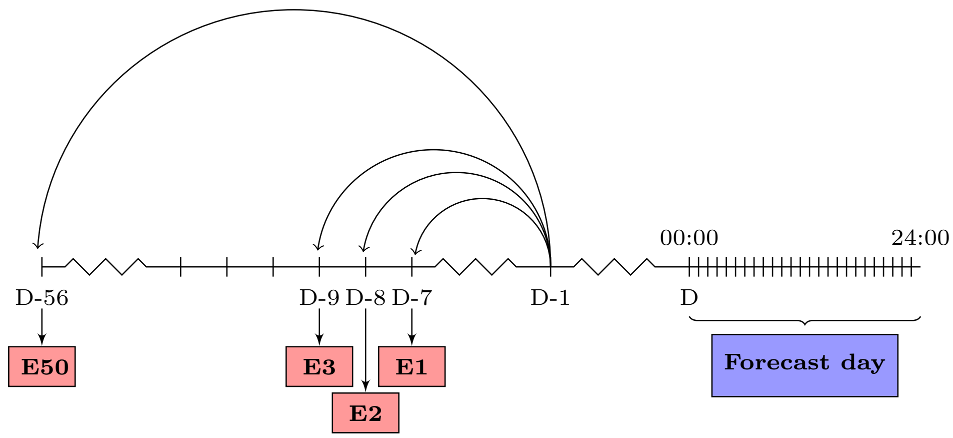

Figure 3.4: How 50 samples are retrieved by season selection.

- **Prognosis selection:** Figure 3.5 shows how the prognosis selection method withdraws samples which have similar ranges of wind generation, supply, demand and exchange flows as the forecasting day is expected to have. Prognosis data for each hour in the forecasting day is thus compared with historical data from the same hour. For instance, the seventh hour (T7) may find similar samples from the seventh hour in day "D-221" and "D-62".

The first selection method is inspired by the last comparable day method but is adjusted to account for the correct historical weekday. The season selection method extend the most recent selection range which might be able to catch seasonal variations in both weather, temperature and maintenance scheduling. However, this approach will not catch differences between weekdays and weekends as the first method would do. The third and final selection strategy is inspired by the load factor variable described in theory which gives a certain insight on how the grid is being utilized. This approach has also been proven effective in other studies

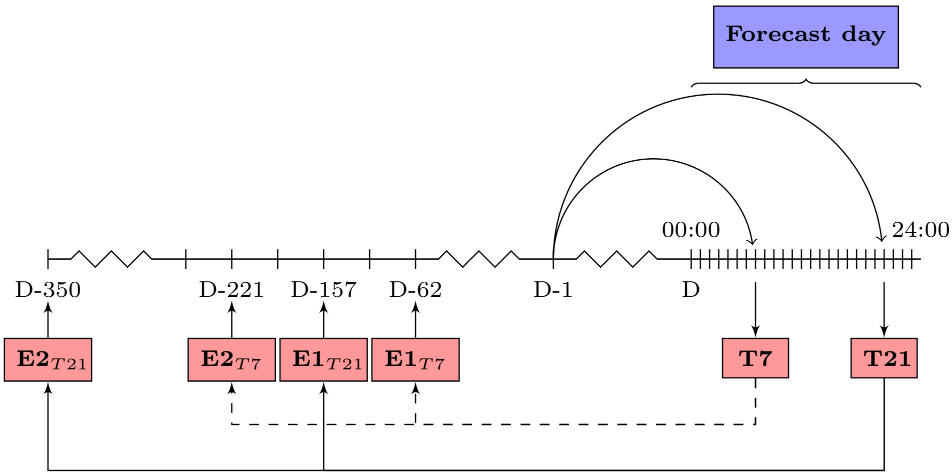

Figure 3.5: How 50 samples are retrieved by prognosis selection.

mentioned.[6] In practice, the demand, supply and exchange flows are portioned by percentage shares from 0 to 100% of maximum capacity. Samples which are within the same interval as the expected value for the forecasting day are then selected. Table 3.2 shows the interval range applied for each bidding area in this model.

Table 3.2: Prognosis selection range for each covariate.

Wind generation [MWh/h]	0 - 50 - 100% of maximum installed wind power
Supply [MWh/h]	0 - 25 - 50 - 75 - 100% of maximum installed capacity
Exchange flow [MWh/h]	0 - 33 - 66 - 100% of maximum NTC
Demand [MWh/h]	Interval on 1000 MWh/h from 0 to 20 000 MWh/h

3.3.5 Stage IV - Line Loss Forecast

With estimations on net-positions and exchange flows in the Nordic bidding areas together with the future line loss rates it is possible to derive the line losses through (3.6) in 3.3.4. The line loss derivation starts the day before the operating day where prognosis data and forecast estimations are performed for every hour during the forecast day. Then, the line loss rates are updated from historical data on the same parameters and applied for each hour and bidding area the upcoming day. The line loss prediction is thus given and the same procedure starts anew for the next day. This ensures that the line loss regression factors are continuously updated before the next prediction period. Moreover, the line losses could also be computed differently depending on the sample selection strategy applied in the line loss rate

[6] Studies in [1] have shown that percentage portioning on demand proved to be beneficial for the the linear regression results. This approach has therefore been tested in this thesis as well.

estimation. In the following case studies, the final line loss predicted is set as the average value derived by the three different sample strategies earlier mentioned: weekday, season and prognosis selection. The final line losses presented in this thesis is the mean value from these estimates as:

$$P_{L_{i,t}} = \frac{P_{Day_{i,t}} + P_{Season_{i,t}} + P_{Prognosis_{i,t}}}{3} \quad \forall i = SE1 - SE4 \quad and \quad \forall t = 1, ..., 24, \tag{3.7}$$

where:

- $P_{L_{i,t}}$ - Final active line loss for each bidding area (i) and hour (t)
- $P_{Day_{i,t}}$ - Active line losses for each bidding area (i) and hour (t) from weekday sample selection
- $P_{Season_{i,t}}$ - Active line losses for each bidding area (i) and hour (t) from season sample selection
- $P_{Prognosis_{i,t}}$ - Active line losses for each bidding area (i) and hour (t) from prognosis sample selection

However, in order to reduce the impact from extreme values the derived line loss forecast has been limited within a certain range. This range has been set to the historical maximum and minimum line losses spotted in the measured line loss data from the two previous years related to the forecasting period. However, some uncertainties have been spotted in the measured data from Svk. For instance has negative losses (i.e. generated energy) been spotted which of course must be caused by an erroneous computation. These kind of rare values have thus been adjusted in the model computation to 1 MWh/h to avoid unnecessary errors. However, due to the slight contingency in the derived measured line losses the line loss boundary has been set to be equal to the 1st and 99th percentile of the combined line losses from the last two previous years. The set limits for each bidding area can be seen in table 3.3.

Table 3.3: Line loss ranges derived from measured losses in 2013 and 2014. Data: Svenska kraftnät, 2016

	SE1 [MWh/h]	SE2 [MWh/h]	SE3 [MWh/h]	SE4 [MWh/h]
Maximum	109	323	267	66
Minimum	4	21	77	3

Chapter 4

Case Studies

This chapter presents three different case studies. The first case study provides the forecast results yielded regarding net-positions prediction for the Swedish, Norwegian, Danish and Finish bidding areas. The second case study provides the forecasts on exchange flows given from the derived net-positions in the previous chapter and certain assumptions on future electricity prices. This third and final case study presents the model results from the modelled line loss rates and resulting line losses.

4.1 Net-position Prediction

Estimation on net-positions is one of the objective goals in this thesis and needed for the exchange flows derivations connected to the Nordic bidding areas. Forecast on net-positions for SE1-SE4 is provided in time from Nord Pool and therefore not included in the model forecast. However, net-position for NO1-NO5, DK1, DK2 and FI requires separated simulations and is, in this model, determined through statistical relationship from known net-demand (see 3.3.2). Although, this data has also been limited which require further estimations on net-demand for the mentioned areas.

4.1.1 Defining Scenarios

In order to examine the quality on the achieved estimates as well as identifications on possible improvements, two scenarios with different sets of data has been performed for all 8760 hours in 2015. The final prognosis data from Nord Pool is also evaluated in this case study.

- **Dataset ND1:** The first simulation predicts the net-positions with data available between 9:00am-10:00am from Nord Pool. This means that demand and wind power prognosis for FI and DK1 & DK2 respectively are unknown.

- **Dataset ND2:** The second simulation forecast net-positions assuming that the prognosis on net-demand is given for all the Nordic areas. This means that the prognosis data for Finland and Denmark is given which otherwise is uploaded after 11:00am usually.

