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Flow based market clearing

GSK strategies

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MASTEROPPGAVE

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Oppgavens tekst

Marketsklareringen i Nord Pool skjer i dag etter NTC-metoden (Net Transfer Capacity). Det arbeides nå med flytbasert markedsklarering, som i større grad tar hensyn til det fysiske nettet. Metoden bruker såkalte "Power Transfer Distribution Factors", som angir sammenhengen mellom endring i nettoposisjoner og endring i injeksjoner. For å finne disse er det nødvendig å benytte "Generation Shift Keys" som brukes for å aggregere PTDFer fra node-til-flyt til område-til-flyt.

I prosjektoppgaven ble det gjort undersøkelser av ulike GSK-strategier for en lengre periode. Kombinasjoner av GSKer ble undersøkt, men samme GSK strategi ble alltid brukt for samme CNE. Dette arbeidet skal nå videreføres ved å variere GSKene per område. Det vil si at man bruker samme GSK for et område, men da CNEer alltid avhenger av flere områder brukes det (potensielt) flere GSKer per CNE.

Innenfor det nordiske prosjektet er det utviklet en Pythonkode som i utgangspunktet kan brukes til oppgaven, men den vil måtte tilpasses. Det er også la Vi ser for oss de følgende oppgaver:

1) Sette seg inn i, beskriv og tilpass eksisterende kode
2) Teste koden og hvis mulig gjøre forbedringer for å redusere regnetiden. En mulighet er f.eks. å kun håndtere aktive restriksjoner.
3) Tilpass og kjør koden for å teste om det er mulig å finne bedre GSK strategier. Metoden baserer seg på å finne beste strategi for ett og ett område i gangen. Det itereres flere ganger inntil forbedringene er innen en toleransegrense, eventuelt et bestemt antall iterasjoner.
4) Resultatene dokumenteres. Det er ikke nødvendig å gå i like mye detalj som i prosjektoppgaven, men det skal fokuseres på de viktige/interessante resultater og store forskjeller, samt årsakene til disse.
5) Sammenlign og diskuter resultatene fra denne oppgaven med resultat fra prosjektoppgaven.

Det er viktig å holde god løpende kontakt med veilederne for å diskutere veivalg og tidsforbruk. Arbeidsmengden er ellers vanskelig å estimere.

Utført ved (institusjon, bedrift): Institutt for Elkraftteknikk
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Oslo, dato 19.01.2015

Preface

This thesis is the final work of my master degree in Energy and Environment at NTNU.
In this work I have had the pleasure of cooperating with expertise at Statnett and Svenska Kraftnet. This thesis is written in co-operation with Statnett, as a part of their and the other Nordic TSOs current work in investigating the possibility to introduce Flow-based market coupling in the Nordic power market. I hope my thesis will be a valuble contribution in this Nordic project.

In this period, not evertyhing have proceeded as planned. I have needed help from my co-supervisors and other people working at the Nordic TSOs to produce and provide both files and code material for me. Through this work I have achived valuable knowledge about the power market and the Flow-based method.

I would like to thank my supervisor Gerard Doorman for valuable inputs, as well as co-supervisor at Statnett Jan Hystad for producing data files. In addition I would also like to thank Katherine Elkington and Johan Setreus at Svenska Kraftnet for coding, helping me understand the coding and help me to be able to proceed my work.
They have all been helpful in answering my questions and helping me understand through sharing of their knownledge.

Trondheim, June 2016

Vegard Bremerthun Svarstad

Abstract

In these days, the Nordic TSOs examines the possibility to introduce Flow-Based(FB) market clearing in the Nordic power market. The FB market clearing will theoretically give a better market solution than the current Net Transfer Capacity (NTC) method, because a simplified grid model included in the market optimization gives the market the ability to prioritize flows that are the most economically efficient in managing congestion.

The simplified grid model contains Power Transfer Distribution Factors (PTDFs), which describe the connection between a change in net position and change in injection. Because the Nordic area is divided into bidding areas, the node-to-line PTDFs have to be aggregated to area-to-CNE PTDFs to reflect how an injection in an area influences the lines in the grid. In this aggregation, a Generation Shift Key (GSK) is used, and describe how a change in net position of an area is divided on the nodes in that specific area.

A GSK strategy is rules or linearization methods for generating the GSK to find the most accurate estimated power flow, compared to the real physical flow. There are no theoretical “right or wrong” methodology when determining the GSK strategy, and there is not necessarily only one general optimal strategy. Therefore, several GSK strategies are developed in the Nordic countries. The task in this thesis is to compare these strategies, and find the optimal GSK in each Nordic bidding area contributing to a most accurate estimated power flow.

The TSOs cannot precisely estimate the power flow in the grid due to uncertainty. To handle the uncertainty, the FB method use the Flow Reliability Margin (FRM). To compare the different GSK strategies and find which one suited in each Nordic bidding area, a Python code is written in this thesis using the FRM parameter. To find the combination of optimal GSKs in each area to minimize the error in estimated flow, the code have the objective to minimize a weighted FRM norm.

The results of the studied period 01.02.2016-17.04.2016 show that it is beneficial to have the optimal GSK in each bidding area instead of one global strategy in the entire system. The areas with the largest benefit of having optimal GSK in the area was NO2 and SE3. The best strategies in these areas are GSK3 and GSK7, respectively. However, in some areas like NO1 and NO3 all GSK strategies performed similar regarding a calculated delta value. This implies that the areas with similar results for all GSKs are strong and non-sensitive areas.

Results show that the characteristics of each area affect which GSK optimal. In general, GSK3 and GSK5 are good strategies in areas with export and mainly hydropower generation from reservoirs, while GSK7 and GSK2 are good strategies when the area has an import of power or mainly nuclear or the generation in the area is mainly from nuclear power plants.

Samandrag (norsk)

Markedsklareringa i det nordiske kraftmarkedet vert i dag utført etter NTC-metoden (Net Transfer Capacity). Denne metoden tek ikkje hensyn til faktisk flyt i nettet, og optimerer samfunnsøkonomisk overskot basert på overføringskapatsitet i nettet.

Det arbeides i dag med å vurdere ein anna metode for markedsklarering i norden, nemleg flytbasert markedskopling (FB). Denne metoden inkluderer ein forenkla modell av nettet og tek i større grad hensyn til det fysiske kraftnettet. Denne forenkla nettmodellen vert framstilt av dei nordiske TSOane. Dette utføres ved å nytte såkalte PTDFs(Power Transfer Distribution Factors). Ein PTDF beskriv korleis ein kraftinjeksjon i eit område lastar ei kritisk linje i nettet.

Sidan det nordiske kraftmarket er delt inn i budområder må PTDFane aggregeres frå node- til områdenivå. For å aggregere node-PTDFar til ein område-PTDF nyttes faktoren Generation Shift Key (GSK). Ein GSK estimerer korleis endring i nettoposisjon i eit område er delt på nodane i området.

Det er ikkje ein gitt metode korleis ein skal finne verdien til ein GSK. Derfor er det utvikla åtte ulike GSK-strategiar i Norden. I denne oppgåva er det utvikla ein metode for å samanlikne desse GSK-strategiane, samt finne optimal GSK i kvart nordisk budområde.

Dei nordiske TSOane klarar ikkje estimere eksakt kraftflyt i kraftnettet på grunn av usikkerhet. For å handtere denne usikkerheten nyttar den flytbaserte metoden faktoren Flow Reliability Margin (FRM). For å samanlikne ulike GSK-strategiar og finne kombinasjonen av optimal GSK i kvart område er det i dette arbeidet skrive ein Python-kode som nyttar faktoren FRM i berekninga. For å finne optimal GSK i kvart budområde som minimerer feilestimatet av kraftflyten har koden som formål å minimere ein målfunksjon basert på ein vekta FRM-verdi.

Resultata i denne studien for perioden 01.02.2016-17.04.2016 syner at det er gunstig å nytte optimal GSK i kvart område istadenfor å nytte den same globalt beste GSKen i alle områder. Områda med størst nytte av å ha optimal GSK i området er NO2 og SE3. Den beste strategien i desse område er henhaldsvis GSK3 og GSK7. Resultat for områder som NO1 og NO3 syner derimot at alle strategiane er like veleigna. Dette skuldast at det er lite sensitive områder der flyten vert estimert bra.

Resultata syner at karakteristikken til området påverkar kva GSK som er optimal i området. Generelt er GSK3 og GSK5 gode strategiar i områder med eksport av kraft og produksjon

som hovudsakeleg er vasskraft med magasin. GSK7 og GSK2 er derimot gode strategiar i områder med større last enn produksjon og områder med hovudsakeleg produksjon frå kjernekraftanlegg.

Contents

Abbreviations

TSO - Total System Operator

NTC - Net Transfer Capacity

TTC - Total Transfer Capacity

ATC - Available Transfer Capacity

FB - Flow based

CNE - Critical Network Element

NP - Net Position

GSK - Generation Shift Key

PTDF - Power Transfer Distribution factor

RAM - Remaining Available Margin

FRM - Flow Reliability Margin

FAZ - Flow at Zero

FAV - Flow Adjustment Value

CWE - Central Western Europe

CGM - Common Grid model

Chapter 1 - Introduction

1.1 Scope

In these days, the Nordic TSOs examines the possibility to introduce Flow-Based(FB) market clearing in the Nordic power market. The FB market clearing will theoretically give a better market solution than the current Net Transfer Capacity (NTC) method, due to a simplified grid model included in the market optimization that gives the market the ability to prioritize flows that are the most economically efficient in managing congestion. A better market solution results in a more precise estimated power flow, and therefore also a socio-economic benefit.

The FB method use Power Transfer Distribution Factors (PTDFs) as flow factors. The PTDFs describes the connection between a change in net position and a change in power injection. To find these PTDFs, Generation Shift Keys (GSKs) are used to aggregate PTDFs from nodal-PTDFs to an area-PTDF. Before implementing the FB method in the Nordic grid, there is a need to examine how to use and find the value of the GSK.

A GSK estimates how a change in net position of an area is divided on its nodes. To find the best approach to calculate the GSK values, there are eight different GSK strategies under examination in the Nordic power market. The reason for several strategies examined is the fact that there is no theoretical "best-way" of how to establish a GSK strategy. When a GSK is established, its value is used to find how a change in net position of a bidding area will influence the nodes within that area.

The scope of this thesis is to look further into a method that enables a comparison of different GSK strategies and search for the optimal GSK strategy in each Nordic bidding area to minimize the error of estimated flow. The aim in this thesis is to find the most suitable strategies applicable for each Nordic bidding areas.

This thesis is a continuance of the project assignment "Flow based market clearing: GSK strategies"[2]. The main difference between the thesis and the project assignment is the method used to investigate the strategies. In this thesis, the optimal GSK for each area is found based on the factor Flow Reliability Margin (FRM).

In the Nordic flow based project, a code in Python that could be used in this work is made by of Katherine Elkington. This code is during this work re-written from scratch, with help from Johan Setreus in Svenska Kraftnät.

The tasks in this thesis are:

- Become familiar with and describe the existing Python code
- Test the code and if possible do improvements to reduce the calculation time. A possibility is to only handle limiting CNEs
- Run the code to find optimal GSK strategies. The method finds the best GSK in one and one area at the time. As long as advantageous, the code iterates. Normally this method results in local minima's, and the iterating will be used to find the effect of the local minima's. The results should be documented. Focus on interesting results and differences.
- When this work starts, there is no good procedure for making prognosis. The current prognosis does not take into account changes in the grid. Thorough this work the TSOs work in parallel making these prognosis and final data files.
- The results are compared to results from the previous work in project assignment.

1.2 Report structure

Chapter 2 gives a brief introduction to the Nordic Power market as well as today’s market clearing method.

Chapter 3 explains the flow based method, and the principles behind.

Chapter 4 describes and discuss the Generation Shift Key (GSK) in general, in addition to the different GSK strategies considered in the Nordic system.

Chapter 5 gives an overview of how this study is performed and the method used to find the optimal GSK for each area.

Chapter 6 presents and discuss results for the combination of optimal GSKs in each area. A long period is the main focus in the study, in addition subperiods are studied in brief. Results are also compared to earlier work.

Chapter 7 concludes the study, and Chapter 8 suggests tasks beneficial to consider in future work.

Chapter 2 - Background

This chapter gives a brief introduction to the Nordic Power market. In chapter 2 of the project assignment “Flow based market clearing: GSK strategies” [2], which this thesis is a continuance of, the background in the Nordic power market is deeper elaborated.

2.1 The Nordic power market in brief

It is crucial to have a balance of production and consumption in the power system. If not, problems or failures can occur when parameters like frequency and voltage reach out of their limits. NordPool and the Total System Operators (TSOs) are set to ensure the balance in the Nordic and Baltic power markets. All participants have an obligation to bid in balance. Because of this, producers cannot sell more than their total production capacity, and consumers cannot buy more than their expected consumption[3].

NordPool is the power market hub in the Nordic countries Norway, Sweden, Denmark and Finland, in addition to the Baltic countries Lithuania, Latvia and Estonia. The Nordic power trades are executed at Nordpool in both Elspot and Elbas market, in addition to the regulation market operated by the TSOs. The TSOs in the Nordic countries are Statnett in Norway, Svenska Kraftnät in Sweden, Energinet.dk in Denmark and Fingrid in Finland.

The Elspot market, or electrical spot market, is the main area of trading in the Nordic/Baltic area. Elspot is also called day-ahead market, because power trade in Elspot happens the day before the delivery. Every day before the auction closure at 12:00 SET, all sellers and buyers in the market submit their bid including price, volume and production or consumption for all hour the next day. Before submitting their bids, the market participants have to make a plan for the selling or purchasing of power for each hour the next day. The participants sets the price and volume for all hours and areas based on aggregated curves for demand and supply [4]. The bid in volume and price will be determined by the equilibrium point of these two curves, as shown in Figure 1.

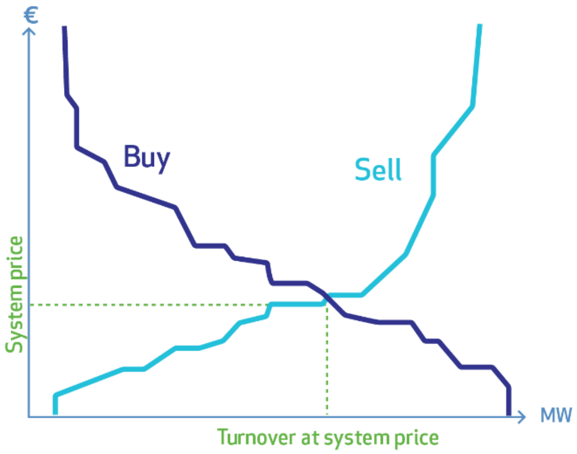

Figure 1: Illustration of the aggregated market curves and the market cross point[1]

Figure 1 show that the price from the market equilibrium is the system price. The system price is what the consumers have to pay and producers will receive for a unit of power in each hour and area. The system price is the clearing price in an unconstrained and loss free market. This is the case if buyers and sellers use single hour bids, which is the most common type of bidding in the Nordic power market. Two other types of bids are block bids and flexible hour bids. These two bid types is elaborated in the project assignment “Flow based market clearing: GSK strategies”, 2015 [2], and will not be elaborated in this thesis.
Further, the continuation of this thesis is related to the Elspot market with single hour bids[1].

Another factor affecting the price is the transmission capacities. When the transmission capacity is limiting, it leads to different prices in different bidding areas. In Elspot the transmission capacities for each area are calculated and posted on NordPool Spot’s website at 10:00 CET. Because of this, the market participants does not need to do explicit reservations on transmission capacity in their bids in Elspot. The capacity will be allocated to the specific market participant according to their bid, and this methodology is called implicit auction[5].

2.2 Congestion management

If there were no loss or transmission constraints in the power system, the system price would be the power price in all countries and areas in the system. In real life, the transmission capacity is limited, and congestion or bottlenecks in the transmission grid often occur.

Congestion will say more capacity requested by the market than available, and physically it can lead to overloaded transmission lines and outages.

In the Nordic system, there are several critical lines which limits the total transferable amount of power. To relieve the congestion, the Nordic system is split into 12 bidding areas, illustrated in Figure 2. The division of areas are established from where long lasting bottlenecks occur, with the purpose of congestion management[6]. The division of areas is stipulated in section 5 of the *Regulations relating to the system responsibility in the power system*, and states that the TSOs is responsible for the division of bidding areas[7]. The regulation state that ”The Transmission System Operator shall divide into Elspot areas in order to handle major and prolonged bottlenecks in the regional and main grids.”

Figure 2: The division of bidding areas in the Nordic power market[8]

When a congestion occur on a transmission an area, the power have to be handled in a way that makes the congestion disappear. The amount of power on the congested line or in the area have to decrease, and the excess must be transmitted to other lines, if the demand is not reduced. This will lead to a sale in the deficit areas and purchase in the areas with a surplus to stabilize the transferred amount of power. Figure 3 shows how this shift of volume affects the price.

To avoid the congestion, the aggregated supply curves will parallel shift to the right in the deficit area. In the surplus area, the aggregated demand curve parallel shifts to the right. This implies an increase of volume in the surplus area, and transmission of power to the deficit area. This leads to a higher price in the surplus area, due to the increased demand. In the deficit area, the price decrease because the import of power to reduce the congestion. Figure 3 show this behaviour.

Figure 3: Shows how the market react in surplus and deficit area when performing a market coupling[1]

With the transport of power from surplus to deficit area and a new intersection, there is now a trading surplus, called congestion rent. Congestion rent appears when there trading occur, and the importing area pays more than the marginal cost of production in the exporting area[9].

Usually the System Operators, the grid company or the Power Exchange receives the congestion rent. In the Nordic countries, the TSO's receive the congestion rent as owners, and an agreement between the Nordic TSO's distributes the congestion rent. When there is a congestion rent, the countries involved shares the income. The TSO's will not receive benefit from the congestion rent, which the revenue regulation in Norway ensures Statnett not to[10].

Congestion management is a crucial challenge in the future grid to avoid not wanted incidents. The winter 2009/2010 in Norway, there were some hours with extremely high prices, as high as 2000% more than the average for the first quarter of the year, due to an abnormal cold winter and a Swedish nuclear power production lower than normal. After this situation, a committee of experts set to consider the future power grid. According to their report "*Flere og riktigere priser -Et mer effektivt kraftsystem*", one of the factors that can affect the congestion management is the approach to calculate cross-zonal capacity[11].

The continuation of this thesis will describe two methods for calculating cross-zonal capacity. The next section 2.3 describes the current Net Transfer Capacity method, and Chapter 3 the Flow-based method. Further, the thesis discuss how the choice of approach for calculating cross-zonal capacity affects the system, considering congestion management.

2.3 The Net Transfer Capacity method

The current power marked model in the Nordic power market is the Net Transfer Capacity method (NTC). The values produced by the NTC method are trading capacities between areas, determined by the TSOs. These NTC values sets the transfer capacities on hourly basis the next day and provided to Nord Pool Spot the day ahead of the market clearing. The NTC values represents the maximum power exchange between two areas compatible with security standards in both areas, and accounts for the uncertainties in the system. In the market algorithm, the NTC values can cause a price difference when they act as constraints[12].

The NTC algorithm only consider commercial exchanges between bidding zones. The TSOs are responsible for handling the real physical and transit flows, and through load flow calculation, the TSOs calculate the NTC assessments. The Nordic TSOs have committed to follow some common principles for determining the capacity and margins through the System Operation Agreement. It includes some security standards to ensure reliable operation of the power system, e.g. the N-1 criterion. The agreement is a part of the Nordic grid code, and in line with the definitions used in the European Network of Transmission System Operators for Electricity (ENTSO-E)[12].

Through static and dynamic simulations for a defined transmission corridor, the TSOs can determine the amount of power possible to transmit in any direction through the corridor before limits are reached. Breaking limitations can lead to thermal overload, voltage collapse and/or different levels of voltage can be included. In the corridor, an arbitrary number of lines of different voltage levels can be included. The capacity set by the TSO is the maximum transmission of active power permitted in corridors between bidding areas within security limits, called the total transfer capacity(TTC)[12].

To calculate the NTC values the TSOs use a three-step process, where the first step is to calculate the TTC value between the two areas. The next step is to calculate the Transmission Reliability Margin (TRM). The TRM is a security margin that accounts for uncertainties of unintended deviations of physical flow, unexpected unbalance and inaccuracies in data and measurements. The TRM values for each connection in the Nordic system are agreed upon in the System Operation Agreement. When TTC and TRM are calculated, the NTC value can be calculated from Equation 2.1 [12].

$$NTC = TTC - TRM \tag{2.1}$$

In the continental Europe, the term Available Transfer Capacity (ATC) is most often used instead of NTC. The ATC value is the calculated NTC value minus the relevant long-term nominations between countries. Long-term nominations are reservation of physical transfer capacity, and these are not allowed in the Nordic countries due to the total capacity between price areas are reserved the spot market. Therefore, the NTC is used in the Nordic system, and further in this thesis.

In Norway, Statnett use transfer capacities calculated up to one year in advance as a starting point when the capacities in price areas are set for the next day[13]. In addition, Statnett runs a weekly power flow simulations to investigate the consequence of planned revisions or outages in the grid[14]. To determine the NTC on an interconnection between two countries, the TSO in both countries calculate the capacity and then use the lowest NTC value. In the calculation of the NTC, both the constraints on the connections between price areas and the transmission constraints inside the areas have to be taken into account.

The market clearing algorithm Nord Pool Spot use today is called Euphemia[15]. This algorithm use a linear constrained optimization algorithm, with an objective function that maximizes the social-economic surplus. The algorithm finds the optimal solution for exchange of power based on capacities and bids from the market. The NTCs between the price areas are the constraints in the market. The grid loss and actual power flow are not accounted for in the algorithm, and leads to deviations between actual and modelled power flow. This deviation is a disadvantage of the NTC method[13].

The NTC and Flow-based (FB) algorithm is formulated generally in the Equation 2.2 [9].

	NTC formulation	**Flow-based formulation**	(2.2)
Objective function:	Maximize social-economic surplus	Maximize social-economic surplus	
Subject to:	$\sum NP_s = 0$	$\sum NP_s = 0$	
	NTC constraints	FB constraints	

In the formulations, the net position NP_s is the difference of supply minus demand. The two formulations show that both have the same objective function, but different constraints. The NTC formulation have stricter or similar constraints compared to the FB formulation, and results in a solution domain for the NTC that is the same or smaller than the FB formulation. This implies that FB gives a theoretically better or equal market solution compared to the NTC method[9].

Chapter 3 further discuss this difference and the flow-based market clearing.

Chapter 3 - Flow-based market coupling

This chapter further introduce flow-based market coupling and argue why it theoretically is a better solution for the Nordic power market than the NTC methodology. Section 3.1-3.6 in this chapter is a processed version of chapter 3 in the project assignment “Flow based market clearing: GSK strategies”[2].

3.1 Introduction to Flow-based market coupling

As earlier mentioned, the Nordic TSOs are investigating the possibility of introducing the FB method in the market clearing, and phase out the present NTC method. The reason for this is the actual gain by increasing the transmission capacity, and in addition a political pressure. In 2014 The European Commission stated in the report *Establishing a Guideline on capacity Allocation and congestion management* [16] that; “The flow-based approach should be used as a primary approach for day-ahead and intraday capacity calculation where cross-zonal capacity between bidding zones is highly interdependent. The coordinated net transmission capacity approach should only be applied in regions where cross-zonal capacity is less interdependent and it can be shown that the flow based approach would not bring added value.”.

In the Nordic countries, SINTEF Energi performed in 2013 simulations on behalf of Statnett, comparing the FB and the NTC method. The results of these simulations showed that FB had a higher socio-economic surplus, better utilization of the transmission grid and more frequent price convergence than the NTC method[17]. These results are all in favour of the FB method, but there is a need to further investigate and test the FB approach before possibly implementing it in the Nordic countries.

3.2 General principles of Flow-based market clearing

One fundamental difference between the NTC and FB method are the drivers of the market-clearing algorithm. In today’s NTC method, the TSOs make capacity allocation in advance of the market clearing. The FB market clearing on the other hand include a simplified grid model in the market-clearing algorithm. The simplified grid model allows the market to prioritize flows, regarding the most economically efficient solution of managing congestion. This leads to a more market driven approach, and increases the capacity. Because of the algorithms ability to model how trades from different bidding areas affects the critical elements in the grid, the algorithm can increase the solution domain for the FB formulation, and thereby increase the transmission capacity. The FB algorithm simulates the actual power flow between bidding areas when a trade occur, and the transmission capacity can increase on profitably ways of trading, by accounting for smaller loss in other trades. This increased solution domain and transfer capacity for the FB method versus the NTC method is illustrated in Figure 4. In Figure 4 NTC is represented by the ATC(Available transfer capacity), because it is the most common term in the continental Europe. As earlier mentioned in section 2.3, the ATC value is the calculated NTC value minus the relevant long-term nominations between countries[9].

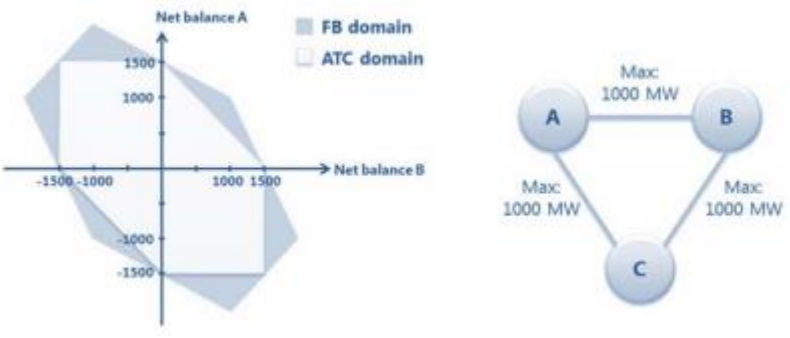

Figure 4: Solution domain for the FB and the NTC formulation illustrated to the left and the grid topology the right[9]

3.3 Market coupling

The flow-based method can increase the transfer capacity in the market coupling compared to the current method. This market coupling can be described in three different phases; pre-market coupling, market coupling and post-market coupling[9].