- **Nord Pool Prognosis:** The above two forecasts on net-positions are thereafter compared with the complete net-position forecast data from Nord Pool. This data is often not available for all areas until latest at 20:00pm.

These three forecasts are presented and examined for 2015 with respect to the mean absolute deviation from the average net-position value in [MW] and [%]. The simulations are also evaluated concerning their achieved correlation factor against the measured net-positions from Nord Pool. A positive correlation means that the estimated data change in the same direction as the measured data whereas a negative correlation tells that the opposite is true. A correlation factor closer to 1 or -1 tells that the match between the two parameters is strong whereas a correlation factor closer to zero tells that the correlation is weak. Note that forecast on net-position for SE1-SE4 is not included in the model forecast since corresponding prognosis data are available from Nord Pool.

4.1.2 Data and Assumptions

- The method approach assumes that there exist a correlation between net-demand, as defined in chapter 6, and net-position. This assumed correlation will however be tested in the proceeding simulations.
- Demand prognosis for Sweden and Norway is only given from Nord Pool for the country as a whole. Fortunately, the area specific demand is given at a later time which makes it possible to derive a reasonable percentage of share of the total demand to each area.
- Demand prognosis for FI is estimated utilizing the last comparable day method (see 3.3.2). Wind prognosis for DK1 & DK2 has been estimated to be equal with the wind conditions of previous day.[1] It is however possible that the GS could extract this data from elsewhere before the time of prediction and thus make these assumptions superfluous.
- The net-positions are derived by the combined least mismatch between the total net-demand for all areas to match a combined Nordic situation. Although, it could be argued that certain areas with high wind for instance have a lesser correlated behaviour which the computation method risk to miss.
- Data has been extracted from the Nord Pool database unless otherwise stated.

[1]This is of course a rather erroneously assumption since the wind conditions could differ immensely from day to day. However, due to lack of data some assumption is required which made this approach simple to adapt. The need of accurate wind forecasts for DK1 & DK2 is hopefully being recognized in the comparison between **Dataset ND1** and **Dataset ND2**.

Table 4.1: Scenario ND1: Net-positions accuracy 2015

	Mean absolute deviation [MWh/h]	Mean absolute deviation [%]	Correlation factor [()]
NO1	303	16.2%	(0.95)
NO2	809	38.6%	(0.64)
NO3	276	34.1%	(0.60)
NO4	266	54.3%	(0.50)
NO5	574	29.9%	(0.61)
DK1	472	70.0%	(0.29)
DK2	253	41.4%	(0.48)
FI	362	19.7%	(0.67)

4.1.3 Simulation Results for 2015

Scenario - Dataset ND1

- **Given data:** Demand prognosis for NO1-NO5 and DK1-DK2.
- **Unknown data:** Demand prognosis for FI and wind prognosis for DK1-DK2
- **Reference data:** Final measured quantities on demand and supply for all Nordic areas from Nord Pool.

Table 4.1 shows the results from the model forecast with dataset ND1. The results show that there exist a correlation between net-demand and net-positions, however, the connection is week (below 0.5) in certain bidding areas. The mean absolute deviation is also large in particular bidding areas (between 40-70%) which in total leads to quite inaccurate net-positions predictions in some cases.

Since this simulation can be computed before the time of line loss prediction, this is also the data applied for the following exchange flow studies where prognosis data on net-positions for SE1-SE4 from Nord Pool is included as well. To illustrate that case the total net-position for Sweden, Norway, Denmark and Finland are depicted in figures 4.1-4.4. The net-position forecast follows the measured values in size and catch certain season variations. However, the daily variation is huge, especially for Norway and Denmark, which blunder the overall expression. On the other hand, the Nord Pool prognosis for Sweden follows the measured data quite well which indicates that the prognosis data from Nord Pool is fairly accurate. Overall, it is obvious the applied net-positions for the following computations have potential of improvement.

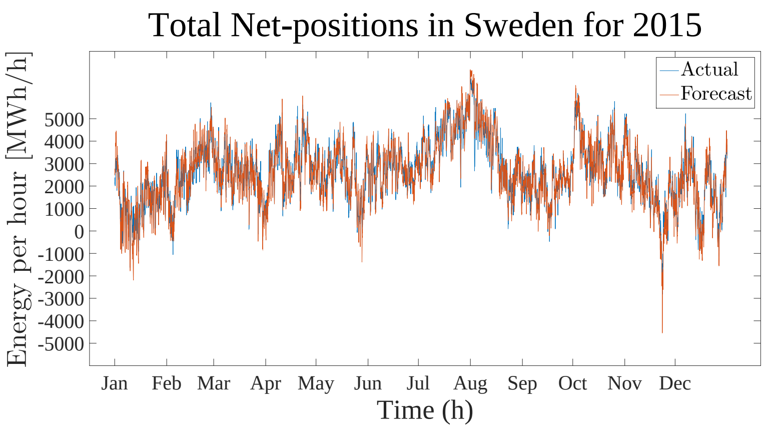

Figure 4.1: Forecast and measured net-positions in 2015 for SE.

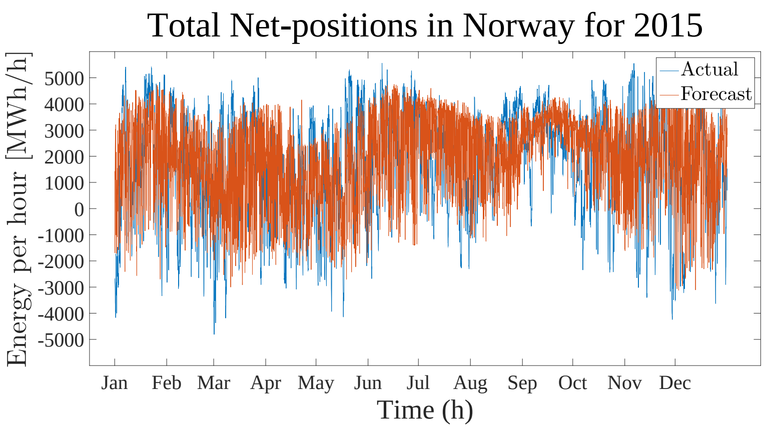

Figure 4.2: Forecast and measured net-positions in 2015 for NO.

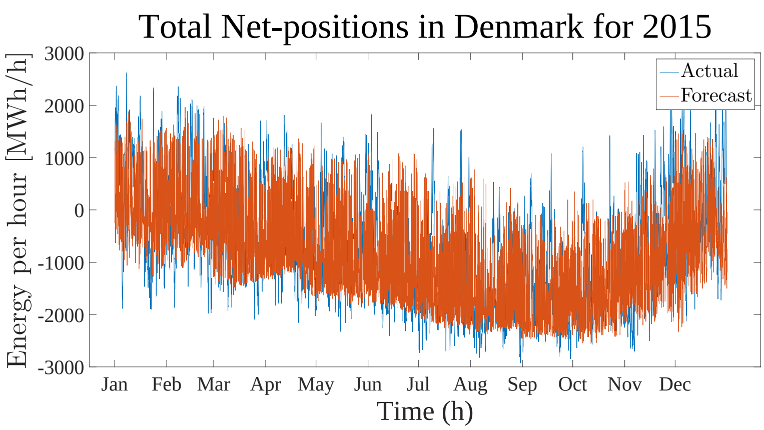

Figure 4.3: Forecast and measured net-positions in 2015 for DK.

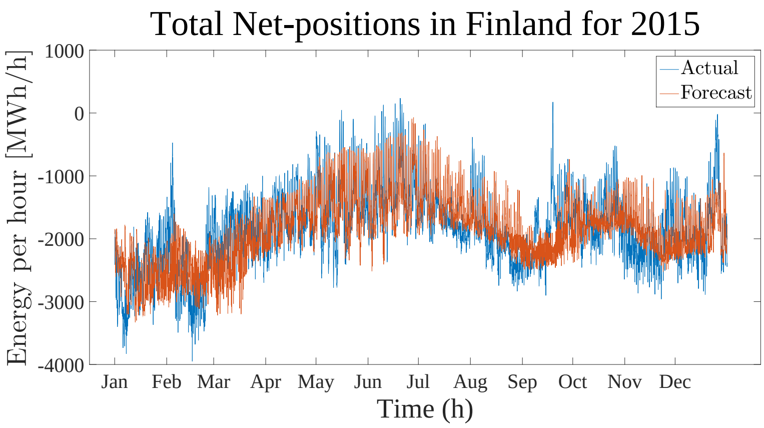

Figure 4.4: Forecast and measured net-positions in 2015 for FI.