In the predatory phase, pre-market coupling, the TSOs calculate capacities and the solution domain in order to deliver grid constraints. The market coupling builds on a base case, containing grid topology, expected net positions and the corresponding flows of all critical network elements(CNEs)[1] for the next day D. The first task for the TSOs is to calculate these factors. Then the TSOs defines the GSKs, CNEs, the corresponding outages and other parameters, in order to create the PTDFs and the market margins or capacities. These parameters will be further explained later in this chapter.
At the end of the pre-market coupling, the parameters are verified and thereafter sent to

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[1] A critical network element is a network element that the TSOs requires to monitor for potential overloads in the future. A network element is a component(e.g. a line or transformator) in the power grid exposed to an electric flow induced by generation and consumption.

NordPool Spot. This phase starts the evening two days before operation, day D-2, and last until 10:00 day D-1, when NordPool Spot publishes the parameters.

The actual solving of the market is called market coupling or market clearing. Market coupling and market clearing are two equal terms, and in this thesis both expressions are used. The Power Exchange perform the market coupling, starting at 10:30 by publishing the FB parameters received from the TSOs pre-market coupling. Then the Power Exchange receives bids from market actors, and the market equilibrium is calculated. The market coupling ends at 13:00 when market results are published.

The last phase of the market coupling is the post market coupling, performed by the TSOs. In the post market coupling market results are verified, congestion income shared and operational security is analysed[9].

3.4 Power transfer distribution factors (PTDFs)

In the FB method, the grid model contains Power Transfer Distribution Factors (PTDF’s), which is the linear relationship for the lines. PTDFs provide information of how a power injection in an area load critical lines in the grid. The PTDF is also called a sensitive parameter because it describes the incremental impact on the system power flow from power transmitted between two nodes or areas.

To calculate how the flow on a transmission line changes with a power transaction between nodes in the system, the PTDFs are used. The PTDF’s provides a linear relationship between the total transferred quantity and the power flow on a specific line[18].

The calculation of the nodal PTDF is based on a standard set of power flow equations. The standard derivation of the power equations results in Equation 3.1 [9].

$$PTDF_{ik,n} = \beta_{ik}(Z_{BUS,in} - Z_{BUS,kn}) \qquad (3.1)$$

where

$PTDF_{ik,n}$ is the PTDF from node n to the line between nodes i and k.

β_{ik} is the susceptance between node i and k, with negative sign. It corresponds to the inverse of the reactance matrix, with the assumption that the resistance is neglected.

$Z_{BUS,in}$ and $Z_{BUS,kn}$ are the impedance matrix, or the inverted Ybus matrix, from respectively node i and n, and node k and n.

The calculation of PTDFs for a line is based on the physical characteristics of the line. A line’s PTDFs are constant if the reactance and grid topology remain unchanged. The TSO calculates the PTDFs ahead of the load flow analysis. The TSO also defines a slack node as the starting point for the calculation of the load flow equations. The choice of slack node will affect the result due to the fact that the pre-calculated PTDFs will give the correct loading on each single line in the grid.

The PTDF describe how a power injection in a node affects the lines in the grid. This relationship is sown in Equation 3.2, and express a lines power flow by the use of a PTDF[14].

$$P_{i,j} = PTDF_{i-j,m-n} \bullet P_{m-n} \tag{3.2}$$

where

$PTDF_{i-j,m-n}$ is the part of a transaction from node n to node m that flows on the line from node i to node j.

P_{m-n} is a new transaction in the grid that will lead to a change in the line flow, P_{i-j} based on the PTDF.

A PTDF describes the electrical impact on nodes, and the PTDF therefore affects the prices at Elspot. In flow based market clearing, the price relation (MCP) between area i and area j is shown in Equation 3.3[19].

$$MCP_i - MCP_j = \sum_{cb} (PTDF_j^{cb} - PTDF_i^{cb}) \bullet \mu_{cb} \tag{3.3}$$

where

$(PTDF_j^{cb} - PTDF_i^{cb})$ is the impact of the PTDFs, and then summarized for all nodes.

μ_{cb} is the shadow price[2] the grid constraint receives in case of a congestion. The shadow price will be the increase of the objective function when the grid constraint is relieved with 1 MW.

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[2] A shadow price, or dual value, is the maximum price for an extra unit of a given limited resource. In this context, the dual value can be a constrained transmission capacity of a specific CNE.

According to Equation 3.3, if there is no congestion in a power system (i.e. right hand side of the equation is zero), the price in the whole system is equal to the system price. If congestion occur, prices in different bidding areas are set in accordance to their PTDF factors (i.e their electrical impact on the bidding constraints), and different bidding areas will have different prices[19].

3.5 Aggregating nodal PTDFs to area PTDF

The PTDFs are so far in this thesis only discussed for a simple network on a nodal basis. The Nordic system will after the implementing of the Flow-based market coupling still not be strong enough to eliminate congestion, and the Nordic system will still be divided into several bidding areas. To handle the PTDFs for a larger system, the node-to-line PTDFs have to be aggregated to area-to-CNE PTDFs. To find an area-to-CNE PTDF, node-to-line PTDFs in that area have to be calculated. The node-to-line PTDF, as earlier described, shows the amount of power injected into a specific node that loads a specific line. When calculating different node-to-line PTDFs in an area, as illustrated in Figure 5, not all lines and nodes are necessarily calculated. This is because of the fact that it is only the influence an injection in an area have on the Critical Network Element (CNE) that is important. A CNE is a specific line or a cross section of several lines which limits the power transferred between areas[9]. The non-critical elements have minor or no influence on the system power flow because they does not limit the transfer of power.

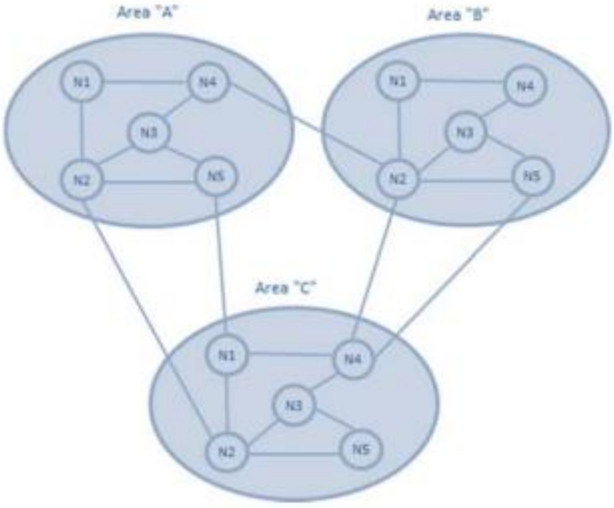

Figure 5: Aggregating of the node-to-line PTDFs into area-to-CNE PTDFs[9]

When aggregating the node-to-line PTDFs into an area-to-CNE PTDF, it have to be accounted for the impact each node have on the line or CNE. If a node is too strongly or too low weighted, the area-to-CNE PTDF is inaccurate. To estimate the area-to-CNE PTDF most accurately, the FB method use shift keys. Shift keys are used to describe how the net position of a node changes with the net position of the area it is a part of. There can be different shift keys related to consumption, generation and different technologies (like wind shift keys).
In this content Generation Shift Key (GSK) is used, and Chapter 4 describes the GSK further.

Equation 3.4 describes the aggregation from nodal to area PTDF formally[9].

$$PTDF_{i,j}^{A} = \sum_{\alpha} GSK^{\alpha} \bullet PTDF_{i,j}^{\alpha} \quad \text{and} \quad \sum_{\alpha} GSK^{\alpha} = 1 \tag{3.4}$$

where

$PTDF_{i,j}^{A}$ is the sensitivity of line i,j to injection in area A

GSK^{α} is the weight of node α on the PTDF of area A

$PTDF_{i,j}^{\alpha}$ is the sensitivity of line i,j to injection in node α.

3.6 Remaining Available Margin

To provide grid constraints to the market optimization in the FB market clearing, the PTDF matrix and the Remaining Available Margin (RAM) are used. The RAM is the available capacity margin of a line that is possible to use in the market clearing. Equation 3.5 show how the RAM is calculated. The relationship between RAM, net position and power flow described in Equation 3.5 is illustrated in Figure 6.

$$RAM = F_{\max} - FRM - FAV - F_{ref}^{'} \tag{3.5}$$

where

$F_{\max}$ - Maximum allowed flow on the CNE

FRM - Flow Reliability Margin

FAV - Flow Adjustment Value

$F_{ref}^{'}$ - The reference flow at zero (FAZ) net position

The F'_{ref} is calculated from Equation 3.6

$$F'_{ref} = F_{ref} - PTDF \bullet NP^{BC} \tag{3.6}$$

where

NP^{BC} - Net position in the Base Case

F_{ref} - The CNEs loading in the base case, given net position reflected in the base case

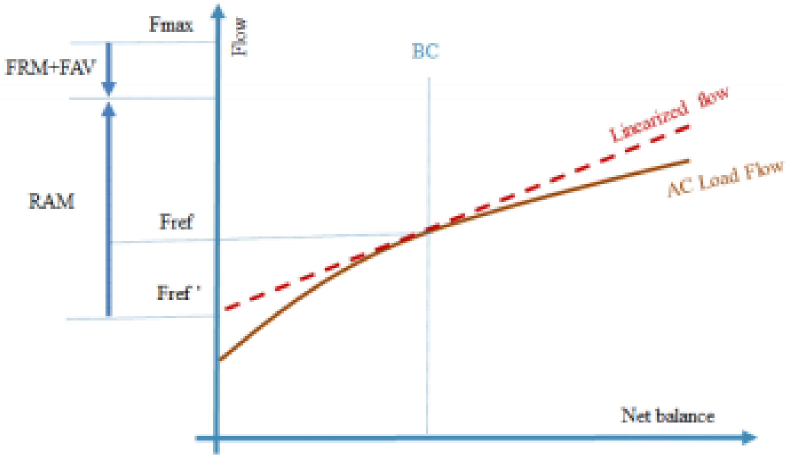

Figure 6: Illustrates the relationship between RAM, net position and flow.[9]

The so-called FB-constraints are formed from the RAMs on the CNEs with their associated PTDFs in Equation 3.7[9].

$$PTDF \bullet NP \leq RAM \tag{3.7}$$

3.7 Flow Reliability Margin

The TSOs cannot precisely estimate the active and reactive flow on each CNE in advance by the flow-based method, due to uncertainty. The uncertainty involved in the capacity calculation for the spot market are caused by phenomena like approximations within the FB methodology (e.g. the GSK), external exchanges and differences between forecasted and realized programs. To prevent flows predicted by the TSOs to exceed the maximum allowed limits of their grid elements, the uncertainty have to be quantified and accounted for in the allocation process. To handle this uncertainty, the flow-based method use the parameter Flow Reliability Margin (FRM). The FRM is a margin reserved in MW, and the size of the FRM is based on a statistical evaluation of the deviation between the forecasted flow of a CNE by the FB method two days ahead, and the actual flow in real time[20].

For each CNE, the FRM reduce the RAM because a part of the free domain provided to the market to facilitate trading across borders have to be reserved to handle uncertainties. This relationship is illustrated in Figure 6.

The approach for determining the FRM values builds on the principle of comparing the results from the flow-based model with observation of the same timestamp in real time. The FRM approach compare the base case day D-2 to a snapshot of the grid day D. The snapshot shows voltages, currents and power flow in the transmission grid at the given time during the present day D.

The approach for the determination of the FRM values is illustrated in the snapshot in Figure 7[9].

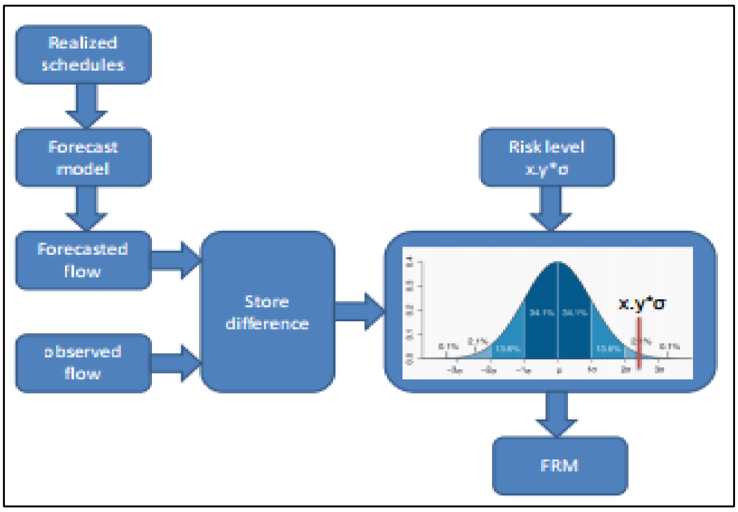

Figure 7: Snapshot illustrating the determination of the FRM value[20]

The flow-based model for day D-2 is adjusted with the realized schedules corresponding to the time the snapshot was taken in order to compare the observed flow from the snapshot with the predicted flow in a proper way. When the schedules are taken into account, both the forecasted and the observed flows accounts for the same commercial exchanges, like intraday trading[9].

The deviation of the actual and predicted flow are further stored for the future to build up a database that allows the TSOs to make a statistical analysis on a significant amount of data. The FRM values are then possible to compute from the distribution of differences between forecasted and actual flows, based on a predefined risk level. According to the report *Methodology and concepts for the Nordic Flow-Based Market Coupling Approach* [9], subsequent effects covered by the FRM analysis by this approach are:

- Uncertainty in load and generation
- Assumptions inherent in the GSK
- Application of a linear grid model, constant voltage profile and reactive power
- Unintentional flow deviation due to operation of load-frequency control
- External trade
- Internal trade

After finding the reference FRM values by the above-mentioned approach, TSOs can use a so-called "operational adjustment" before practical implementation. This small adjustment can be beneficial for the TSOs, because the TSOs should remain critical to the outcome of this theoretical approach in order to ensure the parameters implemented make sense operationally. This kind of manual work are only rarely needed after the theoretical values and the implementation are well tested[20].

The FRM is as mentioned a theoretical reference value. The FRM value is a fixed parameter which should be updated regularly, at least once per year. The reason for regular re-assessment of the FRM value is that the values are a model of uncertainties which the TSOs needs to hedge, considering the constant changing environment the TSOs operate in and the statistical advantage of building up a large sample[20].

Figure 8 summarizes and illustrates the general computation process of the FRM approach.

Figure 8:Summary of the general computation process of the FRM approach[20]

Chapter 4 - Generation Shift Keys

This chapter explains the Generation Shift Key (GSK) in general, and discuss the different GSK strategies considered in the Nordic countries. The chapter is an adapted version of chapter 4 in the project assignment “Flow based market clearing: GSK strategies”[2].

4.1 Generation Shift Key in brief

Generation Shift Keys (GSKs) are in the flow based method used to describe how a change in net position of an area is divided on the nodes in that specific area. Equation 3.4 in chapter 3 shows how the FB method use the GSK to aggregate the node-to-line-CNE PTDFs to area-to-CNE PTDF. The GSK must be linear, due to convexity pre-requisite of the flow based domain. The GSK values are given in dimensionless units, and they can vary for each hour and area[9].

The GSK’s purpose to give the best forecast of the impact on critical branches of a change in net position, when the operational feasibility of the reference production program, projected market impact on units and market risk assessment are accounted for[2].

Normally, the GSK includes power plants that are market driven and flexible in electrical output, like hydro and gas. Less flexible units like nuclear will additionally be used by the TSOs if there is not sufficient capacity of flexible generation matching the planned export or import, or if it is preferable to moderate the impact of the flexible generation units. In the Nordic area, the share of flexible power plants are large and the generation shift key is therefore chosen in this area[20].

4.2 GSK strategies considered in the Nordic area

A GSK strategy is rules or linearization methods for generating the GSK to find the most accurate estimated power flow, compared to the real physical flow. There are no theoretical “right or wrong” methodology when determining the GSK strategy, and there is necessarily not only one general optimal strategy. The optimal GSK strategy can be dissimilar for different bidding areas, time slots or countries. Nevertheless, the GSK is an important parameter in the FB calculation, because it may be one of the major sources of inaccuracies in the FB approach. Therefore, eight different GSK strategies are developed to find the optimal way of calculating the GSK values in the Nordic power market[9].

Table 1 lists a brief description of all eight GSK strategies considered in the Nordic power market[14].

GSK number	Production	Load
1	Max($P-P_{min}$)	0
2	Max($P_{max}-P$)	0
3	P_{max}	0
4	1	0
5	P	0
6	P	Max(0|P)
7	0	Max(0|P)
8	0	1

Table 1: The different strategies considered for the Nordic[14]

These strategies have different approaches to estimate the GSK value. Each strategy have a pre-defined weighting of production and load, as shown in Table 1. In general, GSK1-5 weights according to production, GSK7 and GSK8 weights according to load and GSK6 weights according to both load and production. A more detailed description of these strategies follows in the rest of this section[2].

GSK1 weights free capacity to downwards regulation of the production. The nodes with the largest value of the production expression $P-P_{min}$ are weighted the most, and these nodes are therefore largest affected by a change in an area's net position. The Max-statement in front of the production expression have the purpose to avoid negative values if the machine runs as a load in pump operation.

The next strategy, GSK2, weights free capacity to the upwards regulation of production. The weighting of the nodes is similar as in GSK1, but the weighting in GSK2 is the difference of maximum and actual production, $P_{max}-P$. Therefore, the nodes with the largest positive difference of the maximum and actual production are weighted the most, and therefore most influenced by a change in an area's net position. The Max-statement in front of the production expression is to avoid negative values if the machine exceeds the rated load.

GSK4 weights all production equally, and is therefore called a flat strategy. This GSK is a simple and computationally efficient strategy, due to the PTDFs (both the node-to-line and the aggregated PTDFs) only need to be calculated once because of independent weighting of the actual production.

On the negative side, this flat strategy can seem inaccurate because of two reasons. The first reason is that all nodes are treated as generating nodes by GSK4, even though many nodes are not connected to a generator or load. The second reason is that GSK4 makes it is possible for a node to have higher generation than the maximum installed capacity, given sufficient net injection in the nodes area.

Like the first presented strategies, both GSK 3 and GSK 5 only weight production. GSK3 weights according to the maximum production $P_{max,}$, and GSK5 weights according to actual production P. This makes the nodes with respectively the highest P_{max} and P larger weighted than the other nodes.

The only strategy weighting both the production and load is GSK6. This strategy weights according to the actual production and load. The Max-expression in the load for GSK6 sets possible negative affection of the load to zero. The same Max-expression also leads for GSK7.

The strategies weighting load only are GSK7 and GSK8. GSK7 weights all load according to actual load in each node, and GSK 8 weights all nodes equally according to the loads. GSK8 is, as GSK4 a flat strategy. These two flat strategies will have the same advantages and drawbacks. A flat strategy will be further described and discussed in section 4.3[2].

4.3 How to choose a good strategy?

A good GSK strategy contributes to an estimated flow close to the real physical flow. As earlier mentioned, the optimal strategy can be different in different areas and time slots. It is possible and maybe beneficial to introduce different GSK strategies for different areas and/or periods or hours. However, the GSK values are used to calculate the PTDFs before the market clearing, and the choice of GSK strategy will therefore affect the solution domain. For this reason, “there should be harmonized rules guiding how GSKs are defined in order to avoid potential obscure incentives and to insure transparency in the capacity calculation process”, according to the report *Methodology and concepts for the Nordic Market Coupling Approach* [9].

To illustrate the difference between an appropriate and an inappropriate GSK strategy, the continuation of this section introduce an example, based on an example from the above mentioned report [9].

The red and black dotted lines in Figure 9 illustrate how different linear approximations affects the estimated flow. To estimate the flow, linear approximation of the change in flows according to the net positions is used.

A marginal strategy is illustrated by the red dotted line in Figure 9. A marginal strategy distinguishes between the generators that are most likely to produce power and the generators with uncertainty. The marginal technology represents the aggregated PTDFs for the marginal strategy[14].

The black dotted line in Figure 9 illustrates a flat strategy. A flat strategy weights all nodes equal, and the actual flow F_{ref} on the line from i to j is given in Equation 3.6, when rewriting with respect to F_{ref} .

The brown line in Figure 9 represents the actual real flow on a CNE with varying net position.

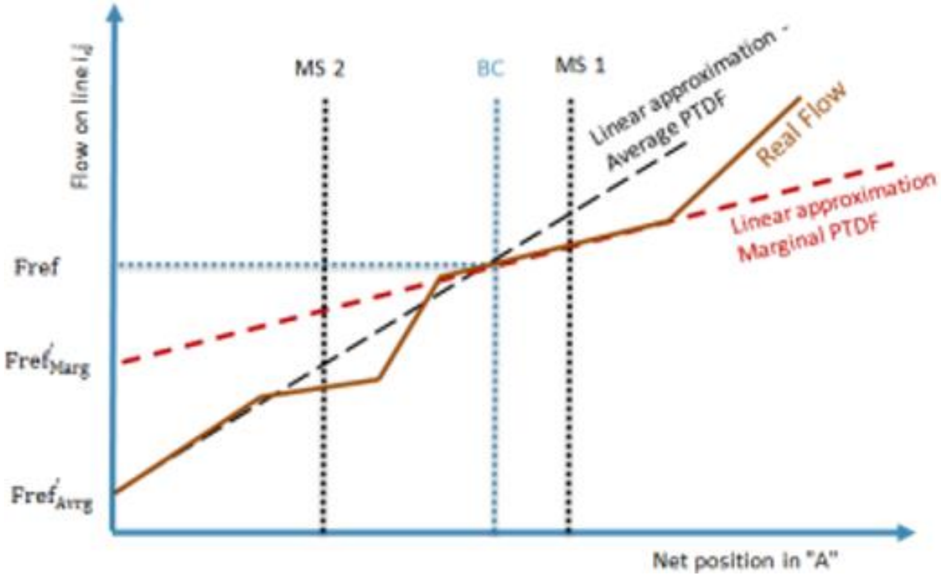

Figure 9: The graph illustrated how good two different GSK-strategies are in different cases. The brown solid line represents the real flow, and the red and black dotted line the estimated flow by respectively a marginal and a flat strategy[9].

The above figure illustrates three cases. In the first case with net position MS2, the flat strategy is the best choice. The flat strategy estimates a more accurate flow than the marginal strategy in this case illustrated in the figure.

If the market solution turns out to be the base case BC, both a flat and a marginal strategy will give an estimated flow equal to the actual flow. The base case is represented by the blue dotted BC-lines in Figure 9.

When market solution is the net position MS1, the marginal strategy will give an approximated flow close to the real flow, according to Figure 9. The flat strategy on the other hand, is located further way from the real flow line and will therefore give a less accurate flow than the marginal strategy.

These cases illustrates the general behaviour of the different approaches. A flat strategy may be a more robust strategy when the market solution is far from the net position of the base case. The flat strategy is most often the strategy closest to the real flow, but it only occasionally predicts the right flow. The marginal strategy presumed most accurate when the market solution is close to the base case. On the other hand, the marginal strategy predicts a flow further from the real flow than the flat strategy when the flow predicted is not right. Therefore, these two different GSK strategies gives the choice between robustness versus accuracy[9].

It is also important to investigate regularly how the estimated flow performs compared to the actual power flow. If needed, the GSK values should be calibrated for the future[9].

In the Central Western Europe (CWE), Flow-based market clearing was implemented in May 2015. The TSOs in the CWE use different GSK strategies. In German, the GSK values are regularly investigated, and the procedure is a bit different for the different German TSO's. TransnetBW updates the GSK every season. Based on an internal analysis performed for the year 2012, a seasonal dependence of power plant availability can be highlighted.
Amprion use a monthly evaluation of the GSK's. When evaluating the GSK, Amprion checks for example whether there are new power plants in the grid or whether a block out of service occur. According to these monthly changes in the grid, Amprion updates its GSKs.
For TenneT, the system TTG considers, the middle and peak load power plants as potential candidates for the GSK's[20].

To access and compare the flow deviations of using different GSK strategies, the CWE countries use the parameter FRM. The method of comparing GSKs in CWE takes into account the physics of the different CNEs, i.e. if the CNEs have largest production or consumption.

A similar method using FRM to values comparing the GSK strategies in different areas will be further discussed in Chapter 5. This method is less based on the physical characteristic of CNEs and areas.

Chapter 5 - Method

In the project assignment “Flow based market clearing: GSK strategies”[2], which this thesis is a continuance of, both relative, absolute and standard deviation of the real and estimated flow was calculated in a script in Visual Basic to find the best and worst GSK strategy in general and in each area. This approach to find optimal GSKs is assumed not that precise and efficient because of the way the strategies were compared. In addition, Visual Basic is not assumed as the most efficient programming language.

This thesis has the purpose to make a similar study, with the same objective to find the optimal GSK to minimize the error of predicted flow. This thesis search for optimal GSK in each area, with focus on making the time duration of the code shorter and the calculations more precise than in the project assignment.

The calculations are done in a code in Python. Python is here chosen because it is an efficient and strong programming language, and the deviation approach used is based on the FB-factor Flow Reliability Margin (FRM). The approach using FRM parameter to access and compare the flow deviations of using different GSK strategies is in use in the CWE countries. The method presented in this thesis take less into account the physics of the different CNEs, i.e. if the CNEs have largest production or consumption.

This chapter explains the method used to find the optimal GSK strategy in each Nordic bidding area based on the FRM approach. The FRM approach is explained in section 3.7, and is in this work used to consider and compare different GSK strategies in a Python code with the objective to find the combination of optimal of GSK strategy in each area. The code will be further explained in the continuation of this chapter.

5.1 Data and the comparing method

In this thesis, the FRM approach is used to investigate and compare the different GSK strategies considered in the Nordic area. Katherine Elkington in Svenska Kraftnät have prior this thesis made a code in Python using the FRM approach. This code have in this thesis been re-written in cooperation with Johan Setreus from Svenska Kraftnät. This code is explained in the next sections.

After the code were written and tested, the work was to plot and analyse the results. The period investigated is 01.02.2016-17.04.2016. This period was chosen due to available data and with the purpose to study a long lasting period.

The Python code extracts useful data from Power World files and use these data in further calculations. The Power World files produced by the Nordic TSOs includes data for simulation of the Common Grid Model (CGM) with the FB method for all areas and all GSK strategies considered in the Nordic countries.

Each data file contains operational data for one hour of operation one day. In the top of each file, the different bidding areas and the interconnectors between the areas are all listed together with their net positions. Further, there are information about the CNE number and name, flow, FAZ, FRM, FAV, RAM and the PTDF matrix , given for one strategy at the time. Results for the event when one strategy is used in all CNEs are then the data in the files. The same is done for all eight strategies, and GSK1 is presented first and GSK8 at the end of the files.

The Power World files includes two different types of files for each hour, one for the actual day D and one for the comparing day D-2. The files for day D are snapshots from the real world, while the files for D-2 are scaled files based on prognosis. In the start of this thesis, the files was not scaled, and the resulting GSKs did not change when iterating because the data for D-2 did not take into account for changes in the grid.

After the Nordic TSOs produced scaled files, including changes in grid topology, day D and D-2 had a proper relationship and realistic simulations was then possible to perform. The files for D-2 now includes the grid topology for day D and the net positions for day D-2. The files for day D are improved from the files used in the project assignment by finding and improve errors in the underlying data used to produce the files. In addition, the Baltic interconnection SE4_NordBalt is included in the new files.

Figure 10 shows how the observed CGM[3] snapshot for day D (down to the left in the figure) and the forecasted CGM base case for D-2(in the upper left corner of the figure) are used in the calculation of the prediction error. This prediction error is the basis in the FRM approach.

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[3] CGM stands for Common Grid Model, and represents the interconnected system and facilitate transmission capacities to be calculated in a coordinated manner. The CGM includes the system with the locations of generation and load units relevant for capacity calculation, grid topology and rules to change this factors during capacity calculation(9)

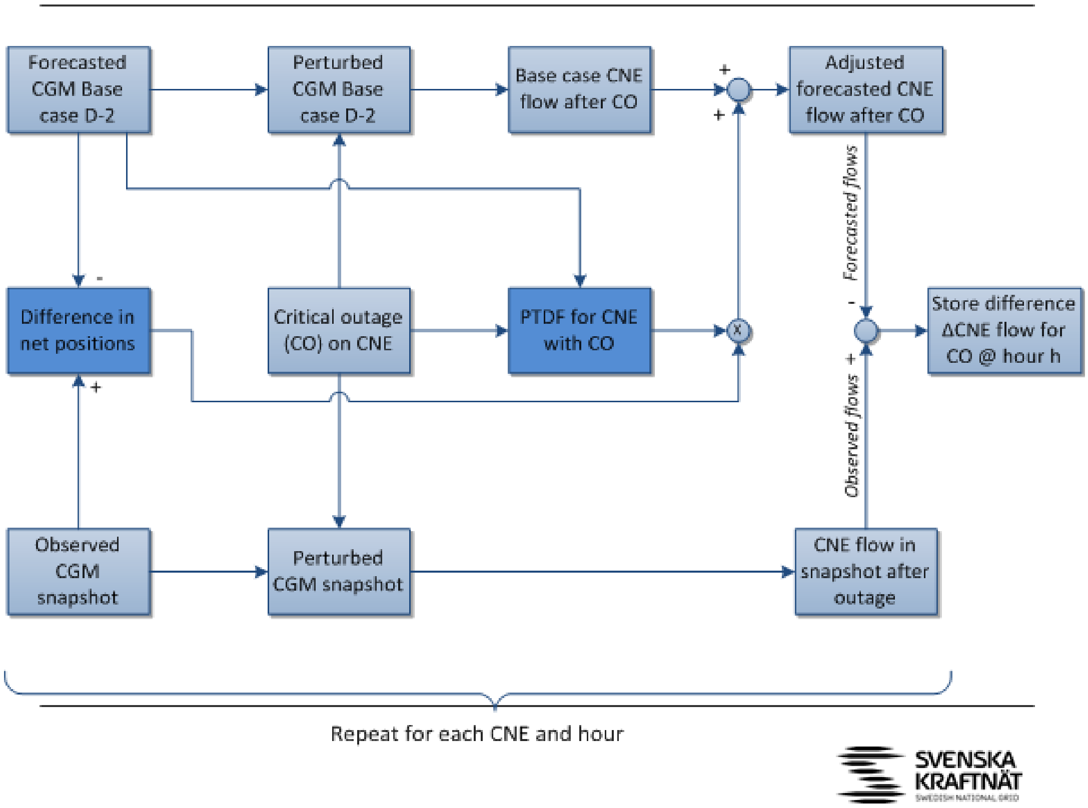


Figure 10: This figure describes how to calculate the prediction error that is the basis for the FRM [21]

In the Python code, Power World files for both day D and D-2 are read in the first iteration and stored in binary files. The following iterations obtain data from these binary files, and use them in the same way as in the first iteration. Binary files are used with the purpose to reduce the time usage related to opening and reading data from files. The reason that the code iterates is that a change in one area can affect the nearest areas. Therefore, a change of the optimal GSK in one area can affect which GSK optimal in another area. The code and the iterations are further explained in the next section.

The main data in the files are the net positions for all areas in addition to the flow on each CNE and the corresponding changes in the PTDF matrix for each GSK strategy. The CNE number and name is the same for all strategies.

The PTDF matrix represents the relationship between the CNEs in the Nordic transmission grid and the bidding areas. There are around 2000 CNEs and 12 bidding areas in the Nordic grid. In these files, the interconnectors in the Nordic main grid are written as virtual bidding areas, making the number of areas in the data files 27. The size of the PTDF matrix is therefore large, around 2000x27, 2000rows and 27 columns. For each GSK strategy there is one PTDF matrix for each hour of the day. This results in eight different PTDF matrices for each hour.

To reduce the time usage of the code, the optimization code reads a list of limiting CNEs produced by another code, and only includes these CNEs in the calculation. When reducing the numbers of CNEs to test, the code use less time to read data and perform the calculations.

The procedure finding the limiting CNEs in the system and then exclude the non-limiting CNEs, have been challenging. The reason for is that the limiting CNEs can be different for each hour of operation, and therefore a list of limiting CNEs are needed for each hour in the period studied. There exists no current file for the limiting CNEs for all dates. Therefore, a code was created to find the limiting CNEs in the Nordic grid. By use of some of the codes written earlier by the Nordic TSOs in the flow-based work, this code downloads NTC data from nordpoolspot.com and then calculate the limiting CNEs for each hour. The criteria for a limiting CNE is RAM(MW) + MZ at Zero – max_flow <1 MW. To store the calculated limiting CNEs for each hour, a csv file including the date, hour and CNE number is created. This csv file is the file of limiting CNEs used in the optimization code.

Another problem with these files was that some individual hours in the period does not exist and some have files that contains only zero as flow values. The files containing zeros as flow values result in error when clipping FRM results. If the FRM is higher than the CNE limit, the FRM value is set to the CNE limit. The code finds the CNE limit from the last hour in the simulation. When there are only zero values for that hour, the result is nan-values.

These two problems are fixed by two tests in the code. Both the hours without files and the hours with files containing only zero interface flow are skipped if the tests are true. Most of the hours have several version of files after the TSOs have upgraded the previous version. The newest version of the PW files are always used in this code, except when the new file exist of zeroes. Then the last version of the files is used. If the hour neither have files including non-zero values for day D or D-2, the hour is skipped.

The main code reads these files, and finds the limiting CNEs for the given hour. The rest of the code only reads data from the Power World files and do calculations for limiting CNEs. Per hour, the number of limiting CNEs is most often are in the range 10-20, and some hours have the same limiting CNEs. For the studied period 01.02.2016-17.04.2016 the total number of limiting CNEs is 227. Including only these limiting CNEs leave out unimportant data from the non-limiting CNEs and reduce the calculation time of the code considerably.

5.2 Brief description of the code

The objective of the code is to find the optimal GSK strategy in each area in the Nordic system, based on the FRM approach with the objective to minimize the FRM norm. The code is split up in two parts. The first part finds the limiting CNEs in the period studied and calculates the FRM limits. The FRMs are calculated for the initial strategy in each area.

The second part is the optimization of the GSKs in each area. This code reads the limiting CNEs from the first part of the code, and calculates the prediction error and the FRM norm for different GSK strategies. The prediction error is illustrated in Figure 10, while the FRM norm is further explained in section 5.3.

In the first part of the optimization, a parameter decide if the GSK strategy is set from a predefined list, or if the strategy in all areas is set to be the initial strategy. The initial strategy is then set by the user before starting the code.

After deciding initial GSK strategy, one area at the time is tested with another GSK strategy. First GSK2 is tested in area 1. If the FRM norm for this situation is lower than the initial, GSK2 is set as optimal GSK in this area and GSK2 included in the list of optimal GSKs. If not, the initial strategy is still optimal, and GSK2 is tested for area 2. This continues for all areas for this strategy, and then the next strategies until all is tested. If the initial GSK is not GSK2, also the initial GSK is tested in all areas because the combination of GSKs in all areas can make it beneficial to change back again to the initial GSK in some areas.

After all GSKs are tested in all areas, the code is considered iterating. The initial strategies in the next iteration is then the resulting list of optimal GSKs after the last iteration. The FRM norm and optimal GSKs is tested the same way as for iteration 1. It can be beneficial to iterate because a change in one area may affect the system and further which GSK optimal in the nearest areas. A so-called brute-force optimization is used in this code to test the optimal strategies, and if advantageous it iterates as long as there are changes in the list of optimal GSKs during the iteration.

Because iterating is time demanding, section 6.1 discuss if iterating is beneficial in the search after optimal GSKs, and if necessary the section discuss how many iterations preferable.

When there are no changes in the list of optimal GSKs for an entire iteration, the optimal combination of GSKs in each area is found. The code then plots a delta function telling how good each GSK performs in each area. The best strategy is set to 100%. All strategies starts with a delta value of 100% initially. If a tested GSK results in a lower FRM norm than the preliminary best FRM norm, the tested GSK is the current best GSK strategy and added to the list of optimal GSKs. Delta for the until then optimal GSK therefore decreases. The change in FRM norm between the old and new optimal GSK is subtracted from the last delta value of the tested GSK in that area, shown in Equation 5.1. The last delta value of the until then best GSK strategy is 100%.

$$\Delta[area][gsk] = \Delta[area][gsk] + ((\mathrm{best\,FRM}) - \mathrm{OldOptFRM}) / \mathrm{OldOptFRM}) * 100 \qquad (5.1)$$

If the FRM norm for the tested GSK is higher than the best FRM norm, the tested FRM does not improve the FRM norm and this GSK is not optimal. The difference between the tested and best FRM norm is subtracted from the last delta value of the tested GSK in that area, shown in Equation 5.2.

$$\Delta[area][gsk] = \Delta[area][gsk] + ((\mathrm{best\,FRM}) - \mathrm{TestFRM}) / \mathrm{TestFRM}) * 100 \qquad (5.2)$$

The theoretical part of the FRM approach is explained further in section 5.3, and the code including the delta calculation is illustrated in the pseudocode in Appendix A.

5.3 The FRM approach used in the Python code

The theoretical use of the FRM approach in the Python code is developed by Katherine Elkington in Svenska Kraftnät [22], and is further explained in this section.

The objective in the code is to find the optimal GSK strategy in each area, which corresponds to the combinations of GSKs in all areas giving the lowest FRM norm value. To find the best combination of GSKs in all areas resulting in the lowest FRM norm value, the PTDFs are evaluated for different GSKs for each area. By assuming known flows for day D, the difference between the actual flow and the flow calculated based on the forecasted PTDFs for day D-2, is calculated. To calculate this deviation, the following equations 5.3-5.5 are used:

$$\begin{array}{c} D{-}2 \\ \mathrm{CNE}_1 \\ \mathrm{CNE}_2 \\ \vdots \\ \mathrm{CNE}_m \end{array}
\begin{array}{c} \begin{array}{cccc} \mathrm{GSK}_1 & \mathrm{GSK}_2 & \mathrm{GSK}_3 & \mathrm{GSK}_n \end{array} \\ \left[\begin{array}{cccc} \mathrm{PTDF}_{1,1} & \mathrm{PTDF}_{1,2} & \dots & \mathrm{PTDF}_{1,n} \\ \mathrm{PTDF}_{2,1} & \mathrm{PTDF}_{2,2} & \dots & \mathrm{PTDF}_{2,n} \\ \vdots & & & \\ \mathrm{PTDF}_{m,1} & \mathrm{PTDF}_{m,2} & \dots & m,n \end{array}\right] \end{array}
\begin{array}{c} \\ \mathrm{AREA}_1 \\ \mathrm{AREA}_2 \\ \vdots \\ \mathrm{AREA}_m \end{array}
\begin{array}{c} D \\ \left[\begin{array}{c} \mathrm{NP}_1 \\ \mathrm{NP}_2 \\ \vdots \\ \mathrm{NP}_n \end{array}\right] \end{array}
+
\begin{array}{c} \\ \mathrm{CNE}_1 \\ \mathrm{CNE}_2 \\ \vdots \\ \mathrm{CNE}_m \end{array}
\begin{array}{c} D{-}2 \\ \left[\begin{array}{c} \mathrm{FAZ}_1 \\ \mathrm{FAZ}_2 \\ \vdots \\ \mathrm{FAZ}_n \end{array}\right] \end{array}
=
\begin{array}{c} \\ \mathrm{CNE}_1 \\ \mathrm{CNE}_2 \\ \vdots \\ \mathrm{CNE}_m \end{array}
\begin{array}{c} D{-}2, D \\ \left[\begin{array}{c} \mathrm{Flow}_1 \\ \mathrm{Flow}_2 \\ \vdots \\ \mathrm{Flow}_n \end{array}\right] \end{array}
\qquad (5.3)$$

$$\begin{array}{cc} & D-2,D \\ \begin{array}{c}\text{CNE}_1\\\text{CNE}_2\\\vdots\\\text{CNE}_m\end{array} & \begin{bmatrix}\text{Flow}_1\\\text{Flow}_2\\\vdots\\\text{Flow}_n\end{bmatrix}\end{array} - \begin{array}{cc} & D,D \\ \begin{array}{c}\text{CNE}_1\\\text{CNE}_2\\\vdots\\\text{CNE}_m\end{array} & \begin{bmatrix}\text{Flow}_1\\\text{Flow}_2\\\vdots\\\text{Flowl}_n\end{bmatrix}\end{array} = \begin{array}{cc} & D \\ \begin{array}{c}\text{CNE}_1\\\text{CNE}_2\\\vdots\\\text{CNE}_m\end{array} & \begin{bmatrix}\text{Error}_1\\\text{Error}_2\\\vdots\\\text{Error}_n\end{bmatrix}\end{array} \tag{5.4}$$

where FAZ is the flow at zero net position, given in the Power World files.

Then an array containing all FRM values can be calculated, such that

$$\text{FRM} = \begin{array}{c}\text{CNE}_1\\\text{CNE}_2\\\vdots\\\text{CNE}_m\end{array} \begin{bmatrix}\text{FRM}_1\\\text{FRM}_2\\\vdots\\\text{FRM}_n\end{bmatrix} \tag{5.5}$$

where FRM_i is a function of the set of Error_d for all d in the wanted period, and i is the areas number. Error_d are calculated from the approach illustrated in Figure 10 in section 5.1, and is observed flow minus predicted flow.

The objective function in the code is shown in Equation 5.6. It is a weighted Frobenius norm of the CNE FRMs, also called FRM norm.

Frobenius norm $$\mathrm{F(x)} = \sqrt{\sum_{i=1}^{n}\left(\frac{FRM_i}{\sqrt{Capasity_i}}\right)^2} \tag{5.6}$$

where

$x = \{GSK1, \mathrm{GSK}\,2, \ldots \mathrm{GSK}\,6\}$

i = the number of the area, from 1 to n.

The expression in Equation 5.6 weights larger lines more than other lines, because the larger lines have a larger impact on the overall system. The objective function express the relative deviation between the actual and calculated flow. In the start of the code, a GSK strategy is set as the initial strategy. Then all GSKs are tested in all areas, and if change of the GSK strategy in one area reduces the current value of the objective function, the new GSK is assumed optimal for that area and included in the updated list of optimal GSKs. The code loops for all strategies, areas and a number of iterations, before finding the optimal GSKs.

The number of iterations is a variable set prior start of the code. If the list of optimal GSKs does not change for a whole iteration, the code ends and the optimal GSKs and the objective value are determined. The reason for considering iterating is because a change in one area may affect other parts of the system, and thereby what affect which GSK optimal in the nearest areas.

The pseudocode of the Python code developed in this thesis are illustrated in Appendix A[22].

5.4 Simplifications in the code

At the start of this work, the original code was not running. After doing some changes in the code, it run for one iteration. The next task then was to improve the code by making it code more efficient and present the results. In addition, the files for day D and day D-2 had the same grid topology in the files. This observation of similar grid in files were found after a few weeks in this work, and resulted in similar results when changing the GSK in each area. After running this code, the optimal GSK in near all areas was the initial GSK.

Because of this, new scaled files were produced by the Nordic TSOs and the whole code were re-written by help of Johan Setreus. The code now uses more advanced methods to more precisely and efficient find the optimal GSK in each area. One of the main changes performed to decrease the time usage was reducing the number of CNEs read and processed from the PTDF-files. Because only the limiting CNEs affects the system, only the limiting CNEs are included for each hour of operation. The code finds the limiting CNEs for each hour of operation by first download NTC data from nordpoolspot.com, and thereafter calculate the limiting CNEs for the period and store these data in a csv file.

In the continuation, the code opens the csv files, and retrieve data only for the limiting CNEs from the Power World files. The total number of CNEs in the Nordic system is around 2000, while the number of limiting CNEs differs for each hour of operation and varies most often in the range from 10 to 20. The CNEs limiting changes for some hours and for the period 01.02.2016-17.04.2016 the total number of CNEs is 227. This reduction of data reduce the time usage of the code considerably.

Another change reducing the time consumption of the code is related to the observation that GSK1 and GSK5 are the same strategy as their implemented in the Power World files today. GSK1 theoretically includes the minimum production, but this parameter is set to zero in the Power World files. Therefore, these two parameters are the same, and GSK1 is not implemented in the right way in the files today. GSK1 is by this argument neither implemented in the Python code nor discussed more in this thesis. Because GSK5 is implemented in the right way in the files, the strategy is presented and discussed in the continuation of this thesis.

Chapter 6 - Results

In this chapter, optimal GSK strategies calculated by the code are presented and discussed. This study focuses on the area level, where all CNEs are sorted to their respective area.

The period studied are 01.02.2016 - 17.04.2016. The period is chosen due to available data and with objective to study a long-lasting period.

Each weekday in the code is estimated based on a previous weekday. At the start of the code, 03th of February is the first present day, with 01th of February as the previous day. The period starts with 03th of January as the present day because the first available day in the data files is 01th of February and the base case for a "normal" weekday is the day two days prior.

The exceptions from a "normal" weekday is Monday and the weekend. The base case for Monday is Friday, and every Saturday and Sunday are estimated based on the previous Saturday and Sunday, respectively. The reason for these exceptions are that the weekend have a different load than the other weekdays. All weekdays from Tuesday to Friday are estimated based on day D-2 two days prior.

6.1 Simplifications and limitations

The total period in this thesis is 11 weeks. In the start of this work the objective was to study a longer period, e.g. a whole year. Because of an observation after a month in this work, there were needs for files for both the current day D and the base case day D-2. This observation discovered that the changes in the grid were not accounted for in the current files. Because of this, the Nordic TSOs made files for day D-2, and the last files were produced in the end of May. There were not time to produce files for a longer period, which limits the period studied to 01.02.2016 - 17.04.2016.

The final code for optimizing the GSK in each area use around 11 hours to perform a simulation of the total period. Therefore, simplifications were made to reduce the time in the running of the code and remove unnecessary calculations for the whole period. Shorter periods were tested to find simplifications and assumptions. It is assumed that these simplifications and assumptions holds for the longer period. Without these simlifications and assumptions the calculation time would be larger than 11 hours.

The subsections below present tests and results for initial GSK, reduction of areas and if any GSKs can be excluded.

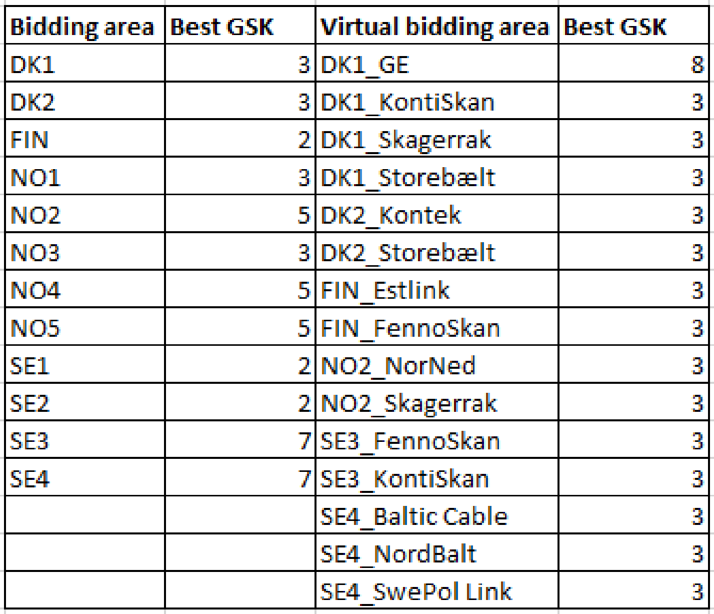
6.1.1 Choice of initial GSK and reduction of areas

Before running the code for longer periods, the choice of initial is studied. Initially the code in this work starts with the same initial strategy in all areas. This subsection discusses if the choice of initial GSK have any impact on the final result. After the discussion, one of the GSKs is chosen as the initial GSK in all areas.

Shorter periods were tested with different initial GSKs with the purpose to study if the initial strategy affects the optimal FRM norm, and therefore also the final list of optimal GSKs in the bidding areas. Samples for several periods up to one month are tested, and all show the same tendency. Only one period, 02-05 March, is therefore presented in this subsection choosing initial GSK.

For this period, results presented in Table 2 indicates that the choice of initial strategy have almost no impact on the real bidding areas. While for the virtual bidding areas, results indicate that the initial GSK is of very large impact.

The results shown in Table 2 show the optimal GSK in each are when GSK3 is the initial GSK in all limiting CNEs in the Nordic system. When the initial GSK is one of the other GSKs, results show that the optimal GSK then is the new initial GSK for mainly all virtual bidding areas. The optimal GSK for the real bidding areas is mainly the same, independent of initial GSK. The resulting optimal GSK in each area is presented in Table B1-B6 in Appendix B for all GSK strategies, in addition to GSK3 in Table 2.



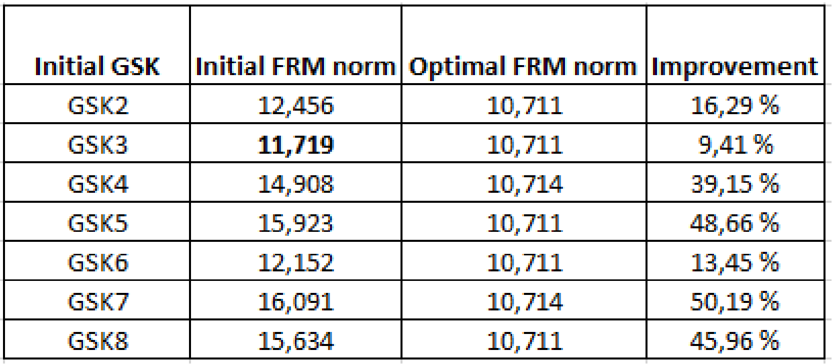
Bidding area	Best GSK	Virtual bidding area	Best GSK
DK1	3	DK1_GE	8
DK2	3	DK1_KontiSkan	3
FIN	2	DK1_Skagerrak	3
NO1	3	DK1_Storebælt	3
NO2	5	DK2_Kontek	3
NO3	3	DK2_Storebælt	3
NO4	5	FIN_Estlink	3
NO5	5	FIN_FennoSkan	3
SE1	2	NO2_NorNed	3
SE2	2	NO2_Skagerrak	3
SE3	7	SE3_FennoSkan	3
SE4	7	SE3_KontiSkan	3
		SE4_Baltic Cable	3
		SE4_NordBalt	3
		SE4_SwePol Link	3

Table 2: Optimal GSK in the real and virtual bidding areas for 02-05 March 2016, GSK3 initial

The virtual bidding areas are the interconnectors in the Nordic power market, and are not real bidding areas. An interconnector is mainly an item in the grid. This causes that we cannot really optimize by weighting between nodes, and the contribution to minimize the FRM norm is therefore almost negligible for the virtual bidding areas. The reason for this result is that when testing and changing GSKs, changing the GSK strategy in the virtual areas have close to zero impact on the FRM norm. Therefore, the GSKs in the virtual areas mainly remain at the initial strategy. The virtual bidding areas are in the continuation of this thesis skipped by these arguments, and only real bidding areas are further studied.

To compare different initial GSKs, the initial FRM norm is used as a factor of comparison. The FRM norm indicates how good the solution is, with the objective to minimize the FRM norm and thereby the error in estimated power flow. The initial GSK resulting in the lowest initial FRM norm is assumed the best choice of initial GSK. The arguments for choosing initial GSK from this approach is that minimizing the initial FRM norm contribute to less change when in the final FRM norm when minimized. In addition, although initial GSK does not seem to impact the optimal FRM norm, we need an initial strategy in all areas in the start of the simulation.

Table 3 shows the initial and calculated optimal FRM norm for different initial GSKs for the period 02-05 March 2016, in addition to the improvement in percent.