Scenario - Dataset ND2

- **Given data:** Demand and wind prognosis for all Nordic areas (although neither Norway nor Finland has any wind power to be reckoned with).
- **Unknown data:** Supply data for Norway, Denmark and Finland.
- **Reference data:** Final measured quantities on demand and supply for all Nordic areas from Nord Pool.

Table 4.2 shows the results from the model forecast Dataset ND2. In this case, the net-positions become more accurate since both the mean absolute deviation reduced and the correlation factor increased overall. The correlation has in fact become substantially stronger in every bidding area. Although, NO2, NO4 and DK1 has still a considerably large percentage deviation between 28% to 43%.

Scenario - Nord Pool Prognosis

- **Given data:** Demand and supply prognosis for all Nordic areas from Nord Pool.
- **Reference data:** Final measured quantities on demand and supply for all Nordic areas from Nord Pool.

Table 4.3 shows the evaluation results from the forecast given by Nord Pool. Here, the results for SE1-SE4 are presented as well which shows that the correlation is reaching 0.96-0.99 with overall low mean absolute deviation (SE3 being one exception). The net-position predictions for both the Norwegian and Finish bidding areas become more precise compared with the previous two scenarios even though

Table 4.2: Scenario ND2: Net-positions accuracy 2015

	Mean absolute deviation [MWh/h]	Mean absolute deviation [%]	Correlation factor [()]
NO1	272	14.6%	(0.96)
NO2	587	28.0%	(0.82)
NO3	209	25.9%	(0.76)
NO4	210	42.9%	(0.74)
NO5	408	21.3%	(0.82)
DK1	230	33.7%	(0.92)
DK2	140	23.0%	(0.86)
FI	327	17.8%	(0.74)

the deviation actually become larger for NO1 compared with Dataset ND2. Moreover, the results in DK1 and DK2 also become less accurate. This, however, is probably explained by the fact that only wind generation seems to be included in the prognosis data for Denmark at first until heat power generation is taken into account later in 2015.

Table 4.3: Scenario PC plans: Net-positions accuracy 2015

	Mean absolute deviation [MWh/h]	Mean absolute deviation [%]	Correlation factor [()]
SE1	124	8.7%	(0.98)
SE2	142	3.9%	(0.99)
SE3	226	17.5%	(0.98)
SE4	126	7.1%	(0.96)
NO1	353	18.9%	(0.97)
NO2	163	7.8%	(0.99)
NO3	152	18.7%	(0.92)
NO4	138	28.2%	(0.94)
NO5	177	9.2%	(0.96)
DK1	434	63.4%	(0.56)
DK2	129	21.2%	(0.88)
FI	249	13.5%	(0.76)

4.1.4 Discussion on Results

The above simulations with dataset ND1 and ND2 - which provide different forecasts on net-positions for the Nordic bidding areas in 2015 - differ from the final measured values. The results show that the mean deviation is still quite large for Dataset ND1 and ND2 even though the deviation reduces some in the latter case. The correlation factor is also quite low in Dataset ND1 whereas the correlation is increased substantially in dataset ND2. The provided prognosis from Nord Pool on the other hand is unsurprisingly more accurate compared to the model forecasts. Both correlation factor and mean deviation is closer to the measured quantities. It is understandable that the results for DK1 is one exception since production plans for heat power generation seems to have been left out in Nord Pool's prognosis data. Although, it is fairly interesting to note that the prognosis data provided by Nord Pool might include certain errors and must be checked before utilized.

Nevertheless, the results from Dataset ND1 and ND2 manage to estimate net-positions within reasonable limits and correlated in a certain degree to the actual turnout. This shows that there might exist a correlation between the net-demand and net-position in one area. If forecasts on uncontrollable generation (i.e. wind power) and demand is given, it is likely that the remaining generation can be estimated by comparing against historical hours with similar net-demand. Hence, it might be worthwhile to elaborate further on this approach. For instance, more uncontrollable generation types such as run-to-the-river and nuclear plants (which may have decided on production plans over several days in advance) could be included in the net-demand derivation and thus reduce the uncertainty connected to the reaming energy supply. Moreover, the final net-positions computations, stated in (3.3) & (3.4), could also take into account the net-demand in adjacent regions while selecting the most similar reference hours for each bidding area.

Moreover, the results show that the model forecast could be considerably improved if wind and demand prognosis would be available from Denmark and Finland. The result also shows that the prognosis from Nord Pool, which are based on production and consumptions plans from the respective TSOs, are fairly accurate. The only issue is that this data is provided irregularly and not always in time to be of any use concerning line loss predictions. However, if these prognosis for NO1-NO5, DK1, DK2 and FI were to be provided at the same time as it is today for SE1-SE4, the net-position model in this thesis would not be needed for the following prediction computations on exchange flows and line losses.

4.2 Exchange Flow Prediction

Exchange flow prediction is also a separate objective goal in this thesis and a vital parameter for the succeeding line loss predictions. This thesis focus on the exchange flows to and from the Swedish bidding areas seen as a linear optimisation problem which allocates the exchange flows from given net-positions and prices for each area. Although, since price forecasts is outside the scope of this thesis, additional assumptions has to be made. Moreover, due to limited information on the conditions in the surrounding European countries (i.e. Netherlands (NEL), Germany (GE), Poland (PL) and Russia(RUS)) certain simplifications is needed there as well. Thus, the exchange flows derived from this model approach shall be seen as a first attempt on a possible strategies on how to predict future exchange flows.

4.2.1 Defining Scenarios

In order to evaluate the method approach, two simulation scenarios with different sets of data has been performed for all 8760 hours in 2015. These results are then compared with exchange flow prognosis provided by Nord Pool when the Elspot market turnout has been decided.

- **Dataset LP1:** The first simulation predicts the Nordic exchange flows with the data available from Nord Pool between 9:00am-10:00am. This means that forecasts on net-positions for NO1-NO5, DK1-DK2 and FI has to be estimated as Dataset ND1 in 4.1. Hourly prices for each area must also be estimated whereas the net transmission capacities for the next day and supply and demand prognosis for SE1-SE4 are given from Nord Pool.
- **Dataset LP2:** The second simulation predicts the Nordic exchange flows assuming that net-positions and prices for the next day are given. This is obvious not the case in reality but would give a fair indication whether or not the exchange flow model approach has been designed in a proper way.
- **Nord Pool Prognosis:** The above two forecasts on exchange flows are thereafter compared with the estimate made by Nord Pool after the Elspot market has been cleared. This data is first given for all inter-connectors between 13:30-14:00pm.

These three forecasts are presented and examined for each hour during 2015 in the same way as the preceding case study. Thus, both the mean absolute deviation from the measured exchange flow in [MWh/h] and [%] together with the correlation factor has been computed.

4.2.2 Data and Assumptions

- The method approach assumes that the exchange flows can be derived through linear programming in a similar manner as within the ATC-method. The achieved results will foretell if this method approach is more or less suitable for these kind of exchange predictions.
- The net transmission capacity limits have been assumed to be equal with the Elspot capacities provided by Nord Pool during the day-Ahead market period.

- Prices for each bidding area has been estimated utilizing the LCD method (see section 2.3.2). Thus, the hourly electricity price is assumed to be equal with previous prices the last comparable day. This is a rather rough assumption since the price could vary substantially between hours and days.[2]

- Historical prices for Netherlands, Germany, Poland and Russia has been limited and thus targeted for assumptions as well. For simplicity reasons, these countries has been given the same assumed future price as the closest most similar Nordic bidding area. The price in DK1 has thus been applied to both Germany and the Netherlands, the price in Lithuania has been applied to Poland and the price in Finland has been applied to Russia. The author is aware that these assumptions are rough, due to the fact that separate price forecasts once again lies outside the scope of this thesis.[3]

- Data has been extracted from the Nord Pool database unless otherwise stated.

4.2.3 Simulation Results for 2015

Scenario - Dataset LP1

- **Given data:** NP prognosis for SE1-SE4, future NTC and historical prices from Nord Pool.

- **Assumed data:** Future prices for each bidding area and NEL, GE, PL and RUS.

- **Modelled data:** Model forecast on Nordic net-positions according to Dataset ND1 in chapter 4.1.

- **Reference data:** Measured quantities on exchange flows from Nord Pool.