Initial GSK	Initial FRM norm	Optimal FRM norm	Improvement
GSK2	12,456	10,711	16,29 %
GSK3	**11,719**	10,711	9,41 %
GSK4	14,908	10,714	39,15 %
GSK5	15,923	10,711	48,66 %
GSK6	12,152	10,711	13,45 %
GSK7	16,091	10,714	50,19 %
GSK8	15,634	10,711	45,96 %

Table 3: Initial and optimal FRM norm, in addition to the improvement, period 02-05 March 2016

According to Table 3, the choice of initial GSK have large impact on the initial FRM norm, and only a minor impact on the optimal FRM norm. Results indicate that the initial GSK only have minor impact on optimal FRM norm, probably because the optimal GSKs found for the bidding areas are really the same after running through the combinations, independent of initial GSK strategy. These optimal GSKs are presented in Table 2 for initial strategy GSK3, and Table B1-B6 in Appendix B for the other initial GSKs.

The approach used to find optimal GSK in each area can be described as a simple form of optimization. Before testing, there were a hypothesis that the approach only finds the local minima's without testing all combinations in the search of the optimum. These tests show that the approach do not only finds the local minima's. This observation regarding local minima's is further discussed in section 6.2 studying iteration in the code.

The result indicates that the initial GSK do not affect the optimal combination of GSK in each area after one iteration. This result also supports that the order of GSKs tested, i.e. GSK8,GSK7, …, GSK2 instead of todays ascending order, is of minor or no impact to the optimal GSK in each area. The order is therefore always ascending from GSK2-GSK8 in the rest of this work. The order of testing the GSKs is also verified through testing.

According to Table 3, GSK3 weighting maximum production is the most appropriate initial strategy.

If all CNEs in all areas have the same GSK, Table 3 indicate that GSK3 is the best global strategy. This study show that optimizing the combination of GSKs in the areas instead of having the same GSK in all CNEs in all areas, decrease the FRM norm compared to the initial value. Therefore, it is beneficial to have an optimized combination of GSKs in each area instead of one global strategy.
In the rest of this thesis only the area level with optimized GSK in each area is studied.

In the continuation of this thesis, GSK3 is chosen as the initial GSK because of smallest initial FRM norm in tested periods. This choice is assumed to be of minor importance because the virtual bidding areas are excluded in the rest of this study, and the results in this section show that the choice of initial GSK have minor or no influence on the final optimal FRM norm and consequently also the optimal GSK in each area.

6.1.2 Can any GSKs be excluded?

Until now, GSK1-8 have been presented and GSK1 is skipped in the calculations. The reason for excluding GSK1 is that the values for this GSK is not calculated in the right way in the Power World files. GSK1 includes the minimum production, but this parameter is set to zero in the Power World files and only the actual production weighted.

Other strategies considered excluded are GSK7 and GSK8. These strategies are prior testing questioned as poor strategies.

To test this statement, periods were tested with all strategies GSK2-GSK8. All periods studied show the similar tendency, and the already discussed period 02-05 March 2016 is therefore still the period in the further discussion.

The optimal GSKs in Table 2 show that GSK7 is the optimal strategy in area SE3 and SE4. Also the plots of the delta function for the period studied in the next section show that these load based strategies GSK7 and GSK8 are not that bad compared to the other strategies. These plots are presented in section 6.3 for all bidding areas for a longer period, and this section also discuss why these strategies perform well in some areas. Therefore, only GSK1 is excluded in the continuation of this thesis.

6.2 Iteration

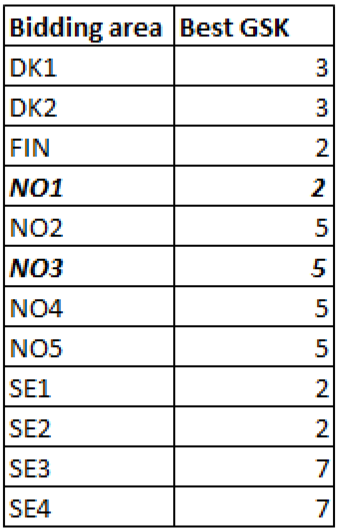
In chapter 5.2, iterating in the search of optimal GSKs in the code was discussed. One iteration is to test all GSKs in each area. First GSK2 is tested in all areas, then GSK3 etc. After one iteration, the optimal GSK is updated in all areas with the objective to minimize the FRM norm. After one iteration, the optimal solution is not necessarily found. Because a change in one area may affect the system and further affect which GSKs optimal in the nearest areas, it can be beneficial to iterate several times in the code.

To test if iterating decrease the total FRM norm and thereby update the list of optimal GSKs, two periods are studied in this section. The two periods are one short period, 02-05 March 2016, and one period of longer duration, 01-28 February. In both periods, initial GSK strategy is GSK3 in all areas in the start of the first iteration. The reason these periods were chosen is that the change in FRM norm is larger than some of the other periods tested and the differences between the GSKs are assumed more visible.

6.2.1 Test for 02-05 March

After one iteration for the period 02-05 March, the FRM norm improves with 9,41 %. The list of optimal GSKs is presented in Table 2. After a second iteration, the optimal GSK only changes in two areas, shown in Table 4. A second iteration only decrease the FRM norm with 0,07%. In the second iteration the result from iteration one is used as initial GSKs.

The result of only a minor improvement after a second iteration show that the new optimal GSK in NO1 and NO3 was also well suited strategies in the first iteration.



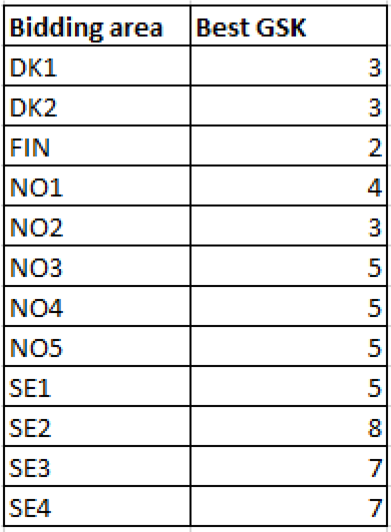
Bidding area	Best GSK
DK1	3
DK2	3
FIN	2
NO1	***2***
NO2	5
NO3	***5***
NO4	5
NO5	5
SE1	2
SE2	2
SE3	7
SE4	7

Table 4: Optimal GSKs in the bidding areas after the 2. Iteration, changes in bold font. Period 02-05 March 2016

A third iteration tested gives no change of the optimal GSKs and no improvement in the FRM norm. The optimal GSKs in each area are therefore the same in the second and third iteration.

6.2.2 Test 01-28 February

The first iteration for the period 01-28 February improves the FRM norm with 16,16% from initially. The list of optimal GSK is presented in Table 5.



Bidding area	Best GSK
DK1	3
DK2	3
FIN	2
NO1	4
NO2	3
NO3	5
NO4	5
NO5	5
SE1	5
SE2	8
SE3	7
SE4	7

Table 5: Optimal GSKs in the bidding areas after one iteration for 01-28 February 2016

A second and third iteration are tested, and both results in no further improvement in the FRM norm. According to the results, the optimal GSKs are therefore the same as in Table 5.

6.2.3 Discussion of iterating

The two previous subsections show results for one short and one medium long period tested for three iterations. Results for both these periods indicates that the improvement of iterating is of minor impact on the system. Because of this, the periods presented in the rest of this thesis only iterate once.

These results also support the assumption that the code does not only find local minima’s when optimizing the combination of optimal GSK in each bidding area. The results show that the code only need to iterate once to find the combination of optimal GSK in each area. The problem of local minima’s are therefore assumed avoided because the tests show no further improvement of iterating.

The calculation time for the code during one iteration in February 2016 is 3 hours, two iterations 6 hours etc. Iterating is pretty much all the calculations and time consuming activities in the optimization code. Limiting the code to only one iteration make the code more efficient and saves several hours in calculation time when running the code.

6.3 Major results

In this section, the combination of optimal GSK in each area is presented and discussed for the period 01.02-17.04.2016. The combination of optimal GSK in each area presented in Table 6 decrease the calculated FRM norm with 6,0 % from the initial FRM norm. The size of this change can affect the size of the deviation between strategies in this period. The optimal GSK, the average delta value of the three next best GSKs and the worst GSK's delta are presented in Table 6.

Bidding area	Best GSK	Average delta next 3 GSKs	Worst delta	Worst GSK
DK1	3	99,7	99,0	8
DK2	3	99,8	99,0	7
FIN	7	99,8	98,0	5
NO1	4	100	99,9	5
NO2	3	98,8	91,7	7
NO3	3	100	99,8	7
NO4	5	99,5	95,6	8
NO5	3	99,2	97,1	2
SE1	5	99,9	99,6	8
SE2	8	99,8	96,9	7
SE3	7	99,4	91,0	5
SE4	7	100	93,2	5

Table 6: Optimal GSKs, the average delta value for the 3 next best GSKs and delta value for the worst GSK in each bidding area for the period 01.02.2016-17.04.2016

How the different GSKs perform in each area is presented graphically in Figure 11 and in numbers in Table C1 in Appendix C. The values presented are the resulting delta value for each GSK tested in each area, representing the change in total FRM norm.

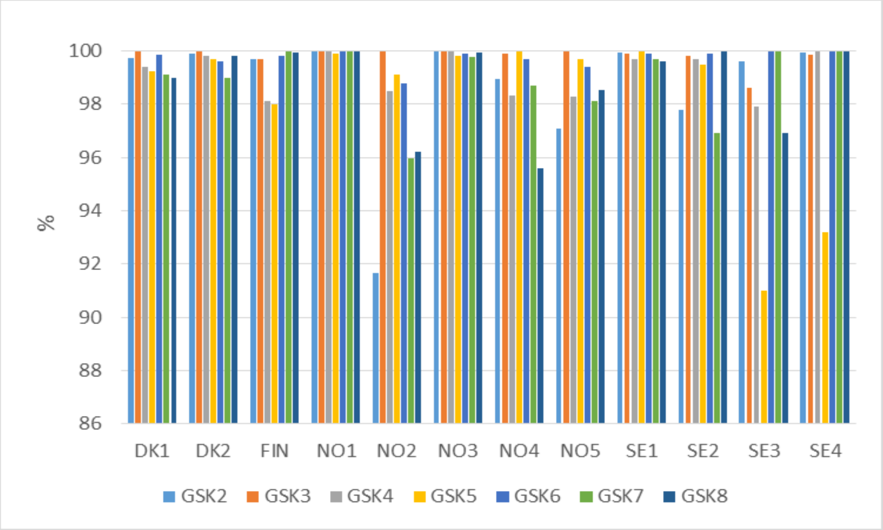


Figure 11: Plot of delta for all GSKs and all areas for the period 01.02-17.04.2016

The following subsections study each area closer, including a brief area description and a closer presentation and discussion of the above presented results.

6.3.1 Denmark

6.3.1.1 DK1

DK1 includes the mainland of Denmark, and is a special area in the Nordic system because of large amounts of installed wind power capacity. Figure D1 in Appendix D shows the large amount of wind production in this period, together with the consumption and total production in DK1.

The simulation result presented in Table 6 shows that GSK3 is the best strategy in DK1. This strategy weights the maximum production in the production nodes, and results indicate that it is the best estimate in this area.

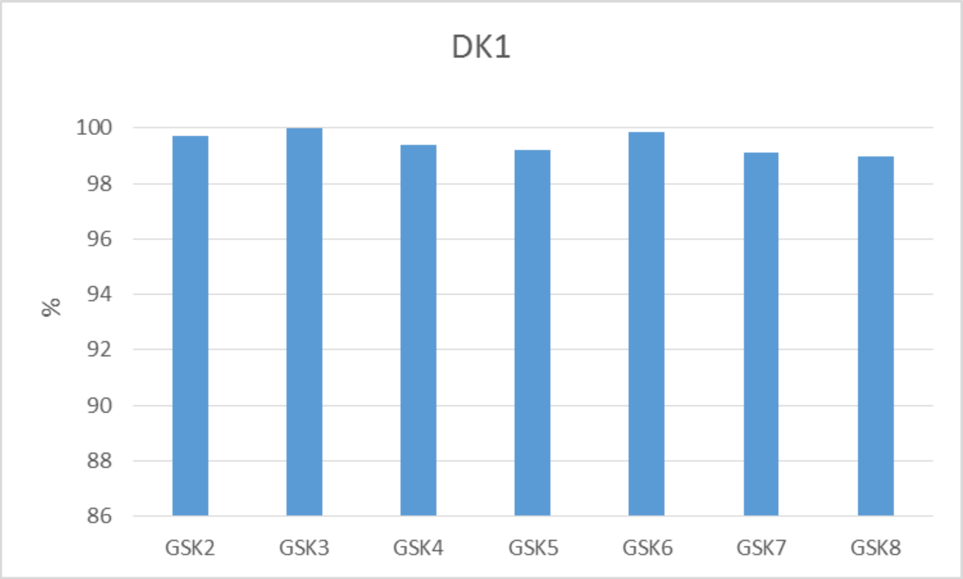


Figure 12: Plot of delta values for different GSKs in area DK1, period 01.02.2016-17.04.2016

According to Figure 12, the other strategies also perform quite well in this area. The load based strategies GSK7 and GSK8 are the less appropriate strategies in DK1.

Another observation is that the results indicate that GSK5 weighting actual production is a bit poorer estimate in this area than the other production based strategies. A possible reason could be that wind production is hard to predict. The wind production is considerable in this area, and the actual production could be hard to predict. This could be the reason why GSK5 performs a bit poorer than the other production based GSKs. However, the changes are not that big in this area. The reason for not that big changes in the area could be because DK1 is a strong and not that sensitive area. Another reason could be that the flow estimate is good in this period.

6.3.1.2 DK2

The eastern parts of Denmark have some installed capacity of wind production, but lower wind production than DK1. Figure D2 in Appendix D show this wind production in addition to both consumption and production in DK2.

According to Table 6, the best strategy in bidding area DK2 is GSK3. This strategy weights the nodes with installed production capacity the largest. However, Table 6 and Figure 13 show that the other strategies perform almost equal in this area, except GSK7. This strategy weighting actual load is performing a bit poorer than the other GSKs according to the results.

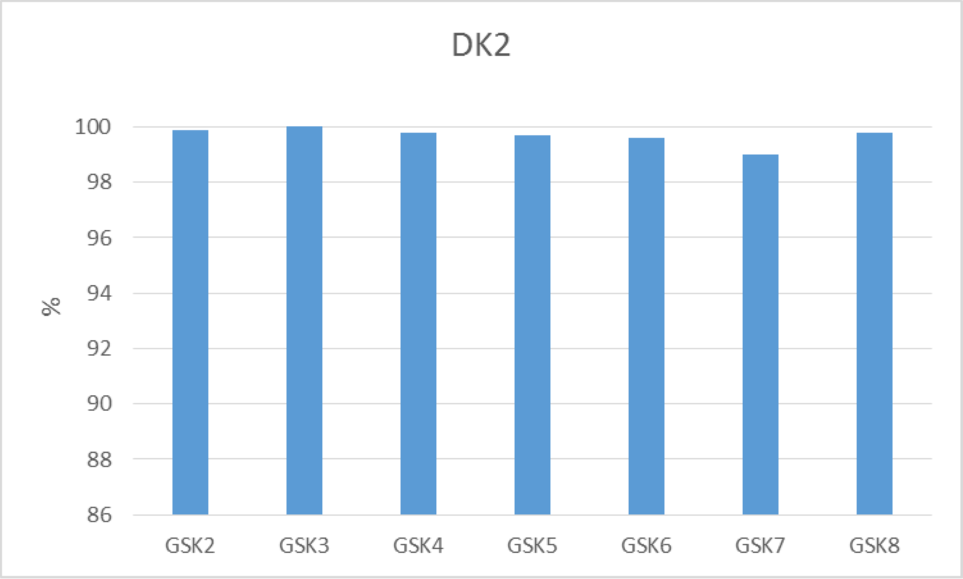


Figure 13: Plot of delta values for different GSKs in area DK2, period 01.02.2016-17.04.2016

Even the flat and easy implemented GSKs perform well in this area, GSK3 is recommended as the optimal GSK in DK2. GSK3 is chosen the optimal GSK here because it performs a bit better than the other GSKs according to the results in Figure 13.

6.3.2 Finland

Finland is only one bidding area, FIN. This is a large area with some large production units. The division of production in this area in 2013 are presented in Figure D3-2. According to Figure D3 this area has higher load than production in the period studied. In addition, the grid in FIN is not highly meshed and close to a radial to the connected grid with a 1500 MW connection in the north and 1200 MW in the southern parts of the area.

The results in Table 6 and Figure 14 show that the best strategy in FIN is GSK7, while the worst is GSK5. FIN is an area with higher consumption than production, which could be the reason the load-based strategies perform well according to Figure 14 and Table C1. The power flow in this area seem to be larger influenced by the load nodes than the production nodes. GSK6 and GSK8 also weights load, and are very good strategies in FIN according to Figure 14.

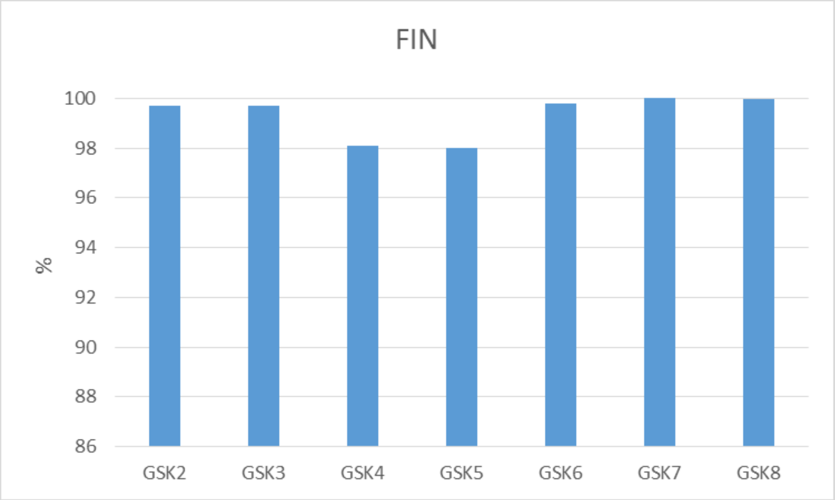


Figure 14: Plot of delta values for different GSKs in area FIN, period 01.02.2016-17.04.2016

GSK2,weighting maximum production, performs well in FIN, although the area has larger load than production. The reason could be that a large share of the production are nuclear production, according to Figure D3-2 presenting the division of production in FIN in 2013. Further, a reason why GSK2 perform well could be that the nuclear production units are not running close to their maximum limits in this period and the margin P_{max}-P is not that sensitive. GSK3 also performs well in this area.

GSK4 and GSK5 perform slightly worse than the other strategies in this area according to the results. GSK4 is a flat strategy weighting all production nodes equally, and GSK5 weights actual production. Because FIN have nuclear production and larger load than production, weighting according to flat production or actual production seems to be not that precise estimates of how the change in the area’s net position is divided on the nodes in the area.

6.3.3 Norway

6.3.3.1 NO1

The southeastern area of Norway, NO1, is the area with the highest population and load in Norway. A lot of the production in this area is without reservoirs, like run-of-river power in Glomma.

The non-storable hydro production is visible in Figure D4-2. In May, the production in NO1 increases, even if the consumption decreases. The increased production is due to the snow melting in May causes increased water flow in the rivers. In the period studied here, Figure D4 shows that the load is larger than the production during the whole period.

Most of the limiting CNEs in NO1 are placed at Hasle, and it is not too hard to estimate the power flow here[23]. This is reflected in the results for all strategies in Figure 15 and Table C1 in Appendix C.

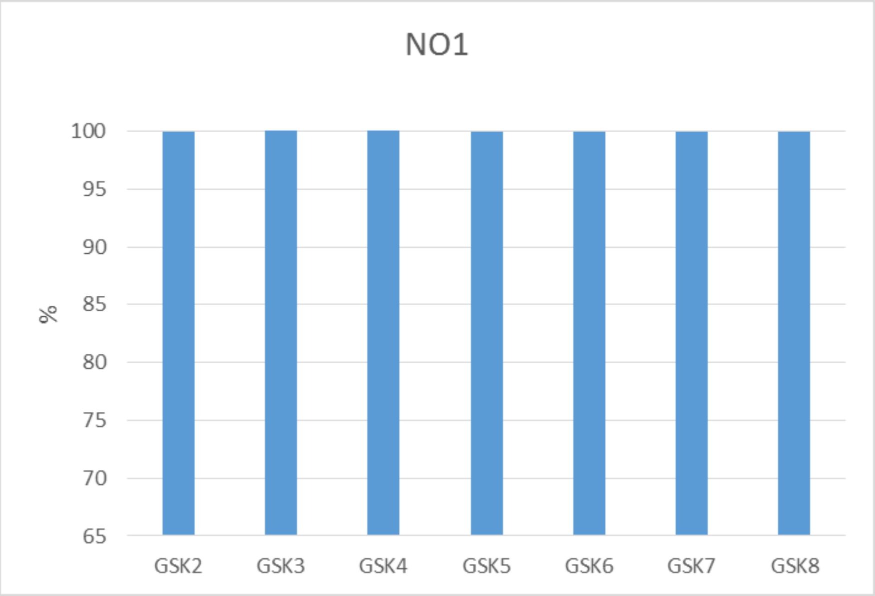


Figure 15: Plot of delta values for different GSKs in area NO1, period 01.02.2016-17.04.2016

By these arguments, the choice of GSK in this area is of minor influence on the estimated power flow in this area. Even if the area has a lot of consumption and non-storable hydropower, all GSKs perform similar because the power flow on the CNEs are predicted relative precise.

By these arguments, GSK4 is chosen as the optimal strategy in this area. GSK4 is a flat strategy that is computationally efficient to implement and does not need that much adjustment. GSK 8 could also be chosen, but the discussion in section 6.6 and results for minor periods arguments for GSK4 being the best choice of flat strategy. The results for this shorter period is further discussed in section 6.4.2.

6.3.3.2 NO2

NO2 includes the southern parts of Norway, and the production and load here are spread within the area. According to Figure D5, NO2 had larger production than consumption in this period in 2016. Figure 16 and Table C1 in Appendix C show that the optimal strategy in this area is GSK3. This strategy weights according to maximum production in nodes. The second best GSK in NO2 is GSK5 weighting actual production. These two strategies probably perform well in this area because the production are mainly hydropower, and the production in NO2 is larger than the load in this period. These characteristics could also be the reason why the results for this area have larger deviation between the strategies compared to the previous areas presented.

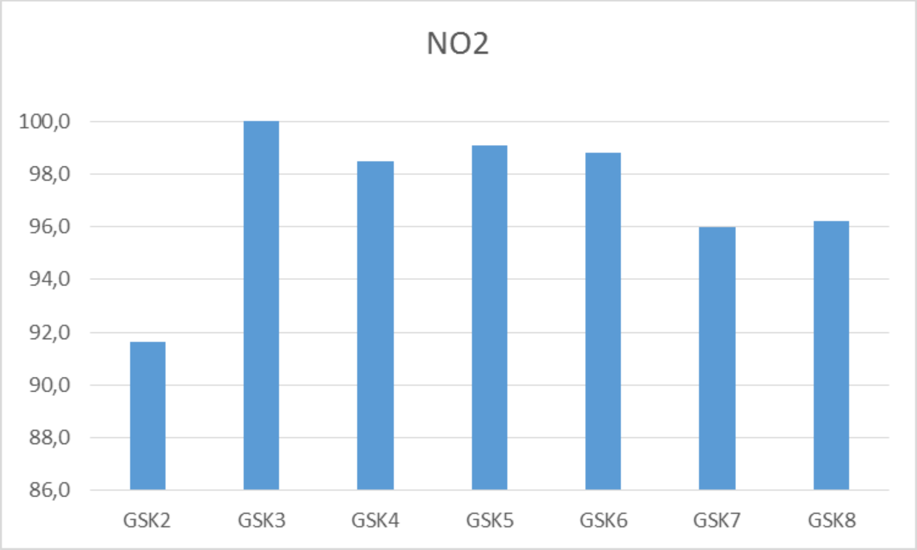


Figure 16: Plot of delta values for different GSKs in area NO2, period 01.02.2016-17.04.2016

The worst GSK in this area is GSK2 according to Figure 16. The production in this area is mainly hydro. Normally hydro units run at their best point, around 85-90% of maximum. Running at their best point can be the reason why GSK2 is the worst GSK in NO2 according to in Table 6 and Figure 16. GSK2, weighting remaining margin P_{max}-P, could be a sensitive and not that well suited strategy in this area.

The load-weighting strategies GSK7 and GSK8 also perform poor in NO2. A possible explanation is that the power flow in this area is larger affected by production than load nodes. This area is closer studied for subperiods in section 6.5.1.

6.3.3.3 NO3

NO3 is the bidding area in middle-Norway. This area is assumed robust and non-sensitive to changes in the power flow. This statement is reflected in results in Figure 17 and Table C1 where all GSKs have a close to equal delta value.