Table 4.4 shows the exchange flows for 13 inter-connectors connected to the Swedish areas.[4] The results shows that the exchange flows generally are either over- or underestimated compared to the measured values. The deviation can be as large as 20%-70% related to the mean absolute exchange flow. However, some exchange flows have a strong correlation with the measured flows. This fact concerns mainly the Swedish internal exchange flows as well as the flows to Germany and Poland.

[2]Although, since price forecasts is outside the scope of this thesis , a simple and quick assumption was necessary in order to make the optimisation problem solvable. Besides, since only the difference in price between two regions is of interest (relate to (3.5) in 3.3.3) it is not vital to estimate the prices exact as long as the sign of the price difference between regions is correct.

[3]It is likely that more sophisticated assumptions could be made with additional statistics data on how the European prices differ compared with adjacent Nordic areas. It is also possible that proper historical data could have been allocated with increased effort. Although, some assumption has to be made and the author saw it reasonable with a simple and quick estimation for model evaluation purposes.

[4]The other 16 exchange flows have been left out for increased readability since they do not take part in the following line loss prediction.

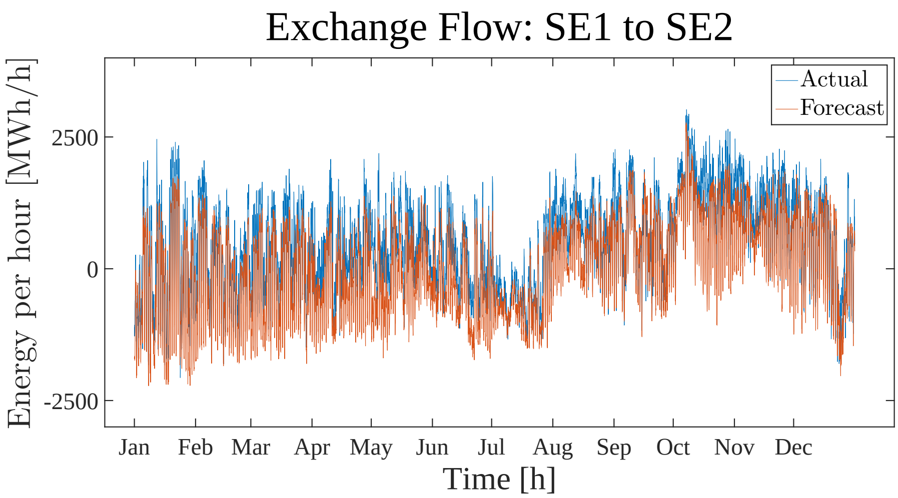

Figure 4.5: Exchange flow between SE1 to SE2.

The flows to and from Norway, Denmark and Finland on the other hand show a weaker correlation between (0.37-0.56) and general a higher mean absolute deviation (Finland being one exception).

Table 4.4: Dataset LP1: Exchange Flow accuracy 2015

	Mean absolute deviation [MWh/h]	Mean absolute deviation [%]	Correlation factor [()]
SE1>SE2	419	50%	(0.90)
SE1>NO4	151	70%	(0.50)
SE1>FI	312	32%	(0.56)
SE2>SE3	658	17%	(0.94)
SE2>NO3	201	57%	(0.53)
SE2>NO4	52	60%	(0.41)
SE3>SE4	698	24%	(0.71)
SE3>NO1	547	55%	(0.55)
SE3>DK1	200	55%	(0.52)
SE3>FI	253	25%	(0.41)
SE4>DK2	375	54%	(0.37)
SE4>DE	105	45%	(0.65)
SE4>PL	76	19%	(0.79)

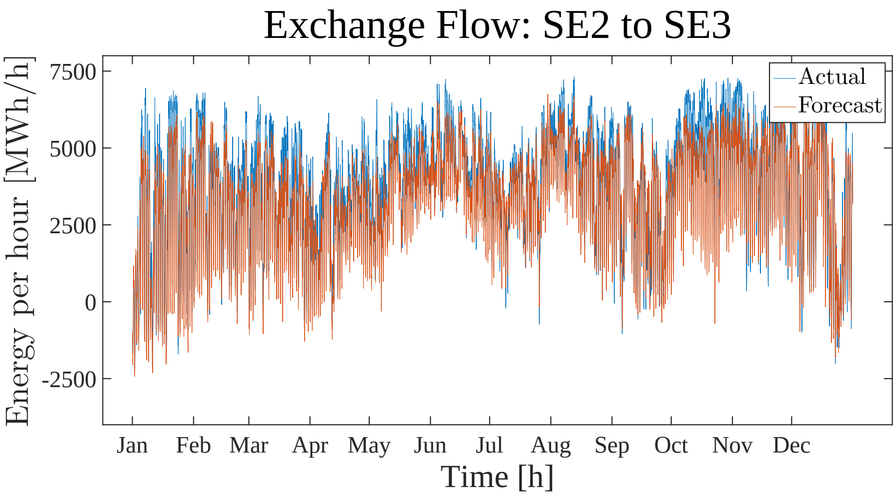

Figure 4.6: Exchange flow between SE2 to SE3.

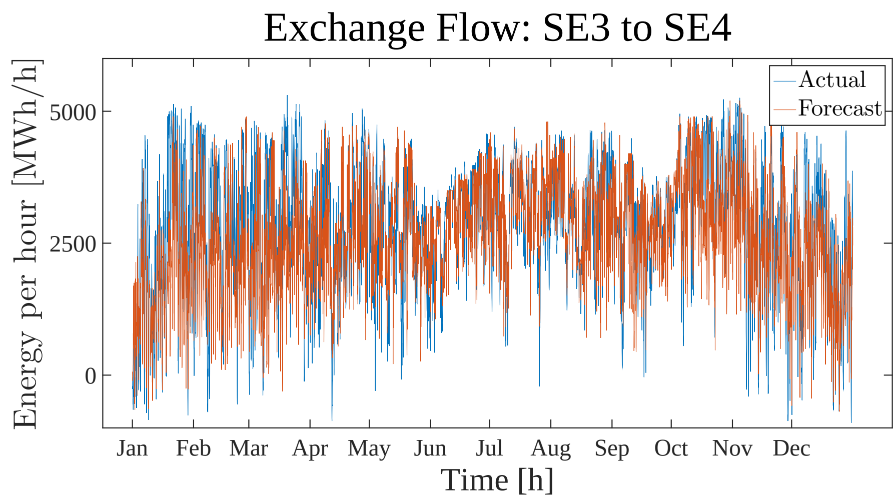

Figure 4.7: Exchange flow between SE3 to SE4.

The mentioned results are the earliest available forecast on exchange flows and thus applied in the following line loss prediction computations. Figure 4.5- 4.7 shows the achieved exchange flows for SE1 to SE2, SE2 to SE3 and SE3 to SE4 which illustrate the impact of high or low mean absolute deviation and strong or weak correlation. The first two figures show a strong correlation between the model forecast and the measured values. The two flows thus vary in a similar manner during the simulation period. Although, the forecast values either over- or underestimate the actual exchange flows which the mean absolute deviation also foretells. SE3 to SE4 has a lower correlation factor which also could be seen from figure 4.7. The other inter-connection links varies according to the result in table 4.4.

Scenario - Dataset LP2

- **Given data:** Measured data on NP, future NTC and actual prices for all Nordic and Baltic bidding areas from Nord Pool.
- **Assumed data:** Future prices for NEL, GE, PL and RUS.
- **Reference data:** Measured quantities on exchange flows from Nord Pool.

Table 4.5 shows the same exchange flows as the previous simulation derived with given values on net-position and hourly prices in the Nordic and Baltic bidding areas [5]. In this case, the mean deviation is improved slightly compared with the previous scenario whereas the correlation factor for every inter-connection links increases up to 0.70-0.99 compared with Scenario - Dataset LP1. The correlation is once again strong for the internal flows in Sweden which is also true for the export/import patterns from Norway.

Nord Pool Prognosis

- **Given data:** Exchange flow prognosis from Nord Pool.
- **Reference data:** Measured quantities on exchange flows from Nord Pool.

Table 4.6 shows the accuracy of the exchange flows estimated by Nord Pool after the market turnout has been cleared. These flows have therefore been derived by the actual trading results from the day-Ahead market (i.e. Elspot). Hence, these flows do not take into consideration changes that would occur on the intra-day market (i.e. Elbas) as well as additional changes derived from balancing market regulations. The absolute deviation from the mean measured flow in this scenario is therefore still significant, between 20-50% for some inter-connection points. The mean absolute deviation is on the other hand smaller compared with Dataset LP1 and LP2. The resulting flows are also strongly correlated with the measured flow for practically all inter-connector links.