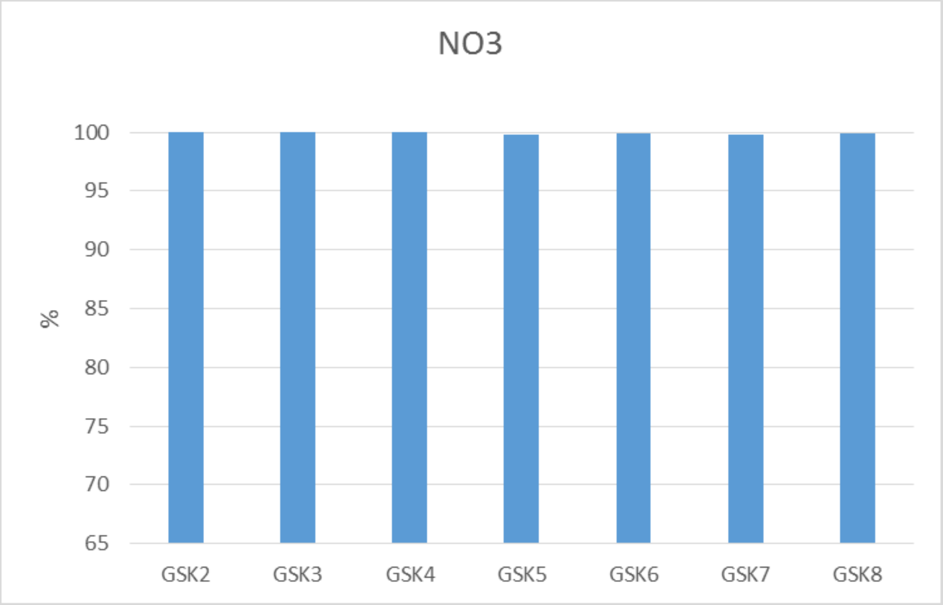


Figure 17: Plot of delta values for different GSKs in area NO3, period 01.02.2016-17.04.2016

However, GSK4 is chosen as optimal GSK in this area because GSK4 is an easier strategy to implement, and its delta value indicates that this is an appropriate strategy in this area.

6.3.3.4 NO4

The bidding area in northern parts of Norway is NO4. This is the Norwegian area with the longest distance from north to south. In addition to the long distance to distribute the power, the grid in this area is not that well developed yet. In the future, there are plans to develop this grid[24]. The generation in this area is mainly hydropower with reservoirs.

NO4 is normally a surplus area with export to NO3 and Sweden[12]. These characteristics with hydropower, export of power and the state of this area's grid, are visible when comparing the strategies, shown in Figure 18. These characteristics could be the reason that there is some deviation between the strategies according to calculated delta values.

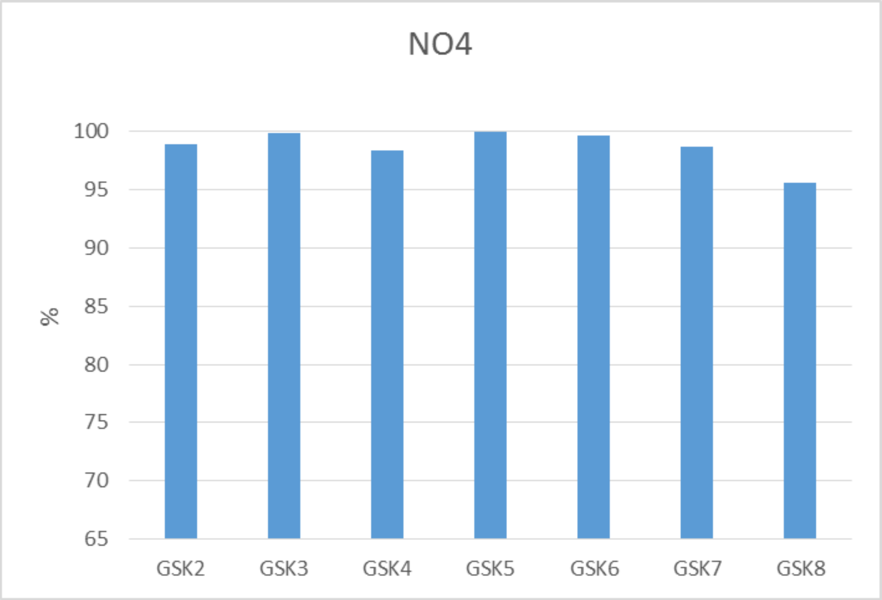


Figure 18: Plot of delta values for different GSKs in area NO4, period 01.02.2016-17.04.2016

The best GSK in this production area is GSK5. GSK5 weights according to actual production, and perform well in areas with large amount of hydropower production and export of power. GSK3 also perform very well in NO4. In this area, like in NO2, these two GSKs are well suited because this production area mainly consist of hydropower producing near their best point.

Probably related to this result, GSK2 perform worse than the two best strategies, according to Figure 18. The reason could be that the hydropower units run close to their best-point. However, the delta value for GSK2 is not that different from the other GSKs in NO4 when comparing to the situation in NO2. The reason the deviations between GSKs are larger in NO2 than in NO4 is probably that the production in MWh in NO2 is over the double of the production in NO4 on average.

The three worst GSKs in this area are the flat and load based strategies, with GSK8 as the worst. In this area with a production surplus, weighting all load nodes equal seem to be a less suited approach. GSK4 and GSK7 weights respectively all production units and actual load, and results indicate that they are not that good estimates in this area with an export of production from hydropower units.

6.3.3.5 NO5

NO5 is located in the western parts of Norway. The eastern parts of this area have production from large hydro plants while both the population and the load are low in these parts of NO5. In the western parts of NO5 there are both large hydropower units and a considerably amount of load related to industry and population. These characteristics causes NO5 to be able to have both large deficits and surplus of power. Figure D8 show that the production is larger than the load in nearly all hours in the chosen period.

Figure 18 show that NO5 has a variation of delta values for the different GSK strategies. The internal division and the production surplus can be reasons for this variation. GSK3 and GSK5 are the best strategies in this area, probably because of export from the area and production from large hydro plants. Table 6 and Table C1 show that GSK3 is the best strategy, and GSK5 near as good as GSK3. This table also show that GSK6 weighting both actual production and load also perform relative good in this area.

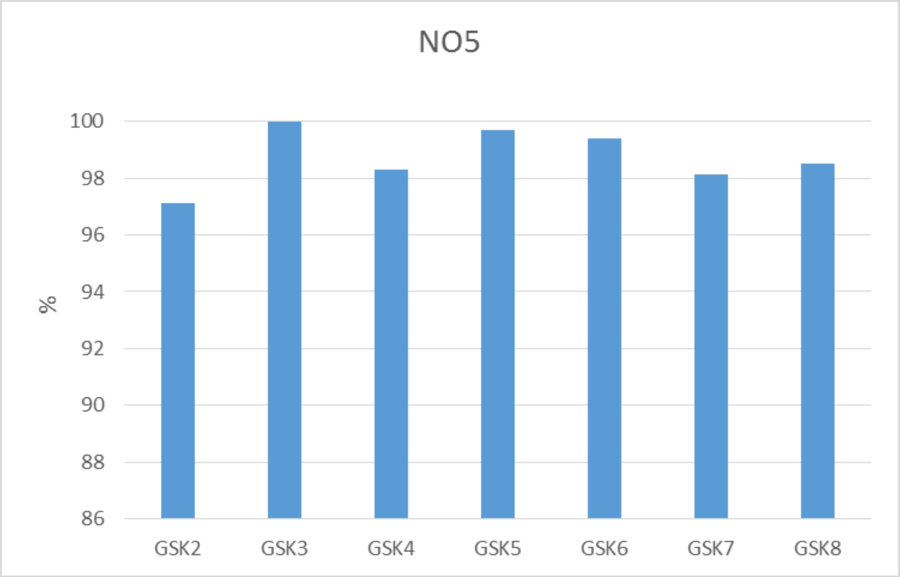


Figure 19: Plot of delta values for different GSKs in area NO5, period 01.02.2016-17.04.2016

The flat strategies and GSK7 are not that good strategies in this area. An explanation could be the characteristics of the area with export and mainly production from hydropower units. The worst strategy in this area is GSK2, probably due to the fact that hydropower units most often operate near their best points.

6.3.4 Sweden

6.3.4.1 SE1

SE1 is the northern parts of Sweden. This area have large amounts of hydro production, and the production is much higher than the load in almost all hours in this period, according to Figure D9. The best strategy in area SE1 is GSK5, according to Table 6. This strategy weights actual production, and often performs well in areas like this with export of power and a high degree of hydro production.

However, according to the delta values in Figure 20 and Table C1, all strategies perform well in SE1. A reason for the similar results for all strategies could be that the load and production in this area are low compared to e.g. SE3. This probably causes larger deviation between strategies in SE3 than in SE1.

However, GSK5 is in Table 6 presented as the optimal GSK in SE1, and is recommended as the optimal GSK here because it perform marginally better than the other GSKs in SE1.

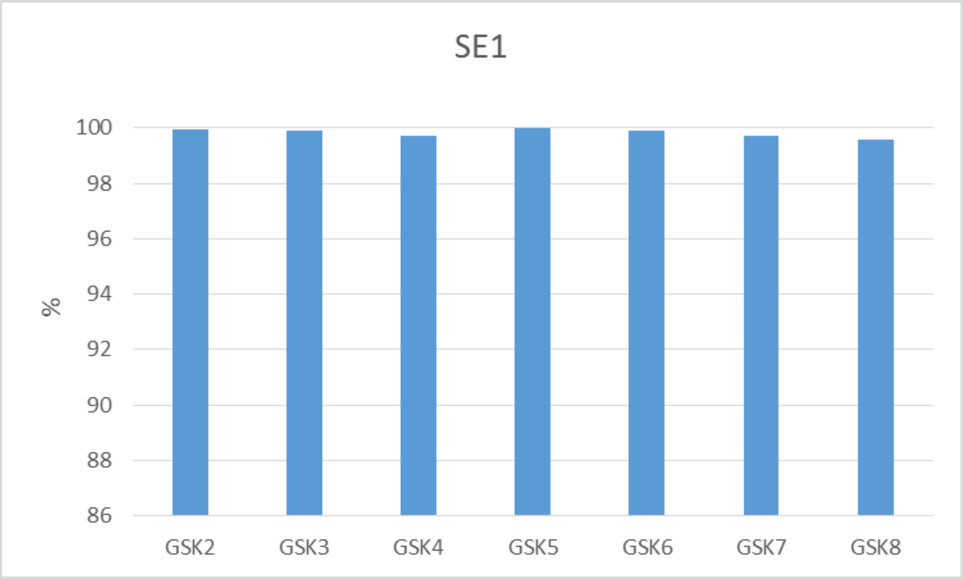


Figure 20: Plot of delta values for different GSKs in area SE1, period 01.02.2016-17.04.2016

6.3.4.2 SE2

SE2 includes the middle-Sweden. In this area the production are higher than consumption in almost all hours in this period according to Figure 10.

The worst strategies in SE2 are GSK2 and GSK7. GSK7 is the worst strategy in this area according to Figure 21. The reason GSK7 perform poor could be that weighting the load nodes according to actual load is a poor estimate in an area with export of power. GSK2 probably perform a bit worse than the other GSKs because the production units are mainly hydropower producing near their best-points.

Figure 21: Plot of delta values for different GSKs in area SE2, period 01.02.2016-17.04.2016

The other GSKs perform quite similar, with GSK8 as the optimal strategy. Weighting all load nodes seem to be a good estimate how the change of net position is divided on the nodes in the area.

6.3.4.3 SE3

SE3 is the Stockholm area in Sweden. Figure D6 shows that the production and load are higher in SE3 than in any other areas, and the relationship between production and consumption are relatively constant throughout this period. The reasons why the load is high in this area are large population and industry in this area.

SE3 has large nuclear power plants, producing around 40% of the total Swedish energy production[25]. These plants are preferable to always run relatively constant and near their maximum capacity, because they are not flexible units. The large share of nuclear production could be the reason that the results for the GSKs are different in SE3 compared to areas dominated by hydropower production.

According to the results presented in Figure 22 and Table C1 in Appendix C, SE3 is the Swedish area with the largest deviation between the strategies. The larger deviation in this area is probably due to the fact that SE3 is the Swedish area with both the largest consumption and production, according to Figure D11 in Appendix D.

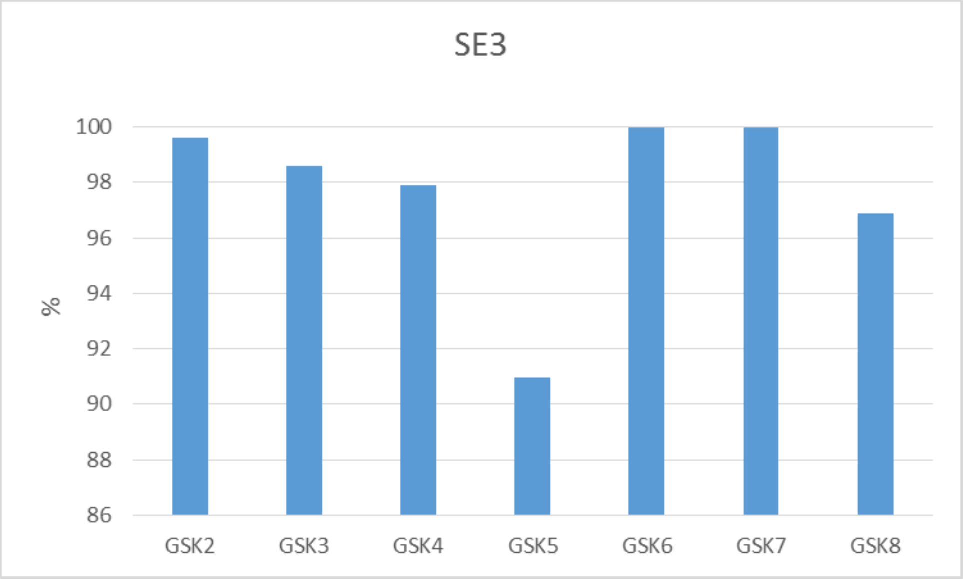


Figure 22: Plot of delta values for different GSKs in area SE3, period 01.02.2016-17.04.2016

The GSK strategies weighting according to actual load are the best strategies in this area, according to Table 6 and Figure 22. These two strategies, GSK6 and GSK7, stands out as the best, with an almost equal delta value compared to the other GSKs. The reason GSK6 and GSK7 are the best in this area, could be that nuclear power dominates the generation in the area, and the production do not vary much. The load nodes may influence the power low larger than the production nodes. Therefore, weighting the actual load is assumed a better estimate than weighting production in SE3.

GSK2 is a strategy performing well in this area. GSK2 weights the remaining production margin P_{max}-P and is the best strategy only weighting according to production. The other strategies perform less good in this area. The reason GSK2 perform better than the other GSKs weighting only production, could be that the weighting P_{max}-P is not that sensitive in this area.

The flat strategies GSK4 and GSK8 weights respectively all production and consumption nodes equal. These two GSKs are not that good strategies to estimate the flow in this area, probably because it is the consumption that impacts the most in SE3. In addition, Figure D11 shows that the consumption changes in this period. This change in consumption could be the reason GSK8, weighting all load nodes equal, does not perform that well in this area.

GSK5 is the worst strategy in SE3, according to the results in Figure 22. An explanation could be that the consumption mainly influence the change in net position in this area, and weighting actual production is therefore not a suitable approach. GSK5 weights actual production, and the relative constant nuclear production in the area could be the reason the results indicate that GSK5 is the worst strategy in SE3.

6.3.4.4 SE4

SE4 is the southern parts of Sweden. In this area the consumption are larger than the production for all hours in this period, according to Figure D12. According to Table 6, the optimal strategy in this area is GSK7 weighting actual load.

Even though GSK7 is the best strategy in this area, Table 6 and Figure 23 also tell that the deviations between the strategies are small. The reason the deviations between the GSK strategies are so small in this area could be that SE4 lays as a radial to the rest of the grid.

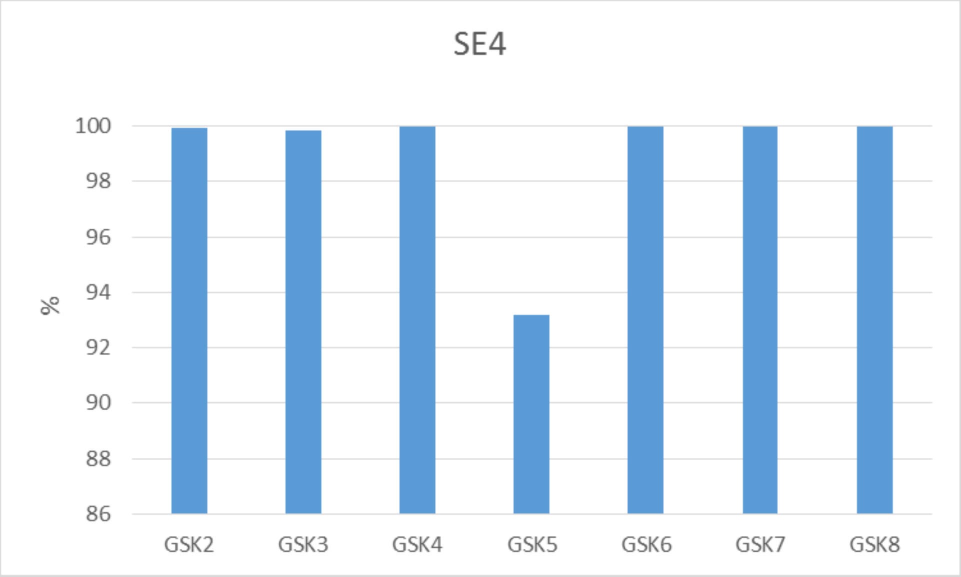


Figure 23: Plot of delta values for different GSKs in area SE4, period 01.02.2016-17.04.2016

However, one GSK perform worse than the other GSKs according to Figure 23. In this consumption area, GSK5 is the only strategy with a delta value not close to 100%. Result shows that GSK5 probably does not estimate the power flow in this area in an appropriate way. GSK5 weights according to actual production, and this weighting could be the reason this GSK is the worst strategy in SE4 with larger load than production.

This discussion concludes GSK4 as the optimal strategy in this area. GSK4 is chosen as the optimal GSK in this are because it is both an optimal GSK in this area in addition that it is an easy implemented GSK that seem to perform well in SE4, according to these results.

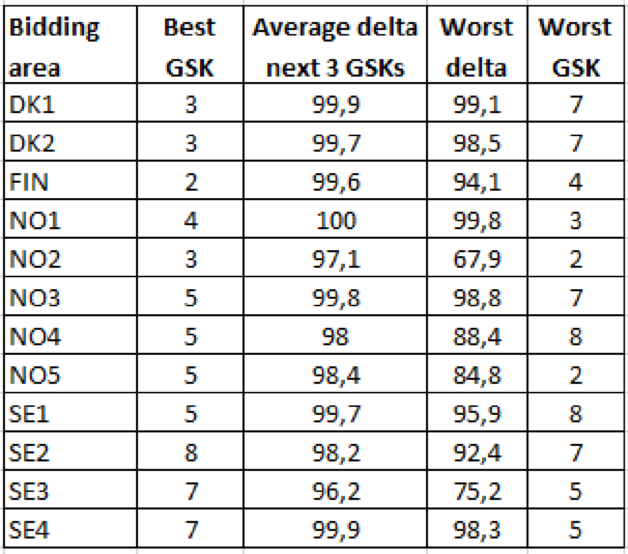
This area and the behaviour of GSK5 are further discussed in section 6.5.3.

6.4 Results for subperiods

In this section, the total period of 11 weeks is divided into three smaller periods. The subperiods are 01.02-28.02, 29.02-27.03 and 28.03-17.04. The division mainly divides the periods into months, and is done to see if the optimal GSK in each area is the same in these months. The three periods is presented in subsections below, and presents first the results before the last subsection discuss the results further.

6.4.1 01.02.2016-28.02.2016

The optimal GSK in each area in the period 01.02-28.02.2016 are presented in Table 7. The optimal GSKs in each area reduce the total FRM norm with 16,2% from the initial condition with GSK3 in all CNEs. In addition, Table 7 present the worst GSK's delta and the average of the three GSKs with the next highest delta values.



Bidding area	Best GSK	Average delta next 3 GSKs	Worst delta	Worst GSK
DK1	3	99,9	99,1	7
DK2	3	99,7	98,5	7
FIN	2	99,6	94,1	4
NO1	4	100	99,8	3
NO2	3	97,1	67,9	2
NO3	5	99,8	98,8	7
NO4	5	98	88,4	8
NO5	5	98,4	84,8	2
SE1	5	99,7	95,9	8
SE2	8	98,2	92,4	7
SE3	7	96,2	75,2	5
SE4	7	99,9	98,3	5

Table 7: Optimal GSKs, average delta value for the 3 next best GSKs and the worst GSK for the period 01-28 February

How the different GSKs perform in each area are presented graphically in Figure 24 and in numbers in Table C2 in Appendix C. The values are the delta value for each GSK in all areas.

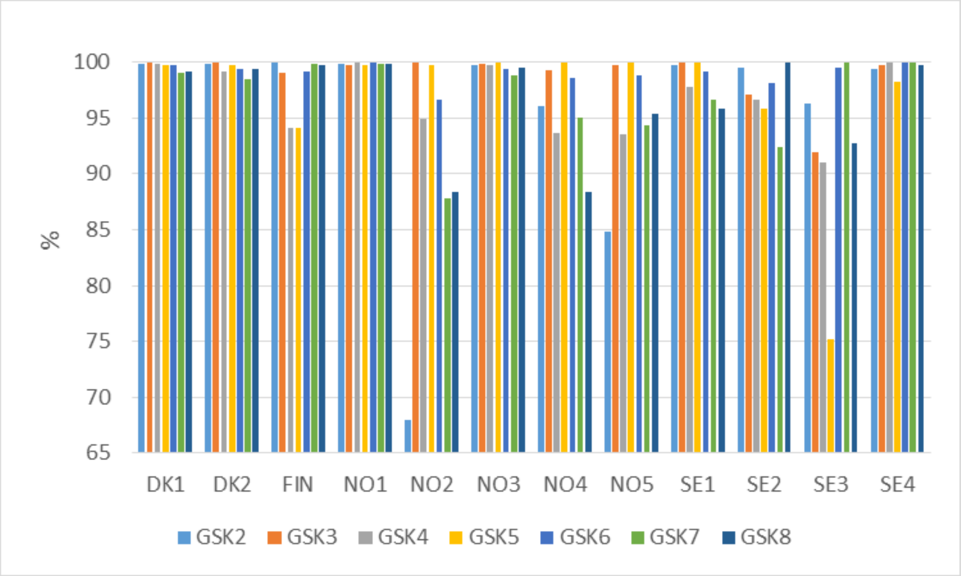


Figure 24: Plot of delta for all GSKs and all areas for the period 01.02-28.02.2016

6.4.2 29.02.2016-27.03.2016

The best and worst GSKs in each area in the period 29.02.2016-27.03.2016 are presented in Table 8. The optimal GSKs in each area reduce the total FRM norm with 1,6% from the initial condition with GSK3 in all CNEs.

Bidding area	Best GSK	Average delta next 3 GSKs	Worst delta	Worst GSK
DK1	3	99,8	98,8	5
DK2	8	99,9	99,7	5
FIN	2	99,9	98,5	5
NO1	4	100	98,7	2
NO2	3	99,7	99,0	8
NO3	3	100	99,9	7
NO4	3	99,9	98,9	8
NO5	3	99,8	99,0	6
SE1	5	100	99,8	8
SE2	6	99,9	98,3	7
SE3	2	99,5	91,1	5
SE4	3	100	95,1	5

Table 8: Optimal GSKs, the average in delta value for the 3 next best GSKs and delta value for the worst GSK in the each bidding areas for the period 29.02.2016-27.03.2016

How the different GSKs perform in each area are presented graphically in Figure 25 and in numbers in Table C3 in Appendix C. The values are the delta value in percent for each GSK for all areas.

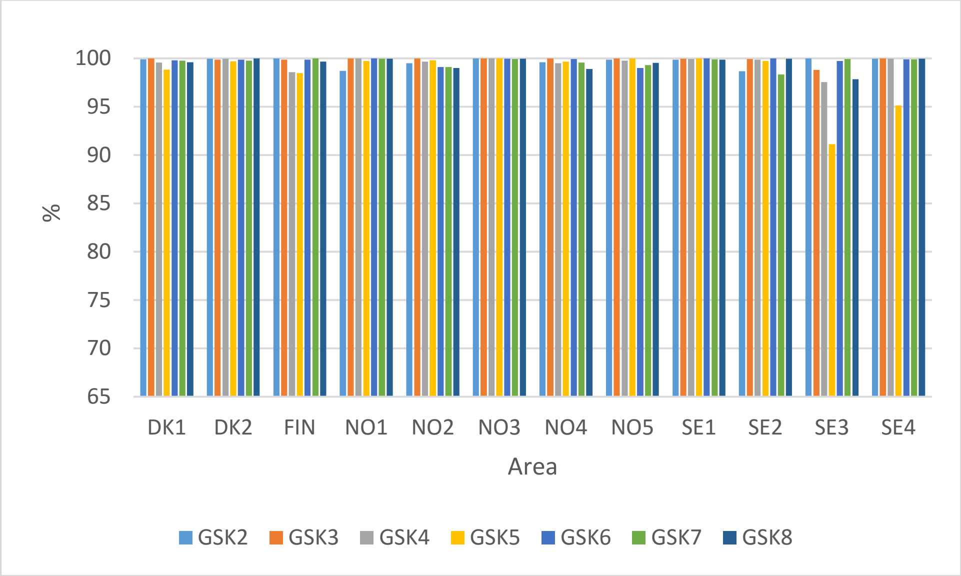


Figure 25: Plot of delta for all GSKs and all areas for the period 29.02.2016-27.03.2016

6.4.3 28.03.2016-17.04.2016

The best and worst GSKs in each area in the period 28.03.2016-17.04.2016 are presented in Table 8. The optimal GSKs in each area reduce the total FRM norm with 5,0% from the initial condition.

Bidding area	Best GSK	Average delta next 3 GSKs	Worst delta	Worst GSK
DK1	3	99,5	96,1	7
DK2	3	99,6	94,6	7
FIN	7	100,0	97,6	3
NO1	5	100	99,8	2
NO2	5	97,8	90,8	8
NO3	4	100	99,4	7
NO4	5	97,6	90,0	8
NO5	5	98,2	93,4	7
SE1	2	99,9	99,7	8
SE2	3	99,8	89,4	7
SE3	2	98,6	78,6	5
SE4	7	100	72,4	5

Table 9: Optimal GSKs, the average in delta value for the 3 next best GSKs and delta value for the worst GSK in the each bidding areas for the period 28.03-17.04.2016

How the different GSKs perform in each area are presented graphically in Figure 26 and in numbers in Table C4 in Appendix C. The values are the delta value of each GSK for all areas.