[5] The price for the surrounding European countries is still assumed to be equal to the adjacent bidding area where the price is given

Table 4.5: Dataset LP2: Exchange Flows accuracy 2015

	Mean absolute deviation [MWh/h]	Mean absolute deviation [%]	Correlation factor [()]
SE1>SE2	384	46%	(0.96)
SE1>NO4	131	61%	(0.92)
SE1>FI	291	29%	(0.77)
SE2>SE3	472	12%	(0.99)
SE2>NO3	136	39%	(0.88)
SE2>NO4	40	47%	(0.81)
SE3>SE4	573	20%	(0.87)
SE3>NO1	412	41%	(0.81)
SE3>DK1	176	48%	(0.74)
SE3>FI	196	20%	(0.70)
SE4>DK2	326	47%	(0.63)
SE4>DE	104	44%	(0.77)
SE4>PL	75	18%	(0.81)

Table 4.6: Nord Pool Prognosis: Exchange Flow accuracy 2015

	Mean absolute deviation [MWh/h]	Mean absolute deviation [%]	Correlation factor [()]
SE1>SE2	298	36%	(0.93)
SE1>NO4	109	51%	(0.87)
SE1>FI	249	25%	(0.80)
SE2>SE3	331	9%	(0.98)
SE2>NO3	168	48%	(0.90)
SE2>NO4	51	59%	(0.82)
SE3>SE4	187	7%	(0.98)
SE3>NO1	214	21%	(0.96)
SE3>DK1	76	21%	(0.94)
SE3>FI	145	14%	(0.76)
SE4>DK2	157	22%	(0.95)
SE4>DE	12	5%	(0.99)
SE4>PL	58	14%	(0.84)

4.2.4 Discussion on Results

The simulation results for the described scenarios show that it is difficult to predict exchange flows the next day. The simulations derived by the developed exchange flow model, dataset LP1 and LP2, suffer from large deviation and occasional weak correlation compared to the measured values. Moreover, the model is also dependent on accurate forecasts on future net-positions and prices for the concerning bidding areas. The forecasts offered by Nord Pool also deviates significantly from the actual flow. This point out that the exchange flows derived at the day-Ahead market is only one portion of the actual flow. Thus in order to obtain even more accurate predictions on possible exchange flows, actions on the intra-day market and balancing market must also be taken into consideration.

However, even if perfect predictions are difficult to achieve, the exchange flow model shows that it is possible to derive exchange flow forecast which has some correlation with the actual flow. The internal flows in Sweden show especially strong correlation with the measured values and the result in Dataset LP2 suggest that higher quality on input data would provide a more precise forecast. In fact, LP2 forecast and Nord Pool prognosis are for some inter-connection links comparable which is interesting to note. The reader should keep in mind though that the data quality in the LP2 case would not be available for forecast computations in real life. However, the developed model do manage to solve the given optimisation problem and allocate exchange flows to the areas with highest price just as the model design intended.

Thus, the exchange flow model seems to be a valid design approach and further modelling could therefore be motivated. At first, in order to reduce the error caused by the price assumption, a separate price prediction model for all concerning areas would be recommended. One possible strategy might be to analyse historical aggregated supply and demand curves which could be adjusted according to the net-positions forecast. The future price could then be derived from where the new aggregated supply and demand curves meet. Secondly, it might be worthwhile to incorporate certain model features developed in the aforementioned Flow Based model in which the network impedance is taken into account. It is possible that these approach would be more aligned with the actual physical flows since network conditions are included apart from economical factors.

4.3 Line Loss Prediction

The main goal with this thesis has been to derive line loss predictions for SE1-SE4 and hour. With forecast data on net-positions and exchange flows available it is now possible to derive a first line loss prediction. In order to evaluate the line loss prediction model, line loss predictions has been computed retroactively for 2015 and then later compared against the GS prediction to determine if the model manage to increase the precision and reduce the total prediction error or not. In this case study, the model predicts line losses for the 1st of January 2015 and continue, day by day, until the 31st of December 2015.

The estimated line loss rate for each day is derived by linear regression of 50 samples selected from the past 365 days from the operating day [6]. The sample period is thus updated whenever the prediction advance to the next day. This is performed three times, one for each sample selection strategy presented in 3.3.4. Note that certain sample selection strategies, such as weekday selection, would extract samples which cover multiple seasons whereas the season selection would just look back the last two months/eight weeks.

Another vital question to ask is whether historical forecast or historical measured data should be applied in the line loss rate estimation. Since the future line losses will be computed by forecast data, it would make more sense to apply historical forecast data in the line loss rate derivation as well. The reason is that any standard error for wind, supply, demand or exchange flows forecast might be adjusted by the regression factors if these were derived by the same data historically. The regression factors would then be designed to derive line losses from the same data source that is applied for the future line loss prediction. Thus, model forecasts on net-positions and exchange flows has to be computed for 2014 as well to be available for the line loss rate calculation.

4.3.1 Defining Scenarios

As been mentioned in **??**, three sets of data will be applied to the model in the following simulations. The reason is to evaluate the improvement rate if higher quality data on forecasts would be available at the time of prediction:

- **Dataset A:** The first simulation predicts the line losses with prognosis data from Nord Pool on demand, supply and wind generation together with model's own derived forecasts on exchange flows.

- **Dataset B:** The second simulation predicts the line losses with prognosis data from Nord Pool on wind generation, demand, supply and estimated exchange flows from the day-Ahead market.

- **Dataset C:** The third simulation predicts the line losses assuming that measured data from Nord Pool on demand, supply, wind generation and exchange flows would be available.

[6] Since the line losses from Svk are given first a week after the operating day there is a gap between the operating day and the most recent historical sample possible to extract.

All three of these datasets are evaluated compared with the reported line loss forecast derived from the GS approach. Both of these line loss forecasts are related to the measured quantity in percentage. A line loss prediction on 100% indicates that the specific prediction match the actual measurement fully whereas a prediction on $< 100\%$ or $> 100\%$ either under- or overestimate the line loss value for that hour. Both the accuracy and precision together with total reduction in line loss mismatch between measured and predicted values is examined for all three datasets. The accuracy states how close the mean value is to 100% whereas the precision describes how large the spread is among the separate predictions. The latter is usually measured by the variance of a given sets of data points which is defined as the square of the standard deviation.

4.3.2 Data and Assumptions

- The line losses are computed through (3.7) with different sets of line loss rates. These line loss rates have been derived from (3.6) by least square estimation from three different sample selections criteria with a total of 50 samples each.
- The measured line loss from Svk is assumed to be given one week after they have occurred. The most recent historical sample is thus extracted one week before the forecasting day.
- The actual line losses are computed by different metering stations in the transmission grid and given by Svk.
- In order to avoid extreme values, the resulting line loss predictions have been limited to a certain range derived from historical line losses in 2013 and 2014. The 1st and 99th percentile of the historical losses conducts the minimum and maximum range of the forecast losses to be kept within. The reason for adjusting the maximum and minimum ranges to these percentile marks is due to the fact that some rare measured line loss values have been identified in the given line loss data from Svk. This approach avoids the most rare data points while ensuring that the forecast losses are kept within reasonable limits.

4.3.3 Simulation Results for 2015

Accuracy and Variance

Table 4.7 and table 4.8 shows the accuracy and precision between the GS approach and the three mentioned datasets. The accuracy in dataset A is worse for SE1 and SE3, higher degree of overestimation, while the accuracy increases for both SE2 and SE4 (i.e. closer to 100% in expected mean value). The model accuracy approaches the target on 100% for both datasets B and C but the predictions are still slightly overestimated in both SE1 and SE3. The precision, measured as variance (the spread of predictions), is on the other hand substantially reduced in all areas compared to the GS approach (the variance in SE1 is just slightly reduced). SE1 and SE4, the two smaller areas regarding load and losses, show a larger variance compared to SE2 and SE3, even for dataset C. The reason to this might be that the line loss value in MWh/h is smaller in SE1 and SE4 than SE2 and SE3. This means that the same prediction in MWh/h would become a larger relative error which might explain why the variance is comparably higher for SE1 and SE4.

Table 4.7: Model Accuracy for 2015

	SE1	SE2	SE3	SE4
GS Estimate	116	106	108	122
Dataset A	119	104	111	108
Dataset B	112	102	109	102
Dataset C	106	101	109	101

Table 4.8: Model Precision for 2015

	SE1	SE2	SE3	SE4
GS Estimate	4917	2082	716	7081
Dataset A	4874	570	480	3341
Dataset B	3058	386	294	1487
Dataset C	1290	211	236	986

These results could also be presented as box-and-whisker plots which illustrate the given line loss predictions from smallest to largest within five specific ranges. The idea is to give an increased understanding of how the accuracy of the prediction is reduced between the GS approach and Dataset A,B and C. The following box-and-whisker plots show the line loss predictions density with the median value in the middle, the interquartile range marked with a box and the lower and higher whisker at ± 1.5 times the interquartile range (around 2.7 times the standard deviation). Line loss predictions outside these ranges are defined as outliers which have been neglected in the following graphs to increase readability.

Figures 4.8-4.11 show the achieved accuracy and precision for each forecast case for each area SE1-SE4 respectively. The figures foretell that the line loss prediction is getting closer to the targeted 100% line which implies that the prediction error is reduced. Dataset A manage to reduce the spread of predictions for all areas where the main achievement can be found for SE2 and SE4. Dataset B reduces the spread even further just as dataset C. The reader should be aware that these plots are hard to compare directly with the given variance, since certain outliers (extreme values) have been neglected in these plots. Further studies on these outliers foretell that a few measurements in SE4 are far of percentage wise (not necessarily the same counting MWh/h instead) which could be the reason why the variance is high for

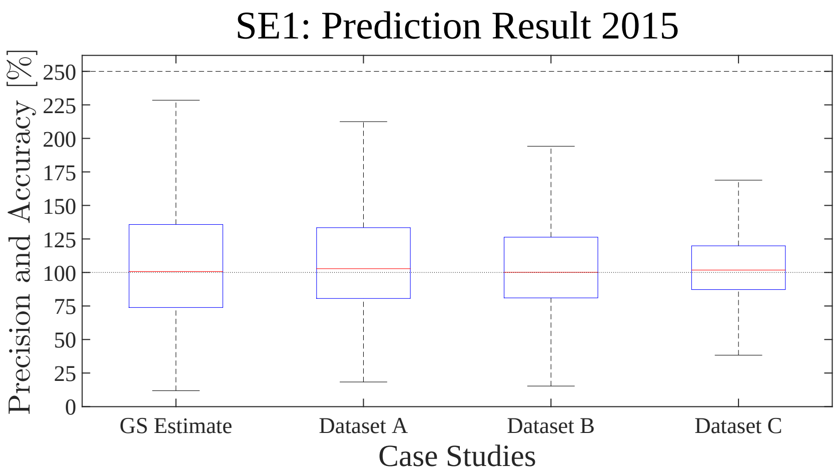

Figure 4.8: Box-and-whisker plot for SE1. Describes the line loss predictions density with the median value in the middle, the interquartile range marked with a box and the lower and higher whisker at ±1.5 times the interquartile range.

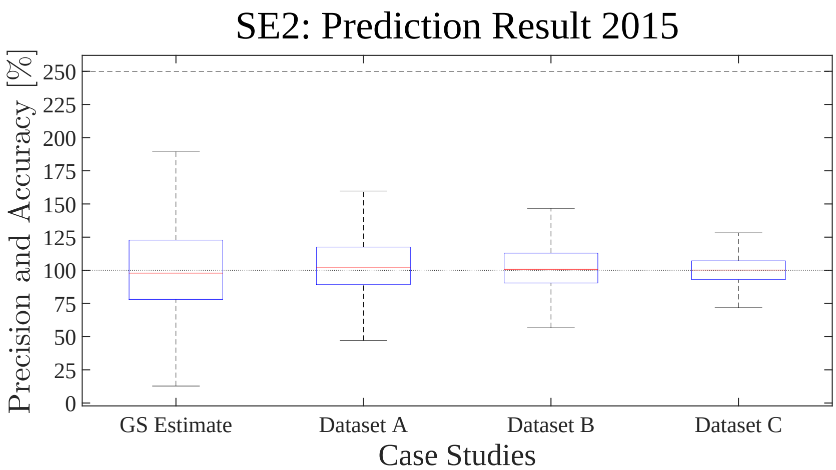

Figure 4.9: Box-and-whisker plot for SE2. Describes the line loss predictions density with the median value in the middle, the interquartile range marked with a box and the lower and higher whisker at ±1.5 times the interquartile range.

SE4 while the spread in figure 4.11 is quite low. SE1 is thus the area which has the largest spread of predictions regarding both variance and the result in figure 4.8. SE3 overestimates the line losses for all cases which might indicate that other parameters, for instance nuclear generation, should be added separately to the linear regression model as well. Moreover, it could also depend on that the input data overestimates the actual quantities and thus affects the line losses in the same way.

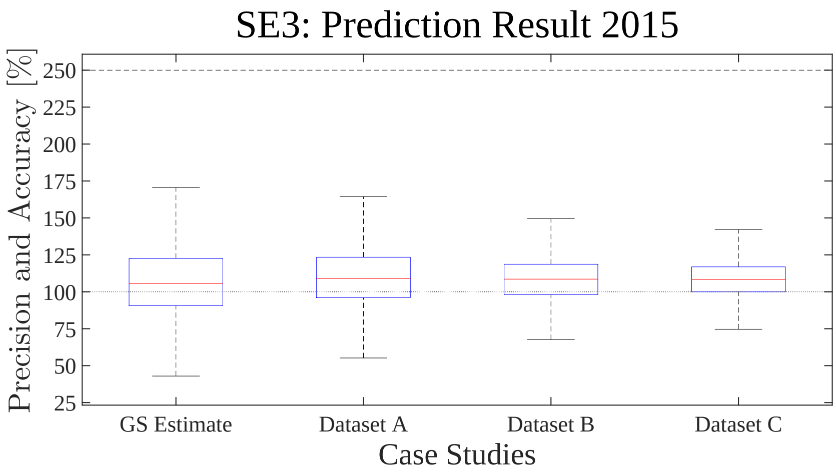

Figure 4.10: Box-and-whisker plot for SE3. Describes the line loss predictions density with the median value in the middle, the interquartile range marked with a box and the lower and higher whisker at ±1.5 times the interquartile range.

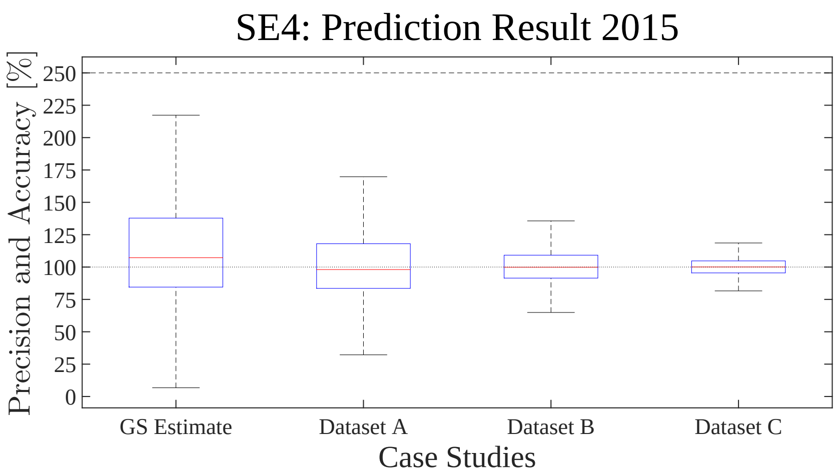

Figure 4.11: Box-and-whisker plot for SE4. Describes the line loss predictions density with the median value in the middle, the interquartile range marked with a box and the lower and higher whisker at ±1.5 times the interquartile range.

Line Loss Absolute Error

Tables 4.9-4.11 show the over-, under- and absolute mismatch between predicted losses and actual losses for the GS approach as well as the three different datasets. Even though the forecast data applied in Dataset A is less accurate than the other two it manage to reduce the total mismatch with 27.6% where the largest reduction occur in SE2. Dataset B manage to reduce the total mismatch with up to 42.2% whereas Dataset C manage to reduce the same with 57.2%. Thus, the simulations show that the suggested model is capable of to predict line losses in a more accurate way than the GS approach and that more precise predictions would be possible if more accurate data would be available. Figure 4.12 illustrates the annual prediction error for each bidding area and dataset compared with the GS forecast.