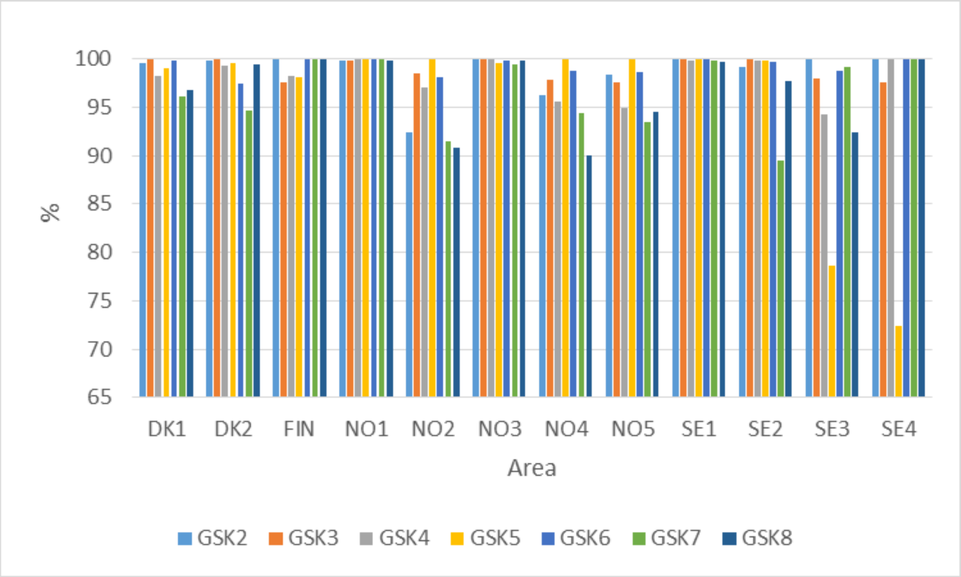


Figure 26: Plot of delta for all GSKs and all areas for the period 28.03-17.04.2016

6.4.4 Discussion of subperiods

The three previous subsections and the results for the total period show that the calculated optimal GSK in each area are not the same for all periods. These results also show that the results presented for the total period lies somewhere between the results for the three subsections, because these periods are parts of the total period.

An important observation is that the period 29.02-27.03 only had an improved FRM norm of 1,6% compared to initial while the period 28.02-17.04 had 5,0 % improvement and 01.02-28.02 16,2% improvement. These different improvements in FRM norm are probably the reason why the presented deviation between the strategies is largest in the first period and minor in the second period. When the total FRM norm only has minor changes, each change of optimal GSK has less impact on the total FRM norm and probably also on the estimated flow. This could also lead to a larger impact on the estimated power flow in the first period, and assumed a better prediction of the flow in the second period with larger change in FRM norm.

Results show that only DK1 has the same optimal GSK in both the total period and all subperiods, according to Table 6 - Table 9. However, Figure 10, Figure 23, Figure 24 and Figure 25 show that the results for the periods are not that different. The optimal GSK in each area in one period is always one of the best GSKs in the other periods.

The worst GSK is the same for all periods in 6 of the 12 Nordic bidding areas. For the 6 areas with dissimilar worst GSK in the different subperiods, the worst GSK in one period is one of the worst in the other periods. The reasons for different result of optimal and worst GSK are illustrated in concrete examples below. The most interesting results with relative large variation between the GSKs in the same areas are further studied in section 6.5.

GSK2 in NO2 perform better in the period in March compared to the first period in February. According to Figure D8, the production is lower in from second subperiod compared the first subperiod. The production is therefore not that close to the maximum limits in the second subperiod. This probably make GSK2 weighting the remaining margin P_{max}-P a better assumption in March than February because the value P_{max}-P is probably larger and less sensitive.

The results for NO4 and NO5 show the same tendency. GSK2 has a lower delta value in the first subperiod compared to the two other subperiods. The reason is probably the same as for NO2 with a decrease in production making GSK2 less sensitive.

These areas have similar characteristics with a surplus of production from hydro plants, and probably therefore the same tendency for GSK2. Actors in all areas want to use their reservoirs to sell their hydropower at the best possible price, and often it occur at the same time. Therefore, it seem to be a similar tendency for when the generation from the hydro plants increase and decrease in these areas. Figure D5, Figure D7 and Figure D8 in Appendix D show this tendency. According to these results, this change in production could affect how well the GSKs perform in different situations.

This observation is further studied and illustrated in section 6.5.1. Only NO2 is studied in this section, because NO4 and NO5 have similar behaviour.

In SE3, GSK5 is the worst strategy in all subperiods according to results presented. However, the deviation between GSK5 and the other strategies are less in the period in March than the two other subperiods. This result is closer examined in section 6.5.2.

GSK5 also perform poor in the results for the last subperiod in SE4. In the two first subperiods, GSK5 perform close to the other strategies. This observation is elaborated in section 6.5.3.

In other areas like NO1 and NO3, the difference between the strategies are minimal, and which GSKs stated as the best and worst does not say that much.

6.5 Discussion of results for some chosen areas

The results in optimal GSK in some areas were a bit different when comparing the three subperiods in section 6.4. These results are also visible in the total period because the period is only two and a half month.

Therefore, this section takes a closer look closer at some concrete examples to study why these areas behave different in some periods, and how it affects the total result.

6.5.1 NO2

In NO2, GSK2 perform worse in the first period than in the two other periods according to delta values in Figure C2-C4 in Appendix C. The reason for this behaviour could be that the production, and thereby also the flow, vary in the subperiod. The production decrease relative suddenly some days in the period according to Figure D5, and also increase other days.

This is seen from the relative similar delta values for all GSKs in the period 29.02.2016-27.03.2016, while the period 01.02.2016-28.02.2016 have larger deviation between the strategies. This is illustrated in Figure 27.

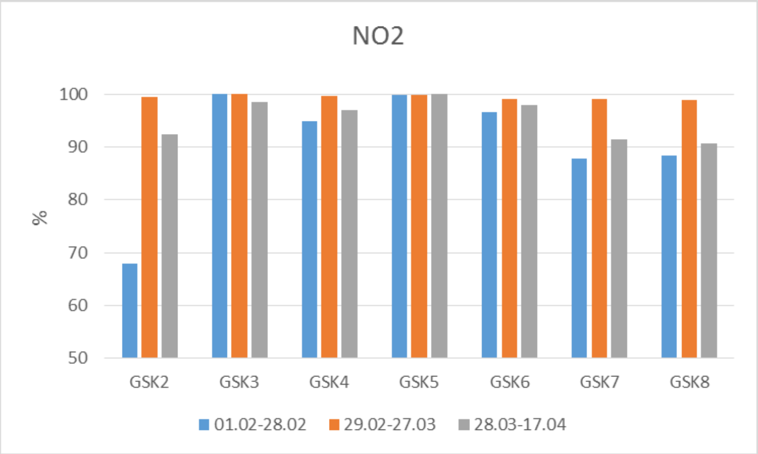


Figure 27: Plot of the delta values in NO2 for the three subperiods

The largest change in production in this area was in the subperiod 05.02.2016-11.02.2016. In this subperiod the maximum production was around the double of the minimum production.

Figure 28 show that the change in flow in this period increase the deviation between the strategies, and GSK2 perform a lot worse than the other strategies. In this situation, the maximum remaining production margin P_{max}-P is a poor estimate. The best estimate in this period is GSK3 and GSK5, which often seem to be the best strategies in areas with large amount of hydro production from units with large reservoirs.

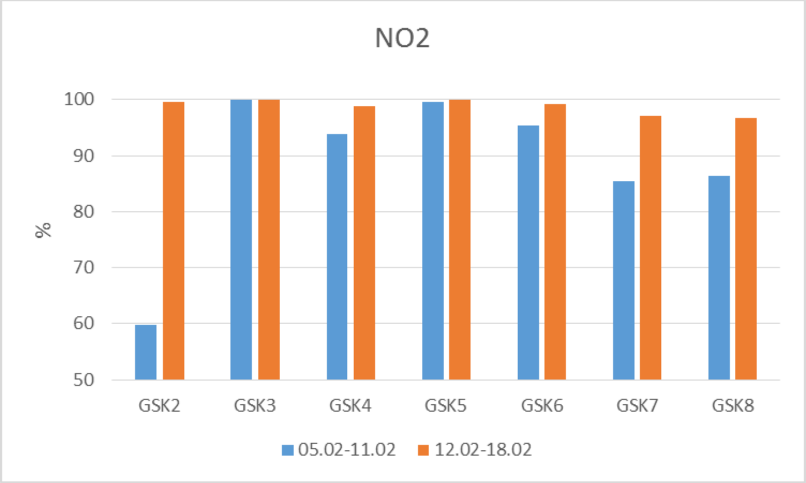


Figure 28: Plot of the delta values In NO2 for two weeks in February 2016

In the period 12.02-18.02, the production is again large and all strategies perform better than in the previous subperiod. In the period 12.02-18.02 GSK3 and GSK5 is still the best, but the deviation between all strategies are decreased because these two strategies do not perform that much better when the production does not change that much.

6.5.2 SE3

In SE3, GSK5 is the worst strategy in all subperiods according to Figure 29. The reason could be that this area has large nuclear production and the load is of larger impact on the power flow than the relative constant production.

However, the deviation between GSK5 and the other strategies are less in the period in March than the two other subperiods according to Figure 29.

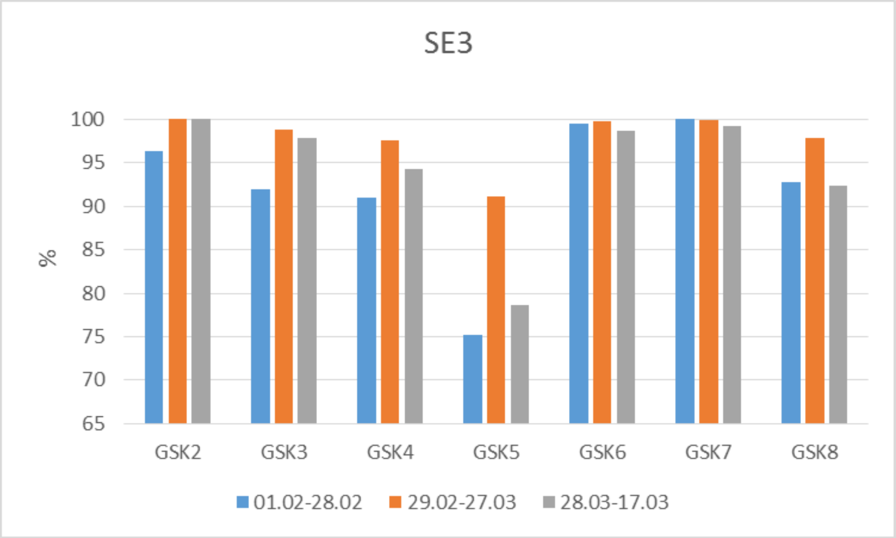


Figure 29: Plot of the delta values for SE3 in each subperiod

In the period 29.02-27.03 all GSKs perform better or equally well compared to the other periods. A reason could be that the load and production have less sudden changes, according to Figure D11. Another reason could be that the error in estimated flow is smaller in this period than in the two other periods, leading to more similar results for the different GSKs.

6.5.3 SE4

SE4 is the southern parts of Sweden, and the grid in this area SE4 lays as a radial to the connected main grid. This characteristic leads to smaller deviations between strategies in this area.

Presented results in this thesis show all strategies perform equally, except GSK5. Especially in the last subperiod in March-April GSK5 perform poor, shown in Figure 30.

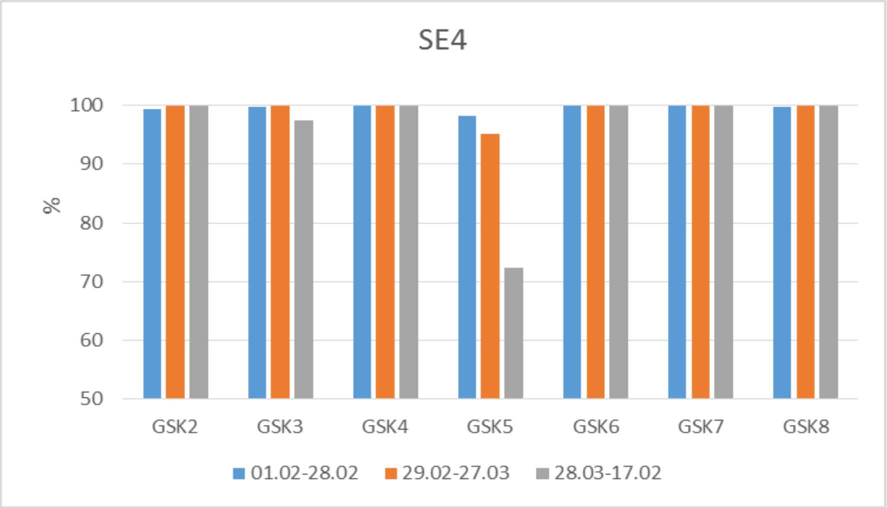


Figure 30: Plot of the delta values for SE4 in each subperiod

The poor results for GSK5 in the last subperiod is closer studied in Figure 31.

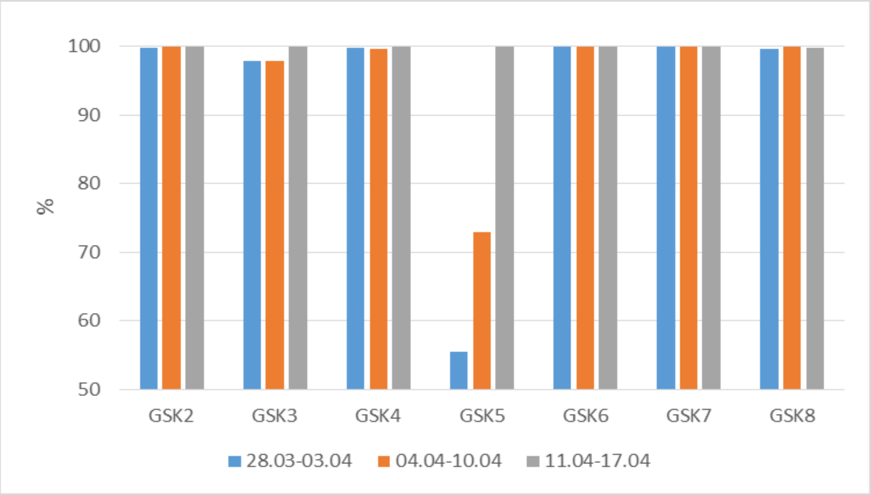


Figure 31: Plot of the delta values for SE4 in each week in the last subperiod 28.03-17.04

The results for each week in the last subperiod in Figure 31 show that the poor delta value for GSK5 in this subperiod is related to the week 28.03-03.04. The other GSKs perform similar and close to 100%.

The results from the project assignment are presented in section 6.8, and they show similar behaviour for all strategies in SE4 with close to zero deviation between the strategies.

A hypothesis is that this result for GSK5 is caused by an error in the data files used in the simulations. This also affect the result in the main period. Another reason could be that the production and consumption in SE3 are larger than in any other Nordic bidding area. Therefore the changes are larger. However, GSK5 is not recommended in this area

6.6 Test of a flat strategy

A flat strategy is the most straightforward and easiest implemented strategy. In addition, a flat strategy may be a more robust strategy when the market solution is far from the net position of the base case. The flat strategy is according to the example in section 4.3 often a strategy close to the real flow, but it only occasionally predicts the right flow. A marginal strategy is presumed most accurate when the market solution is close to the base case. On the other hand, the marginal strategy predicts a flow further from the real flow than the flat strategy when the flow predicted is not right.

Therefore, this section study closer the hypothesis of implementing GSK4 in all nodes. GSK4 weights all production nodes equal. The choice of GSK4 as the tested flat strategy instead of GSK8 is elaborated in the end of Section 6.7.

The solution with a flat is computationally efficient and assumed to be a robust solution. This section study the period 01.02.2016-28.02.2016 with GSK4 as the initial GSK.

The resulting optimal GSK in each area when GSK4 is the initial strategy are the same as presented in Table 5 when GSK3 is the initial GSK. After the optimal GSKs are found, the FRM norm is reduced by 21,4% from GSK4 initially in all CNEs. This fact is also visible in section 6.1.

The results show that a flat strategy is not the best choice of global strategy. In general, it is recommended to use the optimal GSK in each area instead of a global strategy. Results show that GSK4 is recommended in NO1 and NO3 as the optimal GSK. In other areas, GSK4 is most often an average good strategy. However, GSK4 is a poor strategy in some areas with export of power like NO2 and NO5.

By these arguments, GSK4 is only recommended implemented as the optimal strategy in NO1 and NO3.

6.7 The GSKs in general

These results show that the different GSK strategies acts dissimilar in different areas. The combination of optimized GSK in each area contribute to a better estimate of the actual power flow in the grid. The strategies are commented in general below. Areas with delta values that are virtually the same are excluded in this discussion of the GSKs in general.

GSK2 weights according to P_{max}-P, and weights the production node with the largest margin from actual to maximum production the most. This strategy is not the optimal strategy in any areas in the main period in this study. In the shorter periods, this strategy is the optimal GSK in FIN and SE3. In general, results indicate that this strategy is a good strategy in areas with nuclear power production. However, this strategy is assumed less suited in areas like NO2, NO4 and SE2 with mainly hydropower production and export of power.

GSK3 and GSK5 are most often the best strategies in areas with mainly hydro production with reservoir and export of power from the area. In addition, GSK3 perform well in all areas except SE3. GSK3 weights maximum production and is the best average strategy in all areas, according to results presented in Figure 11. This observation is also found in section 6.1.1 when GSK3 is chosen as the best initial and global strategy.

GSK5 weights actual production, and is the optimal strategy in NO4 and SE1 in the main period. These areas have an export of power and the power production is mainly hydropower. In other similar areas like NO2 and NO5, GSK5 performs well as the second best strategy. In these areas, GSK3 is the optimal strategy. GSK5 is the worst strategy in FIN, SE3 and SE4. SE4 have an import of power, and the results indicate that the actual power production in is a bad estimate of how a change in net position is divided on the nodes in this area. SE3 is an area with a large share of nuclear production. Nuclear production do not vary that much, and could the reason why the actual production is not the best approach to estimate the power flow in this SE3. FIN is an area with both import of power and a share of nuclear production, and this could explain why GSK5 do not perform that good in FIN.

GSK6 is the only strategy weighting both actual production and load, and is in this study neither the optimal nor the worst strategy in any areas. The weighting of this strategy make it an average good strategy according to the results of this work.

GSK7 weights actual load and is the best strategy in FIN and SE3. These areas have nuclear production and a relative flat production curve compared to other areas. This could be the reason why the actual load gives a good estimate of the actual power flow. This strategy performs not that well in areas with export of power or mainly hydropower production. GSK7 is the worst strategy in NO2 and SE2. In these areas, the production is much higher than the load in the main period. This could be the reason the results indicate that weighting the actual load in this area gives the wrong picture of the flow in the grid.

The two flat strategies GSK4 and GSK8 are most often average good strategies. When the production is high in areas with large hydropower production, the flat strategies perform not that good.

GSK4 is assumed as the most robust flat strategy in this study. According to the results, GSK4 is never the worst strategy and the optimal strategy in NO1 and NO3. GSK8 is the best GSK in SE1 and the worst in NO4. In areas with large hydropower production, GSK8 always perform poorer than GSK4. Therefore, GSK4 is recommended as the best choice of flat strategy.

6.8 Comparing of results

As mentioned, this thesis is a continuation of the project assignment “Flow based market clearing: GSK strategies”, 2015[2]. The main difference of the project assignment and this thesis is the calculation method used to compare the strategies.

The main results for the period 12.01.2015- 26.03.2015 in the project assignment are presented in Table E1 in Appendix E. These results are relative deviation calculated by a code in Visual Basic. The best and worst GSK in both the master thesis and project assignment are presented in Table 10.

	Results master thesis		Results Project assignment	
Bidding area	**Best GSK**	**Worst GSK**	**Best GSK**	**Worst GSK**
DK1	3	8	5	7
DK2	3	7	8	5
FIN	7	5	7	4
NO1	4	5	3	8
NO2	3	7	5	7
NO3	4	7	5	7
NO4	5	8	2	7
NO5	3	2	2	7
SE1	5	8	7	4
SE2	8	7	7	2
SE3	7	5	8	5
SE4	7	5	7	2

Table 10: Optimal and worst GSK in the master thesis and the project assignment

Only trends and comparison of results for this thesis and the project assignment are presented.

Observations of similar results in the two studies when comparing results in Table 10 and Table C1 are:

- Very little difference between the strategies in NO1, like in the thesis
- GSK7 and GSK8 bad in NO2. GSK3 the second best with low deviation value in the project assignment and the best strategy in the thesis
- In NO4 and NO5 the load strategies perform poor
- Load based strategy best in SE2
- GSK7 best and GSK5 worst in SE3
- Little difference between the GSKs in SE4 in the project assignment. This result is also observed for all GSKs in this thesis, except GSK5
- GSK7 and GSK8 the best strategies in FIN, and GSK5 the worst
- GSK7 the worst GSK in DK1

Observed differences are:

- Larger deviation between GSKs in NO3 in the project assignment than in the thesis
- GSK5 the optimal GSK in DK1 in the project assignment, the worst in the thesis (however, the difference of the strategies are small in the thesis)
- Near no deviation between strategies in SE4 in project assignment, while GSK5 clearly stands out as the worst GSK in SE4 in this thesis
- GSK2 is the best strategy in NO2 in the project assignment while it is the worst in the master thesis.
- GSK7 is the best strategy in the project assignment and the worst in the master thesis for SE2

The above-mentioned observations show that there are more similarities than differences between the two studies. Table 10 show that the best and worst are not the same in so many areas, but the best strategy in an area in one of the two studies is most often well performing in the other study. This result of relative similar results make the results in this thesis more reliable, as well as the project assignment.

Both approaches to compare the GSKs weights the deviation in a similar way using the Frobenius norm. However, the approaches used in these two studies are different. The thesis use the FRM approach to describe the uncertainty in flow estimation, while the project assignment use a somehow easier approach in the calculation of the relative deviation.

The difference in approach is probably one of the reasons for the mentioned differences, especially for the best and worst strategies in NO2 and SE2. Another reason for these differences is the period studied. Both periods are around 11 weeks long, but the period in the project assignment starts and ends around a month earlier than in this thesis. This thesis includes April instead of January in the period, which is normally a month with higher average temperature and lower load than January. In addition, the load and production curves are different for these periods in both different years and months included in the periods.

The conclusion is that even these two studies are done in different periods and years with different approaches, the results is not that different and seem to support each other.

Chapter 7 - Conclusion

Flow-based market coupling includes a grid model in the clearing of the power market, and therefore provide a better market solution than the NTC method by accounting for real physical power in the grid. This improved market solution will give an increased socio-economic surplus. The improvement means that the error in the estimated power flow is decreased and the estimated flow is closer to the actual power flow. This will say a better calculation of the grid capacity and the consumer will benefit through lower prices and the grid companies benefit by having a more accurate estimate of the power flow in the grid.

To describe the connection between a change in net position and a change in injection, the parameter PTDF is used as a flow factor. To find the aggregated PTDF from a nodal to an area level, it is necessary to use Generation Shift Keys. A GSK describes how a change in net position of an area is divided on the areas nodes.

To estimate the actual flow in the best way, there are eight different GSK strategies considered in the Nordic power market. In this work, these GSKs are all compared and examined, except GSK1. GSK1 is excluded from this study because it is not implemented in the right way in the data material used in this work.

The thesis search for the combination of optimal GSK in each bidding area minimizing the total error in the estimate of the power flow. The main period of this study was 01.02.2016-17.04.2016. To find the combination of optimal GSK in each bidding area, a code in Python was written. The method used in this code bases on the Flow Reliability Margin (FRM). The FRM is a parameter used to handle the uncertainty in the estimation of the power flow.

The objective of this work is to minimize the error in estimated power flow in the Nordic grid after implementing flow based market coupling. To minimize the error, optimal GSK in each area is found by minimizing the calculated FRM norm. This study show that it is beneficial to implement the optimal GSK in each area instead of one global optimal GSK.

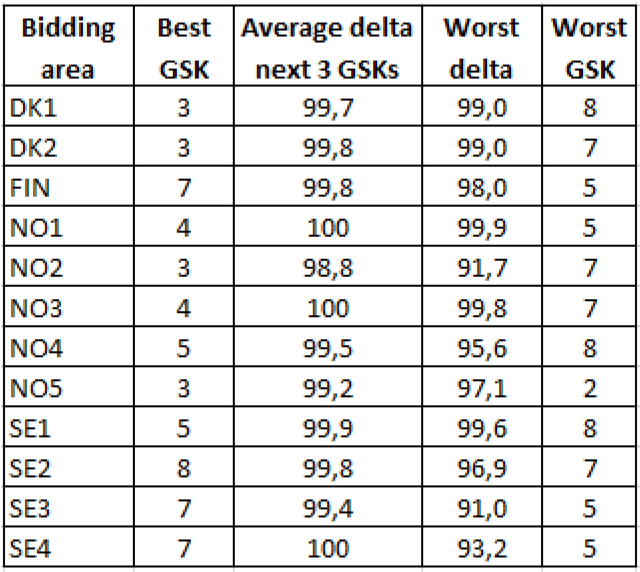
The different areas have dissimilar characteristics regarding grid, generation and load. These characteristics can be the reason why some strategies are well suited in some areas and less suited in other areas. The final table of optimal GSK in each area are presented in Table 11.

In this thesis, also subperiods are studied. The three tested subperiods show that the change in FRM norm is larger in the period 01.02-28.02 than 29.02-27.03. This observation is probably the reason why the differences between the GSKs in each area are largest in the first period.