Table 4.9: Total line loss overestimated mismatch for 2015

	SE1	SE2	SE3	SE4	Total
GS Estimate	54 525	161 620	149 480	54 538	420 160
Dataset A	47 026	114 220	147 810	27 517	336 580
Dataset B	37 238	84 489	124 940	15 141	261 810
Dataset C	27 461	49 089	118 560	8075	203 190

Table 4.10: Total line loss underestimated mismatch for 2015

	SE1	SE2	SE3	SE4	Total
GS Estimate	-65 848	-193 360	-87 693	-34 082	-380 990
Dataset A	-55 273	- 97 765	-58 925	-31 501	-243 460
Dataset B	-53 314	- 85 726	-43 151	-19 054	-201 240
Dataset C	-40 841	- 57 818	-32 709	-8498	-139 870

Table 4.11: Total line loss absolute mismatch for 2015

	SE1	SE2	SE3	SE4	Total
GS Estimate	120 370	354 980	237 170	88 620	801 140
Dataset A	102 300	211 990	206 740	59 018	580 040
Dataset B	90 552	170 210	168 090	34 195	463 050
Dataset C	68 301	106 910	151 270	16 573	343 050

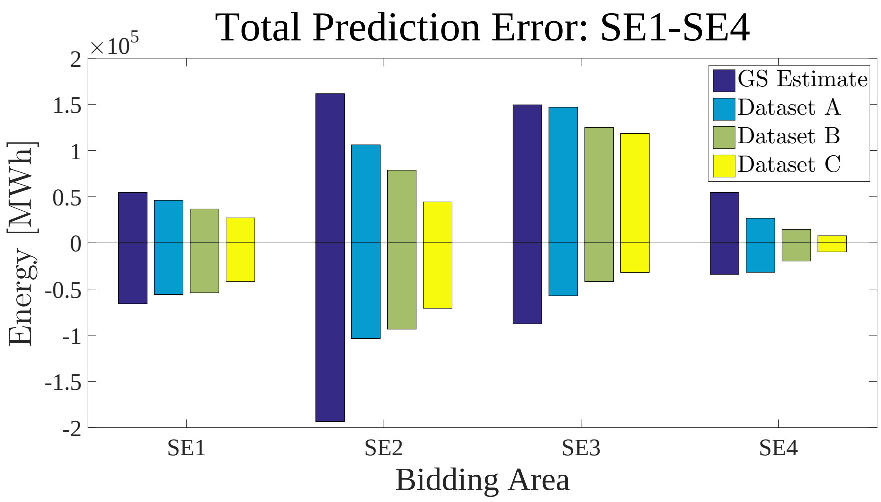

Figure 4.12: Annual total prediction error for each bidding area and forecast.

4.3.4 Discussion on Results

The above results show that a linear regression model is suitable for line loss predictions and that a large reduction in total annual prediction error is possible even with simple and rough forecasts. Thus, the designed model is seemingly able to reduce the economical cost related to inaccurate line loss predictions which is the third and final objective goal in this thesis. Project that the related cost to this error was around 25 million SEK for 2015 and that this cost would be direct proportional to the prediction error. This means that suggested model with data from dataset A would reduce the total cost with 6.9 million SEK for 2015. If the data in dataset B would be available, i.e. with the prognosis data given from Nord Pool at 13:30-14:00 am, this reduction would be around 10 million SEK instead. The maximum reduction is of course achieved in the final dataset scenario in which the reduction would be 14.3 million SEK. Thus, the model would have provided a substantial economical profit in 2015 if the model would have been designed by then.

Although, before this conclusion can be made more simulations, presumably over several of years, would be required in order to validate these results. There might still exist contingencies and specific conditions during 2015 which derived a more favourable result than would have been the case for another simulation year. Thus, further simulations are required before these results can be confirmed in a scientific manner. The data on measured line losses might also be recommended to review, since certain values could be questioned. However, it would be correct to say the model design shows interesting results and has potential to reduce the line loss prediction error for the Swedish bidding areas.

The dedicated reader might notice that the model mange to reduce the prediction error differently among the Swedish bidding areas. Predictions in SE1 show a larger variance and spread compared with the other areas and predictions in SE3 still overestimates the line losses slightly. Why this is the case remains unknown but one reason could be that the input data for these areas might have been less accurate compared with the input data applied in the other areas. Line losses might also be more volatile and difficult to predict in an accurate way for larger areas such as SE1 (regarding geographical size) and SE3 (regarding installed capacity and general demand) than with the somewhat smaller areas SE2 and SE4.

The line losses in these areas might also be dependent on covariates that have not been identified in this thesis which, if added, could improve the model even further. Other parameters, such as frequency deviations, might have a larger influence on certain areas than others. A large share of frequency reserves are located in SE1 and SE2 in which continuous up- and down regulation might affect the line losses more compared with SE3 and SE4. However, this explanation might be questioned since the precision in SE2 is higher than SE1 for all forecast scenarios (even the GS approach). Although, since the total line losses are in comparison lower in SE1 it is reasonable that a relative line loss prediction measurement would derive in a larger variance.

Model Extensions

It is interesting to note that the prediction error is not reduced to zero even with measured input data from Nord Pool. This is however reasonable since every prediction model consist of certain fluctuations and is affected by its limitations. For instance, the measured data from Nord Pool cannot be regarded as exactly equal with actual physical energy flow as discussed in 3.2.2. The model also neglects rapid changes within the hour since it only consider the average energy quantity by the hour. Moreover, network topology changes, possible line faults and frequency variations as mentioned are also parameters neglected in this model but which has some connection to the actual line loss.

Nevertheless, the results point towards that the designed model is proper. Further modelling and experiments on the same parameters might also increase the precision even further. First, instead of including the total supply and demand in each area more accurate results might be derived if these would be divided into reasonable subcategories (such as industry, nuclear, commercial services, hydro etc.) providing that forecast data on these categories are available. The wind generation parameter, which is already applied in the model, had a positive effect on the prediction precision. Thus, the generation composition factor considered in the GS approach (mentioned in 2.4.1) seems to be a valid aspect to consider further. The results also show that the sample selection strategy had a large impact on the given line loss rates and thus the derived line loss prediction. Sample selections strategies based on similar day, season and/or prognosis selection achieve different predictions precisions which indicate that the choice of sample strategy is important. The prediction accuracy varies with adjustments in the sample selection strategy, for instance with another total number of samples and time-period length, and it is thus hard to make a definite conclusion. Although, the season selection strategy reached the most accurate results by the three sample selection methods even though the average of the three overall was the best option. Further experiments on sample selection strategies would probably help increase the prediction precision even more than derived in this thesis.

Day-Ahead vs. Elbas Prediction

The fact that line losses have to be reported during the day-Ahead market opposes another constraint to the prediction model as well as for the GS approach. If Svenska kraftnät was allowed to trade losses at Elbas however, they would be able to predict the losses more accurately with the additional information given during that time. The result shows that, just with prognosis data from Nord Pool, this would by reduce the prediction error with 42% compared with the GS approach. However, there exist some concerns with trading losses at Elbas which should be mentioned. First, since it is likely that the price on Elbas is higher than the Elspot price, the total line loss cost would increase overall. Thus, the best option would be to first trade losses on Elspot with the predictions available and then adjust these losses on Elbas later on.

However, trading at Elbas is handled by direct offers and bids which means that it could be hard to find the exact bid to cover the remaining losses. Moreover, it might even exist occasions when no suppliers are willing to offer additional energy at Elbas at a reasonable price. Alas, even if line losses might be easier to predict during the Elbas trading window, it might still be recommended to not allow Svk to act on Elbas for policy reasons. An alternative option would be to contract another market participant to be BRP regarding transmission line losses, which would be allowed to adjust their first prediction on Elbas. All in all, in a line loss prediction perspective it would however be favourable to trade losses at Elbas since the prediction accuracy is increased substantially for all bidding areas.

Future Challenges

An final interesting topic to discuss is how line loss predictions would be influenced by future major changes in the grid, such as the introduction of the Nord Balt cable and SouthWestLink in 2016 and 2017. It is also possible that the introduction of the aforementioned links might increase the losses considerably in certain areas. A quick analysis on the measured line loss for SE4 during February and March 2016, when the NordBalt cable was put in operation, shows that the maximum line loss value has increased to 91 MWh/h. This corresponds to an increase with 38%

compared with the previously defined limit on 66 MWh/h in 3.3.5. Since the transmission capacity on the link is similar two both the link to Germany and Poland the increased line loss must be due to other reasons specific to the NordBalt cable.

If the SouthWestLink would behave in a similar way as the NordBalt cable, the line losses would thus increase further in SE3 and SE4 and probably impact the prediction error as well. New transmission links in Norway, increased rates of bi-directional flows and larger share of intermittent energy sources would increase the overall uncertainty which also will affect line loss predictions. It is thus likely that line losses in all areas will become more complex to predict in the future which highlights the need of an adequate line loss prediction model design.