This could also lead to a larger impact on the estimated power flow in the first period, and an assumed better prediction of the flow in the second period with a minor change in FRM norm.

The discussion earlier in this thesis discuss calibrating of the optimal GSK in some of the areas because some of the strategies perform quite similar. NO3 is the only area with a change of optimal GSK after this calibration. The GSK in NO3 changes from GSK3 to GSK4 because both strategies perform equal in this period and GSK4 is an easier strategy to implement in the system.

Table 11 is the updated table of optimal GSK in each Nordic bidding area.
This table includes changes from Table 6 argued for in Chapter 6.



Bidding area	Best GSK	Average delta next 3 GSKs	Worst delta	Worst GSK
DK1	3	99,7	99,0	8
DK2	3	99,8	99,0	7
FIN	7	99,8	98,0	5
NO1	4	100	99,9	5
NO2	3	98,8	91,7	7
NO3	4	100	99,8	7
NO4	5	99,5	95,6	8
NO5	3	99,2	97,1	2
SE1	5	99,9	99,6	8
SE2	8	99,8	96,9	7
SE3	7	99,4	91,0	5
SE4	7	100	93,2	5

Table 11: Calibrated list of optimal GSK, average delta value for the 3 next best GSKs and delta value for the worst GSK for each bidding area for the period 01.02.2016-17.04.2016

These strategies are recommended as the best strategy to implement in each of the Nordic bidding areas to decrease the error in estimated power flow.

Chapter 8 - Further work

The period studied in this thesis is two and a half month from 01th of February to 17th of April 2016. The data files used in this work produced by the Nordic TSOs were finished at the end of this work. Because of time limitations, it was not time to make files for a longer period.

Results for the subperiods show that the optimal GSK can differ in different periods, and this reflects the final result of optimal GSK in each area in the main period. In addition, this study only include the coldest part of the year in the Nordic countries. Therefore, it is recommended to study a longer period in the future, e.g. a whole year. A longer period would be less affected by results for some single days and will give a better picture of which GSK suited in each Nordic bidding area.

In a new study, different periods of the year should be tested and compared against each other. In some areas, it may be beneficial to e.g. use one strategy in the winter and another strategy in the rest of the year. In addition, study both low and high-load hours would be interesting.

The different GSK strategies are in this thesis compared by evaluating the change in the total FRM norm, when only limiting CNEs are included. In the future, it would be interesting to compare the GSKs by evaluating the change in only the limiting CNEs in the actual area tested. In addition, the FRM norm could be separated into one FRM norm for each area, and then summarize the FRM norm for all areas to find the total FRM norm. This approach using the areas FRM norm to compare the GSKs would probably give a larger deviation between the strategies in each area than the approach used in this thesis.

In a new study, it would also be interesting to study how good the estimates of the flows are to see how large impact the changes of GSK in the areas have. To print the calculated estimated flows in the areas, some changes are needed in the current code. Printing the errors was considered in the end of this work, but there were no time to finish this in the current work.

Some areas and CNEs have special characteristics regarding consumption and/or production. It can be interesting to test an approach setting the GSK strategies in these areas or CNEs based on the physical characteristics. The codes design is such that these kind of changes are easy to implement.

The thesis show that the code does not find only local minima's when optimizing the GSK in each area. However, studying the affection from change of optimal GSK in one area on its neighbour areas is recommended to test. In this approach, three strategies are recommended tested. One strategy weighting according to production (e.g. GSK3), one load (GSK7) and one combined (GSK6). A flat strategy (GSK4) can also be included if the calculation time of the code allows it.

These strategies permute for each area and its neighbour areas, while the other areas e.g. have the optimal GSK found in this thesis. For an area with 2 neighbours, it is needed to perform 3^3 (27) different simulations. For 12 areas the total number of simulations are then 324. The idea behind is that the GSK is of largest impact in the area the CNE belongs and its neighbour areas. The further away from the tested area, the less noticeable is a change in the tested area.

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Appendix

A Pseudocode for the optimization code in Python:

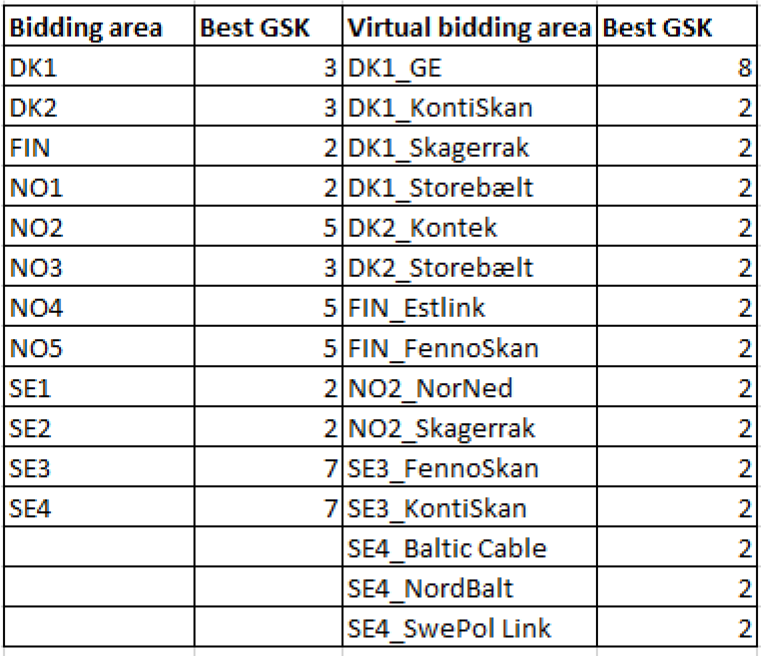
A1: Part 1

```
GSKsToLoad=[2,3,4,5,6]
if use_initial_gskFile=True
  GSK=readgsklist
else
  GSK=$[GSK_2\ GSK_3\ ...\ GSK_{27}\ ] \leftarrow [6\ \ 6\ \ ...\ \ 6\ ]$
limCNEs=LimitingCnes()
init_frmNorm=initial_frmNorm(GSK,limCNEs)
best_gsk,best_frm_norm, delta=brute_force_optimization()
best_gsk.to_csv(Filename)
plot(delta)
```

A2: Part 2

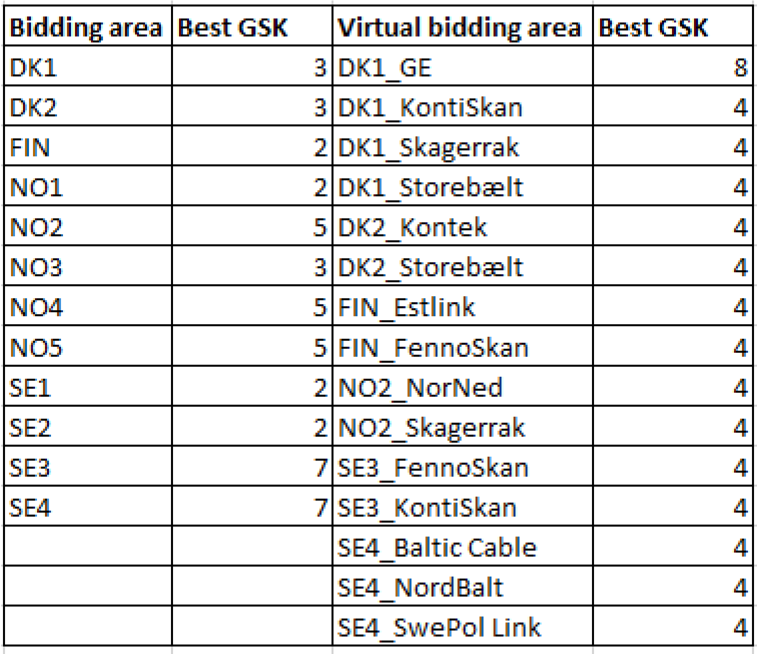
```
def brute_force_optimization()
  best_FRM_norm=self.init_frmNorm
  TestNorm=best_FRM_norm
  GSKOpt=self.GSK
  testGSK=GSKOpt
  for  gsk in GSKsToLoad
   for  area in GSK
     delta[area][gsk]=100
   end for
  end for
 for  gsk in GSKsToLoad
   for  area in GSK
     testGSK[:,area]=gsk
     Error,cnelim,cnenames=calculate_errors(file,Datefrom,Dateto,GSK,GSKToLoad,limCNE)
     TestNorm=frmNorm(Error,cnelim)
     if  testNorm<bestFRM_norm
         bestFRM_norm=testNorm
       GSKOpt=testGSK
       if not gsk==2:
          for i in range(1,gsk):
            if delta[area][gsk]==100:
             delta[area][gsk]=delta[area][gsk]+((bestFRM_norm-AllNorms[area][i-1])/AllNorms[area][i-1])*100
       delta[area][gsk]=100
       AllNorms[area][gsk]=testNorm
     else
       testGSK=GSKOpt
       delta[area][gsk]=delta[area][gsk]+((bestFRM_norm-TestNorm)/TestNorm)*100
       AllNorms[area][gsk]=testNorm
    end if
  end  for
 end  for
return  best_gsk,best_frm_norm, delta
```

B Optimal GSKs for different initial GSKs for a shorter period



Bidding area	Best GSK	Virtual bidding area	Best GSK
DK1	3	DK1_GE	8
DK2	3	DK1_KontiSkan	2
FIN	2	DK1_Skagerrak	2
NO1	2	DK1_Storebælt	2
NO2	5	DK2_Kontek	2
NO3	3	DK2_Storebælt	2
NO4	5	FIN_Estlink	2
NO5	5	FIN_FennoSkan	2
SE1	2	NO2_NorNed	2
SE2	2	NO2_Skagerrak	2
SE3	7	SE3_FennoSkan	2
SE4	7	SE3_KontiSkan	2
		SE4_Baltic Cable	2
		SE4_NordBalt	2
		SE4_SwePol Link	2

Table B1: Optimal GSK strategy in the real and virtual bidding areas for the period 02-05 March 2016, with initial GSK2

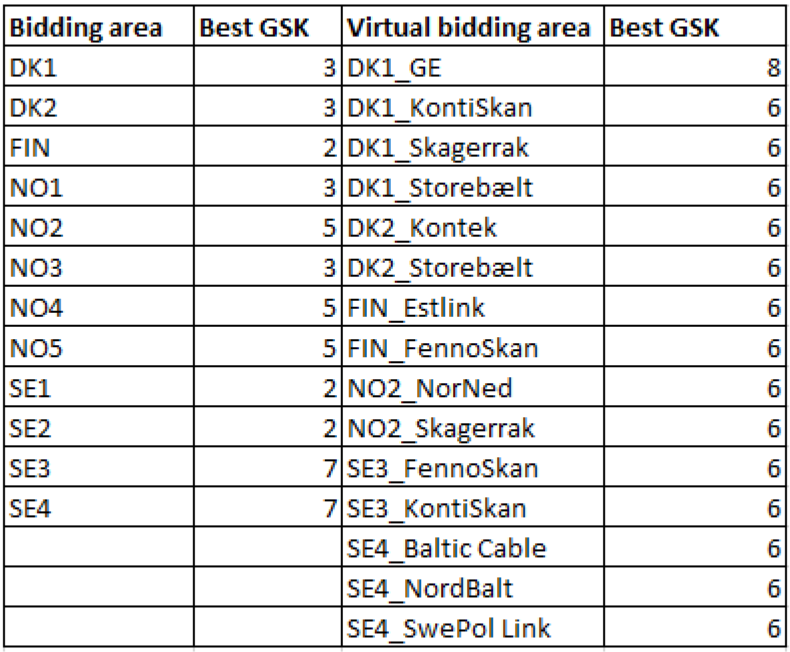


Bidding area	Best GSK	Virtual bidding area	Best GSK
DK1	3	DK1_GE	8
DK2	3	DK1_KontiSkan	4
FIN	2	DK1_Skagerrak	4
NO1	2	DK1_Storebælt	4
NO2	5	DK2_Kontek	4
NO3	3	DK2_Storebælt	4
NO4	5	FIN_Estlink	4
NO5	5	FIN_FennoSkan	4
SE1	2	NO2_NorNed	4
SE2	2	NO2_Skagerrak	4
SE3	7	SE3_FennoSkan	4
SE4	7	SE3_KontiSkan	4
		SE4_Baltic Cable	4
		SE4_NordBalt	4
		SE4_SwePol Link	4

Table B2: Optimal GSK strategy in the real and virtual bidding areas for the period 02-05 March 2016, with initial GSK4

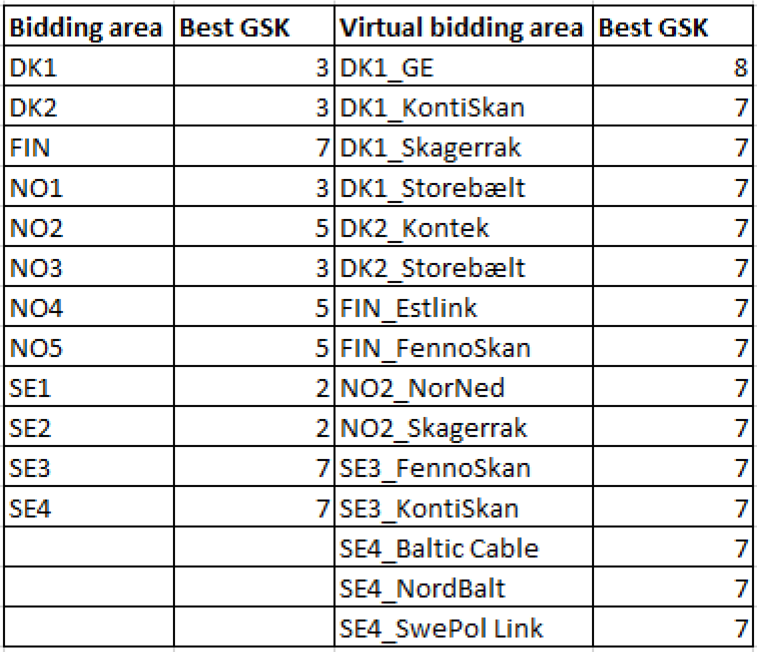
Bidding area	Best GSK	Virtual bidding area	Best GSK
DK1	3	DK1_GE	8
DK2	3	DK1_KontiSkan	5
FIN	2	DK1_Skagerrak	5
NO1	3	DK1_Storebælt	5
NO2	5	DK2_Kontek	5
NO3	5	DK2_Storebælt	5
NO4	5	FIN_Estlink	5
NO5	5	FIN_FennoSkan	5
SE1	2	NO2_NorNed	5
SE2	2	NO2_Skagerrak	5
SE3	7	SE3_FennoSkan	5
SE4	7	SE3_KontiSkan	5
		SE4_Baltic Cable	5
		SE4_NordBalt	5
		SE4_SwePol Link	5

Table B3: Optimal GSK strategy in the real and virtual bidding areas for the period 02-05 March 2016, with initial GSK5



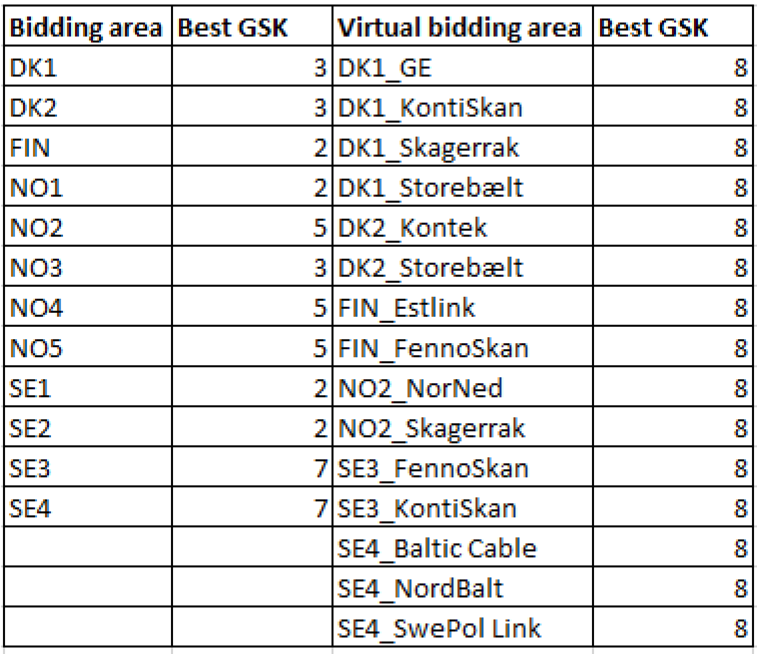
Bidding area	Best GSK	Virtual bidding area	Best GSK
DK1	3	DK1_GE	8
DK2	3	DK1_KontiSkan	6
FIN	2	DK1_Skagerrak	6
NO1	3	DK1_Storebælt	6
NO2	5	DK2_Kontek	6
NO3	3	DK2_Storebælt	6
NO4	5	FIN_Estlink	6
NO5	5	FIN_FennoSkan	6
SE1	2	NO2_NorNed	6
SE2	2	NO2_Skagerrak	6
SE3	7	SE3_FennoSkan	6
SE4	7	SE3_KontiSkan	6
		SE4_Baltic Cable	6
		SE4_NordBalt	6
		SE4_SwePol Link	6

Table B4: Optimal GSK strategy in the real and virtual bidding areas for the period 02-05 March 2016, with initial GSK6



Bidding area	Best GSK	Virtual bidding area	Best GSK
DK1	3	DK1_GE	8
DK2	3	DK1_KontiSkan	7
FIN	7	DK1_Skagerrak	7
NO1	3	DK1_Storebælt	7
NO2	5	DK2_Kontek	7
NO3	3	DK2_Storebælt	7
NO4	5	FIN_Estlink	7
NO5	5	FIN_FennoSkan	7
SE1	2	NO2_NorNed	7
SE2	2	NO2_Skagerrak	7
SE3	7	SE3_FennoSkan	7
SE4	7	SE3_KontiSkan	7
		SE4_Baltic Cable	7
		SE4_NordBalt	7
		SE4_SwePol Link	7

Table B5: Optimal GSK strategy in the real and virtual bidding areas for the period 02-05 March 2016, with initial GSK7



Bidding area	Best GSK	Virtual bidding area	Best GSK
DK1	3	DK1_GE	8
DK2	3	DK1_KontiSkan	8
FIN	2	DK1_Skagerrak	8
NO1	2	DK1_Storebælt	8
NO2	5	DK2_Kontek	8
NO3	3	DK2_Storebælt	8
NO4	5	FIN_Estlink	8
NO5	5	FIN_FennoSkan	8
SE1	2	NO2_NorNed	8
SE2	2	NO2_Skagerrak	8
SE3	7	SE3_FennoSkan	8
SE4	7	SE3_KontiSkan	8
		SE4_Baltic Cable	8
		SE4_NordBalt	8
		SE4_SwePol Link	8

Table B6: Optimal GSK strategy in the real and virtual bidding areas for the period 02-05 March 2016, with initial GSK8

C Delta values for different periods

Delta values calculated by the optimization code. 100% is the best and the lower the worse.

Area	**GSK2**	**GSK3**	**GSK4**	**GSK5**	**GSK6**	**GSK7**	**GSK8**
DK1	99,7	100	99,4	99,2	99,8	99,1	99,0
DK2	99,9	100	99,8	99,7	99,6	99,0	99,8
FIN	99,7	99,7	98,1	98,0	99,8	100	100
NO1	100	100	100	99,9	100	100	100
NO2	91,7	100	98,5	99,1	98,8	96,0	96,2
NO3	100	100	100	99,8	99,9	99,8	99,9
NO4	99,0	99,9	98,3	100	99,7	98,7	95,6
NO5	97,1	100	98,3	99,7	99,4	98,1	98,5
SE1	100	99,9	99,7	100	99,9	99,7	99,6
SE2	97,8	99,8	99,7	99,5	99,9	96,9	100
SE3	99,6	98,6	97,9	91,0	100	100	96,9
SE4	99,9	99,9	100	93,2	100	100	100

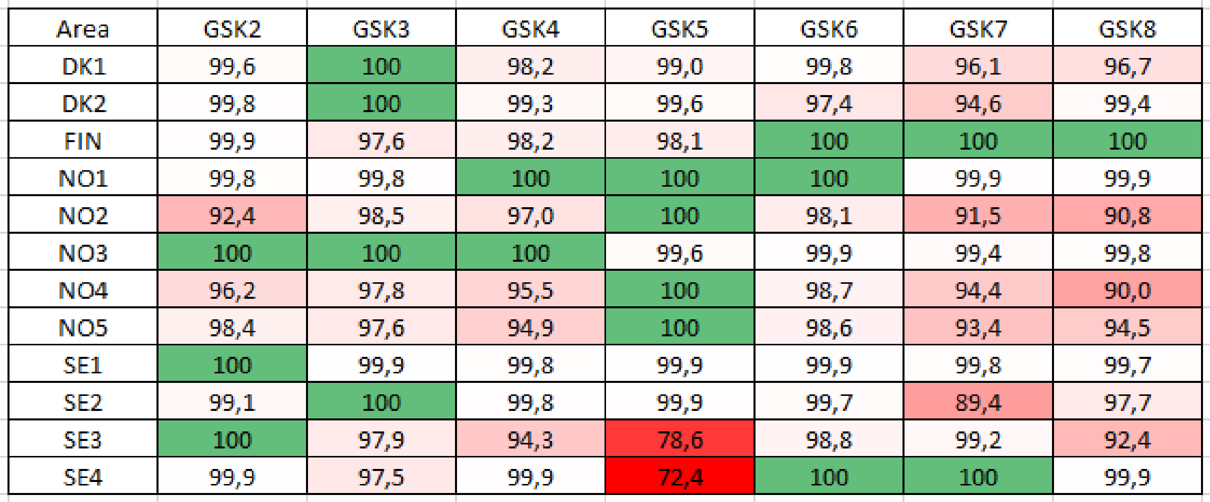
Table C1: Delta values for all GSKs in each area in the period 01.02.2016-17.04.2016.

Area	GSK2	GSK3	GSK4	GSK5	GSK6	GSK7	GSK8
DK1	99,9	100	99,9	99,8	99,8	99,1	99,2
DK2	99,9	100	99,2	99,7	99,4	98,5	99,4
FIN	100	99,1	94,1	94,1	99,2	99,9	99,7
NO1	99,9	99,8	100	99,8	100	99,9	99,9
NO2	67,9	100	94,9	99,8	96,6	87,8	88,4
NO3	99,8	99,9	99,7	100	99,4	98,8	99,5
NO4	96,1	99,3	93,7	100	98,6	95,1	88,4
NO5	84,8	99,8	93,5	100	98,8	94,3	95,4
SE1	99,8	100,0	97,8	100	99,2	96,7	95,9
SE2	99,5	97,1	96,7	95,8	98,1	92,4	100
SE3	96,3	92,0	91,0	75,2	99,5	100	92,8
SE4	99,4	99,8	100	98,3	100	100	99,8

Table C2: Delta values for all GSKs in each area in the period 01-28 February 2016.

Area	**GSK2**	**GSK3**	**GSK4**	**GSK5**	**GSK6**	**GSK7**	**GSK8**
DK1	99,9	100	99,6	98,8	99,8	99,8	99,6
DK2	100	99,8	100	99,7	99,9	99,8	100
FIN	100	99,9	98,6	98,5	99,9	100	99,7
NO1	98,7	100	100	99,7	100	100	100
NO2	99,5	100	99,7	99,8	99,1	99,1	99,0
NO3	100	100	100	100	100	99,9	100
NO4	99,6	100	99,5	99,7	99,9	99,6	98,9
NO5	99,8	100	99,8	100	99,0	99,3	99,5
SE1	99,9	100	99,9	100	100	99,9	99,8
SE2	98,7	99,9	99,8	99,7	100,0	98,3	99,9
SE3	100	98,8	97,5	91,1	99,7	99,9	97,9
SE4	100	100	100	95,1	99,9	99,9	100

Table C3: Delta values for all GSKs in each area in the period 29.02.2016-27.03.2016.



Area	GSK2	GSK3	GSK4	GSK5	GSK6	GSK7	GSK8
DK1	99,6	100	98,2	99,0	99,8	96,1	96,7
DK2	99,8	100	99,3	99,6	97,4	94,6	99,4
FIN	99,9	97,6	98,2	98,1	100	100	100
NO1	99,8	99,8	100	100	100	99,9	99,9
NO2	92,4	98,5	97,0	100	98,1	91,5	90,8
NO3	100	100	100	99,6	99,9	99,4	99,8
NO4	96,2	97,8	95,5	100	98,7	94,4	90,0
NO5	98,4	97,6	94,9	100	98,6	93,4	94,5
SE1	100	99,9	99,8	99,9	99,9	99,8	99,7
SE2	99,1	100	99,8	99,9	99,7	89,4	97,7
SE3	100	97,9	94,3	78,6	98,8	99,2	92,4
SE4	99,9	97,5	99,9	72,4	100	100	99,9

Table C4: Delta values for all GSKs in each area in the period 28.03-17.04.2016.

D Production and consumption in the Nordic areas in January-May 2016

In Figure D1-D12 below, the actual production and consumption in each Nordic area are presented, based on data from NordPoolSpot[26].

In the figures the both hourly and average daily production and consumption for the hours in each day are presented.