Chapter 5

Closure

This chapter gathers the main conclusions and results drawn from the designed models and simulations, provides general recommendations and suggestions on future studies.

5.1 Main Conclusions

THE LINE LOSS PREDICTION MODEL MANAGE TO REDUCE THE PREDICTION ERROR

It is, with rather simple estimations and assumption, possible to improve the precision and accuracy and thus reduce the unnecessary cost related to inaccurate predications. The results show that the designed line loss prediction model manage to reduce the annual absolute mismatch with 27.6% for 2015 compared with the Grid Supervisor approach. The designed model has a potential to reduce the prediction error twice as much (with 57.2%) if more accurate forecasts on exchange flows would be available. The additional cost related to this prediction error could be reduced with around 6.9-14.3 million SEK annually which is a reduction to be reckoned with. Further estimations over several years is recommended in order to validate these results however.

LINEAR REGRESSION ON LINE LOSS RATES IS A SUITABLE PREDICTION STRATEGY

There exist a certain relationship - line loss rate - between line losses in each bidding area and the wind generation, supply, demand and exchange flows associated to these areas. The linear regression model has proven to be a suitable approach deriving this relationship and allow the predictor to predict line losses from hourly forecasts on wind, supply, demand and exchange flows. Proper selection of historical samples is however crucial while deriving suggested line loss rates for these parameters the next day.

It is recommended to leave out no-load losses and study the squared relationship of exchange flows to reach the highest model precision. Wind generation is a desirable parameter to include and it is likely that nuclear generation prognosis for SE3 might be able to increase the model precision for this particular region even further. It is also possible to expand the suggested model with more detailed parameters in search for increased accuracy and precision.

NET-POSITIONS AND EXCHANGE FLOWS ARE HARD TO PREDICT AND REQUIRE FURTHER MODELLING EFFORTS

Accurate forecast on the hourly net-positions and exchange flows the next day are difficult to achieve. However, it is possible to receive rough forecasts through linear programming and estimates on corresponding net-positions, transmission line capacities and simple assumptions on electricity prices. The internal exchange flows are in some regards surprisingly well correlated with the measured flows. The Last Comparable Day method also manage to reach net-positions forecast which show high correlation with the actual values in certain areas. However, both of these forecasts show large mean absolute deviation which highlights the need for further modelling efforts.

TRADE LOSSES ON ELBAS WOULD IMPROVE THE PREDICTION ACCURACY AND PRECISION

Allowing Svenska kraftnät to trade losses on Elbas would lead to reduced line loss predictions error. The developed model suggest that the prediction error could be reduced with 42.2% when the market turnout and first exchange flows predictions can be retrieved from Nord Pool. The fact the Svenska kraftnät is prohibited to adjust there line losses at Elbas introduces costs that could otherwise be avoided. However, it is uncertain whatever this would be an ideal procedure due to probably higher prices, limited offers at the intra-day market and unwilling violation against current policies.

LINE LOSSES Will BE MORE COMPLICATED TO PREDICT IN THE FUTURE

Line losses prediction will most likely be more complicated in the future and thus become a more important field of research. Larger exchange flows, increased shares of intermittent energy and introduction of new transmission links will make it harder to predict both supply, demand and exchange flows. This will definitely affect the transmission line losses as well. Thus, future research on line loss prediction models must include methods on how to predict their required input data for the next day in order to be useful for TSO applications.

5.2 General Recommendations

Line loss predictions is an important task at Svenska kraftnät and is likely to be even more so in the future. Thus, it is recommended to pay more attention to possible line loss strategies and, with this thesis as starting point, make sure that a line loss model is adapted and utilized as aid to the GS. The suggested model, designed in Matlab, could perhaps be easier to use if converted to Excel which is a more common tool applied frequently in industry applications. Moreover, the Matlab model also require certain toolbox extensions currently not available at Svk which also would recommend a conversion to Excel.

Furthermore, it would also be worthwhile to investigate if certain data at Nord Pool could be provided earlier than what is the case today. It might even be possible to retrieve the same kind of data utilized in this thesis between the Nordic TSOs directly than go through Nord Pool. A higher degree of synchronisation between the the Nordic TSOs and Nord Pool, to make sure that data is uploaded as early as possible, would also be recommended.

Moreover, since certain values in the measured line loss data could be questioned, due to either large changes between certain hours and extremely low and/or high values, it might be suitable to review the data and make any corrections if necessary. Since the line loss prediction is compared against this data it is vital that it can be trusted by the Grid Supervisor.

5.3 Future Studies

This study show that future studies in this research field is not only a welcomed contribution but also a motivated one. Several model extensions and improvements are possible regarding both the net-position and exchange flow model but also the line loss prediction model as a whole. Price prediction models and further sample selection strategies are two examples on all the possibilities there is. Another possibility is to add certain Monte Carlo Techniques to the developed model in order to provide probability ranges to the predicted line losses. This approach might also be plausible to further investigate what the actual regulation cost would be based on expected up- and down regulating prices.

Although, the main and most important suggestion for future work would be further simulations over several years with the developed model design. This is vital not only to support or question the retrieved results but also to investigate further how line losses are about to be affected with the ongoing changes in the power system. Further analysis on how network topology changes due to general maintenance affect the line losses would also be a valid research goal.

Alas, even if the model approach seems to be a valid strategy, other approaches would be just as interesting to study further. The author has limited knowledge behind the concept of Neural Networks but that approach seems promising according to other studies previously mentioned. Neural Network would probably be able to analyse a larger quantity of data more efficiently than the developed linear regression model and also take into account other parameters. Moreover, a Neural Network approach would also be able to include a feedback loop which could update the upcoming forecast depending on the most recent prediction results. This would indeed be a welcomed contribution.

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Appendix A

Exchange Flow Model

Table A.1: Coupling matrix on how each bidding area is connected to the other areas. Positive sign mark import, negative sign mark export and zero mark no connection.

	SE1	SE2	SE3	SE4	NO1	NO2	NO3	NO4	NO5	DK1	DK2	FI
SE1	-	1	0	0	0	0	0	1	0	0	0	1
SE2	-1	-	1	0	0	0	1	1	0	0	0	0
SE3	0	-1	-	1	1	0	0	0	0	1	0	1
SE4	0	0	-1	-	0	0	0	0	0	0	1	0
NO1	0	0	-1	0	-	1	1	0	1	0	0	0
NO2	0	0	0	0	-1	-	0	0	1	1	0	0
NO3	0	1	0	0	-1	0	-	1	1	0	0	0
NO4	-1	1	0	0	0	0	-1	-	0	0	0	0
NO5	0	0	0	0	-1	-1	-1	0	-	0	0	0
DK1	0	0	-1	0	0	-1	0	0	0	-	1	0
DK2	0	0	0	-1	0	0	0	0	0	-1	-	0
FI	-1	0	-1	0	0	0	0	0	0	0	0	-
NEL/DE	0	0	0	-1	0	-1	0	0	0	-1	-1	0
PL	0	0	0	-1	0	0	0	0	0	0	0	0
LT	0	0	0	-1	0	0	0	0	0	0	0	0
EE	0	0	0	0	0	0	0	0	0	0	0	-1
RUS	0	0	0	0	0	0	0	-1	0	0	0	-1

Table A.2: Connections definitions with maximum (export) and minimum (import) net transmission capacities (NTCs) [34]

Connections	Co. number	Max NTC [MW] (export)	Min NTC [MW] (import)
SE1 > SE2	1	3300	-3300
SE1 > NO4	2	600	-700
SE1 > FI	3	1500	-1100
SE2 > SE3	4	7300	-7300
SE1 > NO3	5	1000	-600
SE1 > NO4	6	300	-250
SE3 > SE4	7	5300	-2000
SE3 > NO1	8	2095	-2145
SE3 > DK1	9	680	-740
SE3 > FI	10	1200	-1200
SE4 > DK2	11	1300	-1700
SE4 > DE	12	615	-615
SE4 > PL	13	600	-600
SE4 > LT	14	700	-700
NO1 > NO2	15	2200	-3500
NO1 > NO3	16	500	-500
NO1 > NO5	17	300	-3900
NO2 > NO5	18	500	-600
NO2 > DK1	19	1632	-1632
NO2 > NEL	20	723	-723
NO3 > NO4	21	200	-1000
NO3 > NO5	22	200	-200
NO4 > FI	23	100	-100
NO4 > RUS	24	56	0
DK1 > DK2	25	590	-600
DK2 > DE	27	585	-600
FI > EE	28	1016	-1000
FI > RUS	29	1460	-320

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