DK1

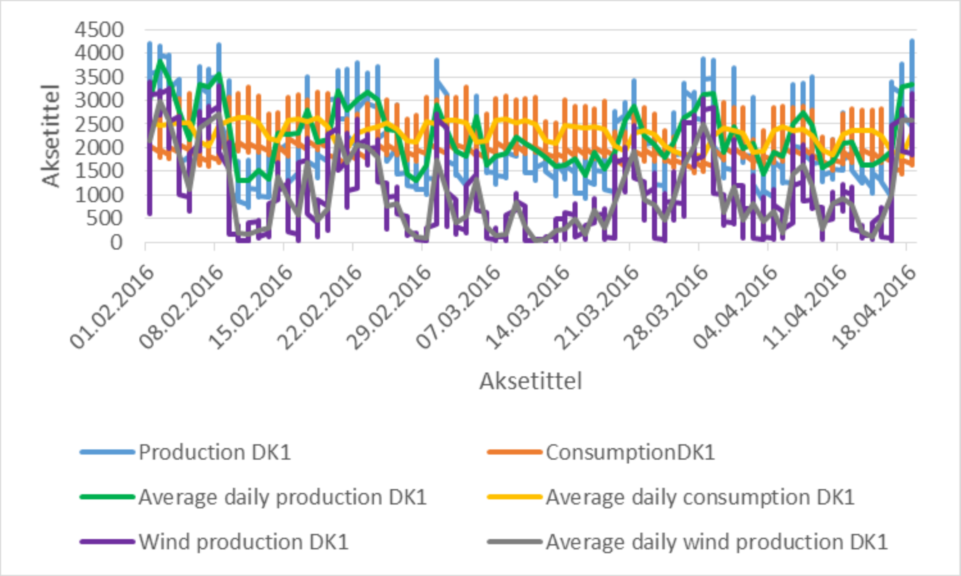


Figure D1: Production and consumption in DK1 01.02-17.04 2016

DK2

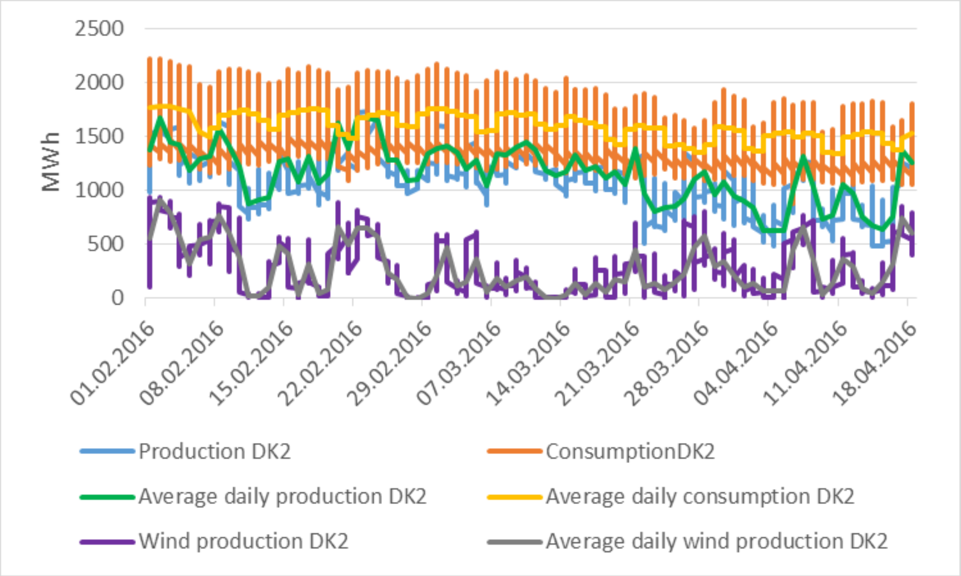


Figure D2: Production and consumption in DK2 01.02-17.04 2016

FIN

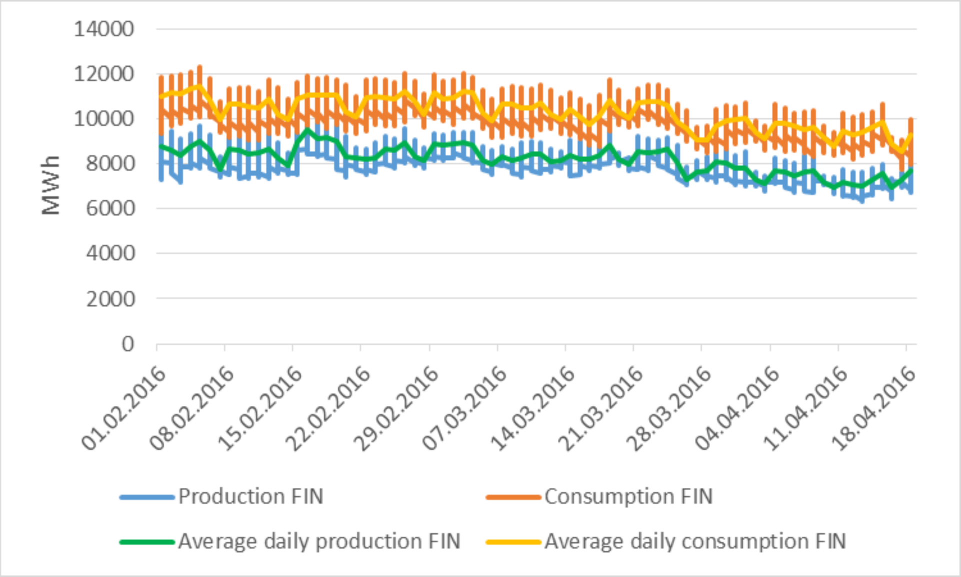


Figure D3: Production and consumption per hour in FIN the period 01.02-17.04 2016

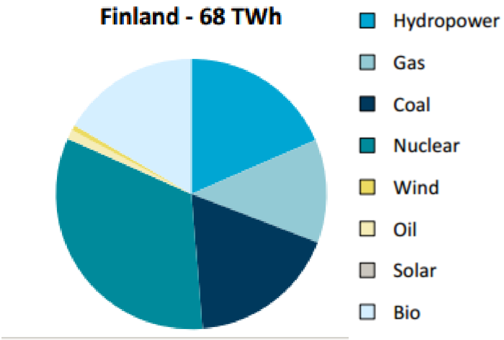


Figure D3-2: Power production in FIN 2013[27]

NO1

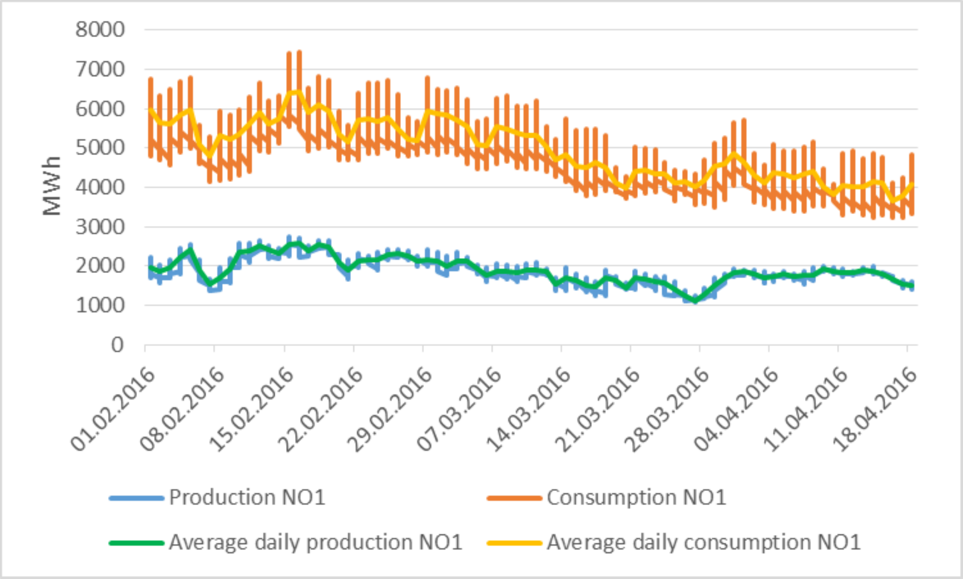


Figure D4: Production and consumption hourly in NO1 the period 01.02-17.04 2016

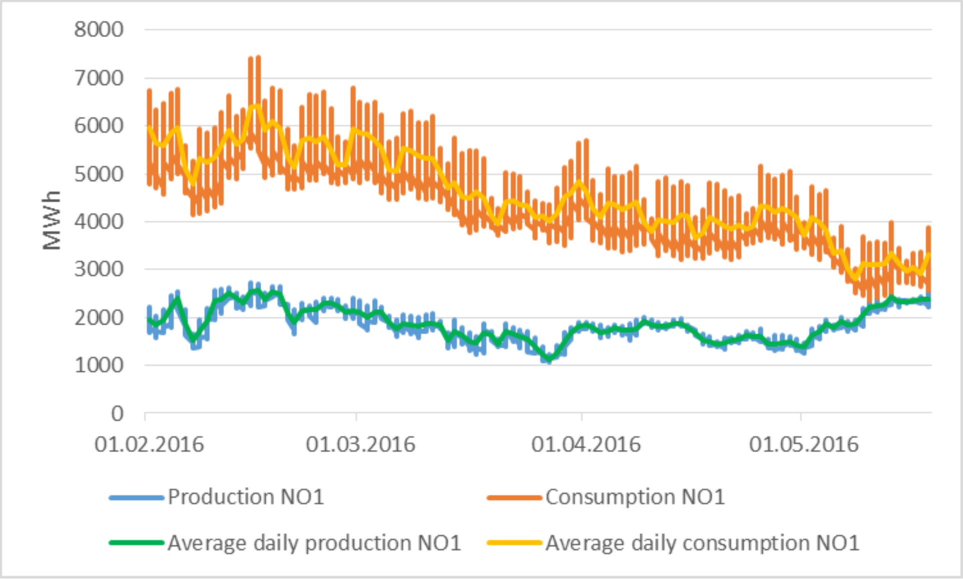


Figure D4-2: Production and consumption hourly in NO1 01.02-18..05.2016 to show behaviour in May

NO2

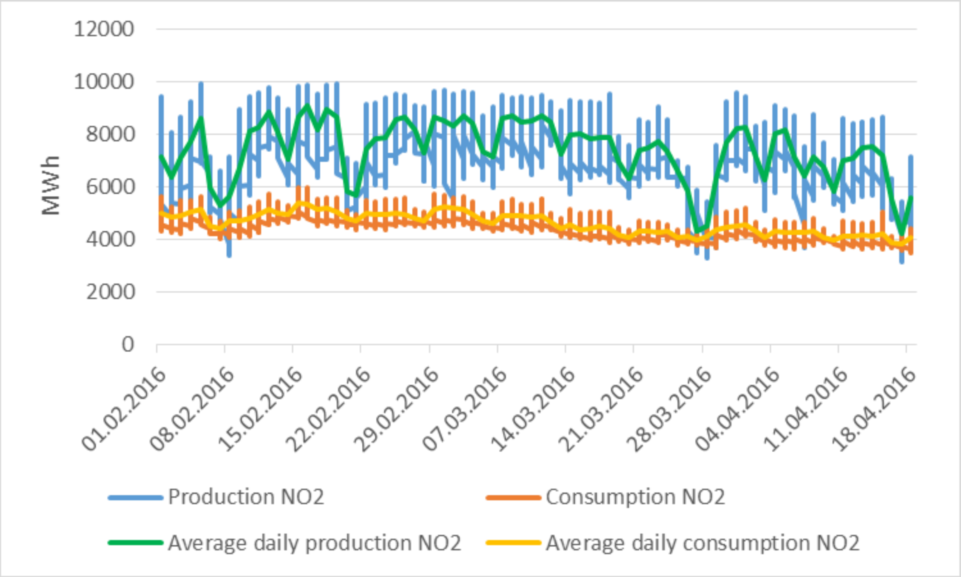


Figure D5: Production and consumption hourly in NO2 the period 01.02-17.04 2016

NO3

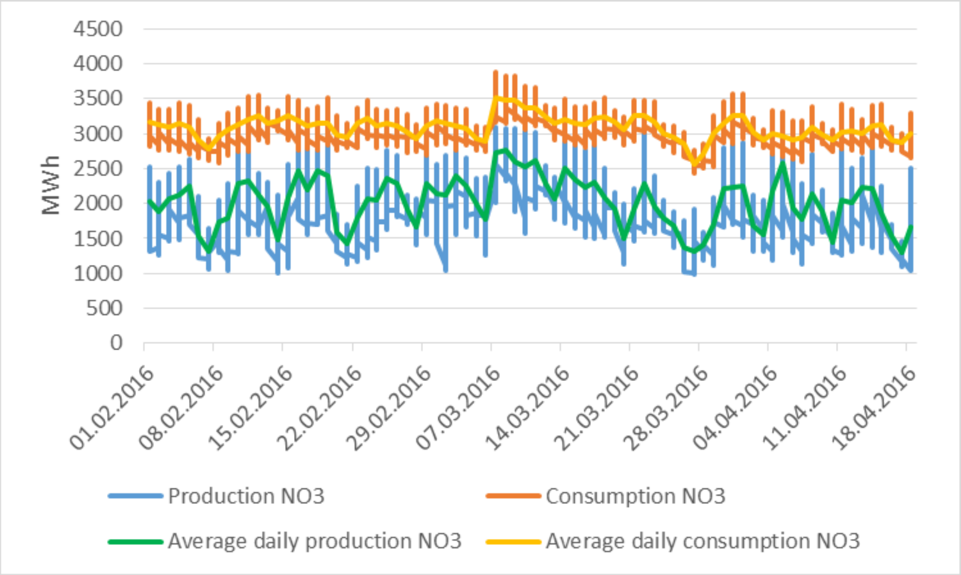


Figure D6: Production and consumption in NO3 01.02-17.04 2016

NO4

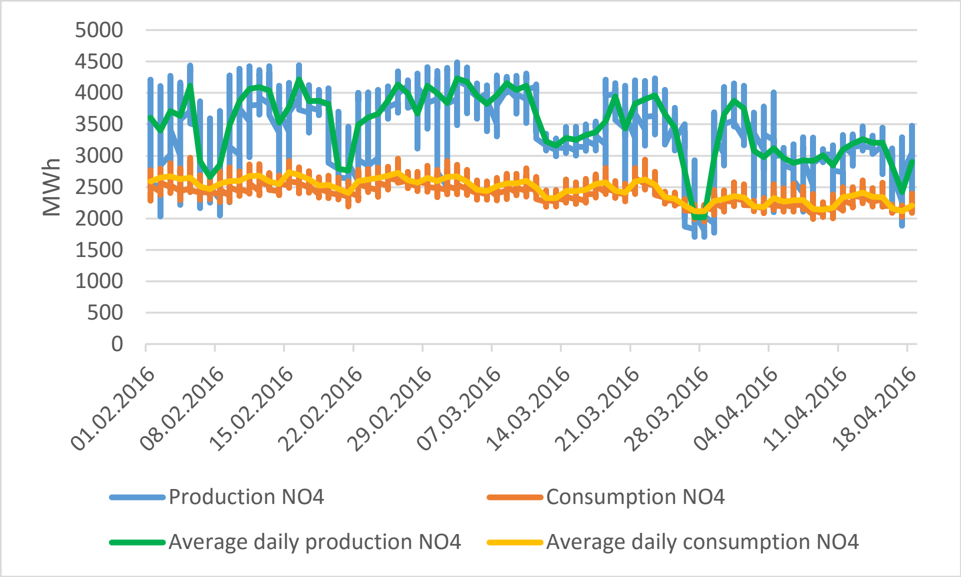


Figure D7: Production and consumption in NO4 01.02-17.04 2016

NO5

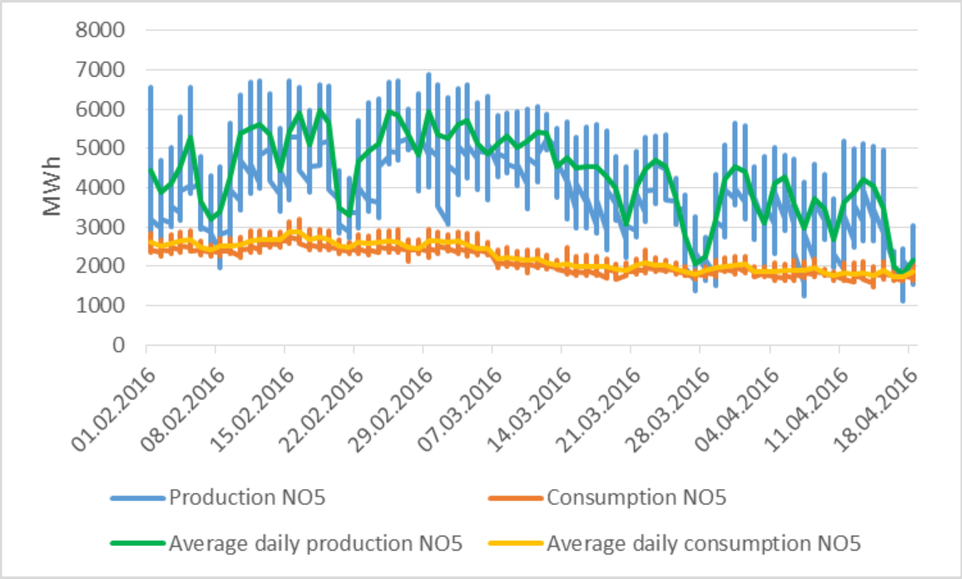


Figure D8: Production and consumption in NO5 01.02-17.04 2016

SE1

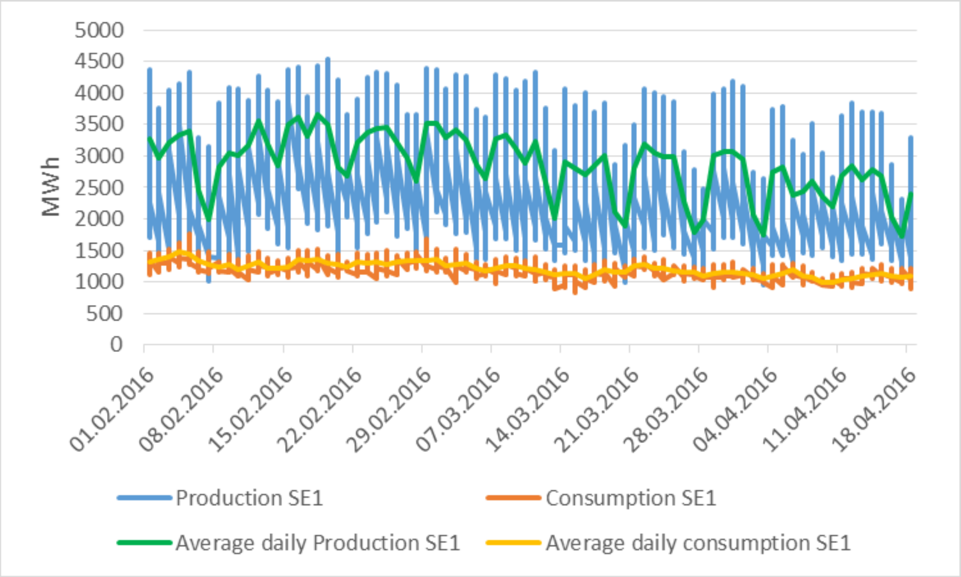


Figure D9: Production and consumption in SE1 01.02-17.04 2016

SE2

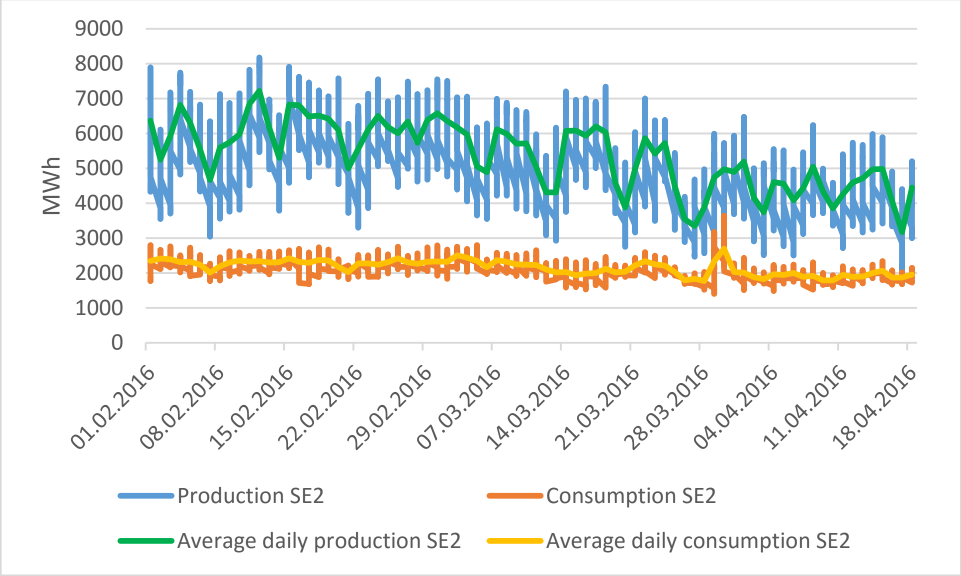


Figure D10: Production and consumption in SE2 01.02-17.04 2016

SE3

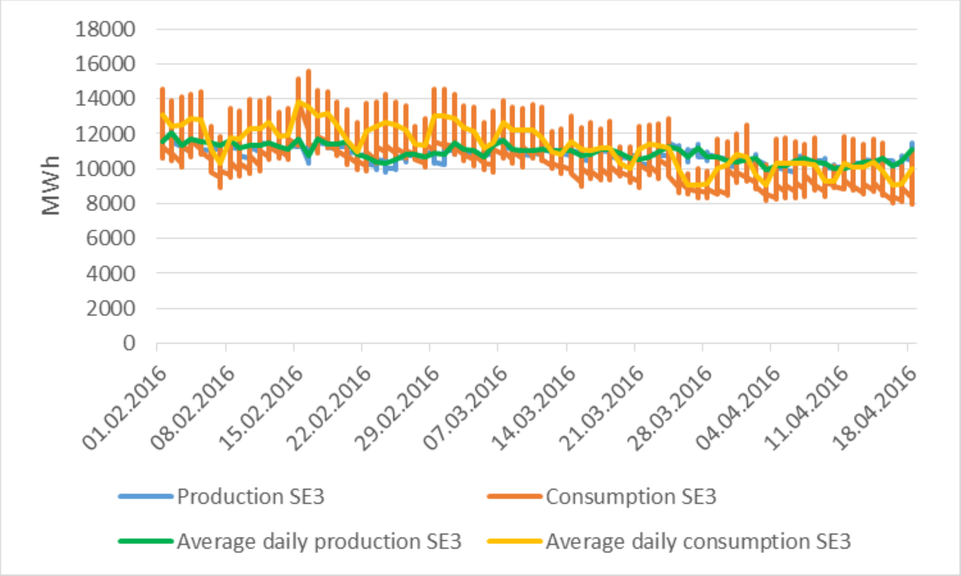


Figure D11: Production and consumption in SE3 01.02-17.04 2016

SE4

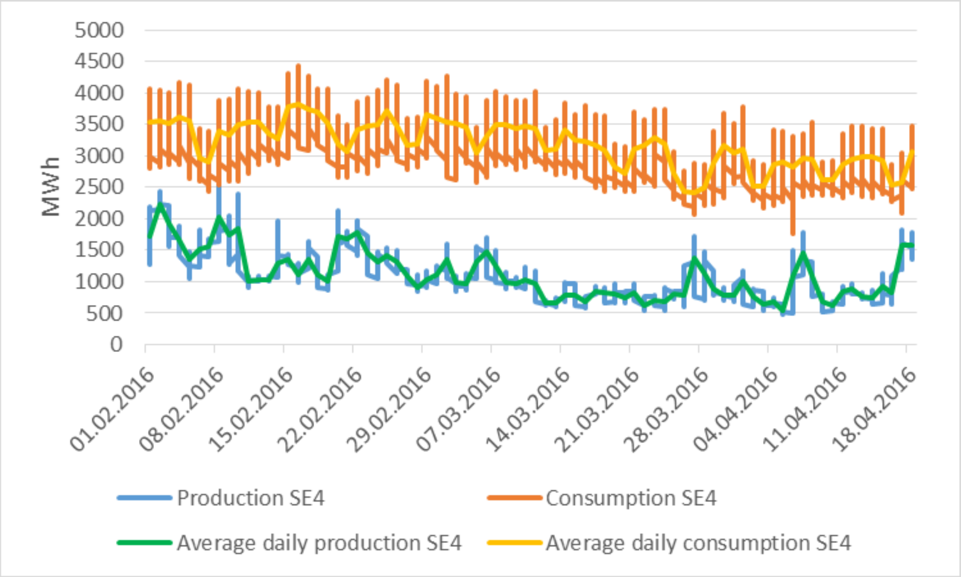


Figure D12: Production and consumption in SE4 01.02-17.04 2016

E Results project assignment

Area	GSK 1	GSK 2	GSK 3	GSK 4	GSK 5	GSK 6	GSK 7	GSK 8
NO1	2,03 %	2,05 %	2,02 %	2,16 %	2,03 %	2,08 %	2,30 %	2,36 %
NO2	6,14 %	6,41 %	6,17 %	6,63 %	6,14 %	6,32 %	6,85 %	6,78 %
NO3	4,33 %	4,62 %	4,42 %	4,43 %	4,33 %	4,85 %	5,14 %	4,75 %
NO4	7,31 %	6,65 %	7,00 %	7,08 %	7,31 %	7,31 %	7,34 %	7,19 %
NO5	4,98 %	4,76 %	4,89 %	5,66 %	4,98 %	5,22 %	6,34 %	6,11 %
SE1	5,33 %	5,41 %	5,39 %	5,42 %	5,33 %	4,97 %	4,85 %	5,06 %
SE2	4,33 %	4,80 %	4,45 %	4,59 %	4,33 %	4,20 %	4,16 %	4,46 %
SE3	3,23 %	2,72 %	2,93 %	3,17 %	3,23 %	2,29 %	2,32 %	2,27 %
SE4	0,69 %	0,69 %	0,68 %	0,68 %	0,69 %	0,65 %	0,64 %	0,69 %
DK2	7,18 %	6,51 %	6,54 %	6,51 %	7,18 %	6,72 %	6,62 %	6,49 %
FIN	7,84 %	7,70 %	7,81 %	8,20 %	7,84 %	5,90 %	5,53 %	5,71 %
DK1	4,03 %	4,36 %	4,17 %	4,59 %	4,03 %	4,34 %	5,01 %	4,57 %

Table E1: Results from the project assignment, showing relative deviation on the area level for each GSK