Balancing Contributions in the Nordic Electricity System

Who bears the brunt of electricity production and consumption patterns?

Eduard Reinier Antoine Overmaat
Abstract

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The share of intermittent weather-based renewable electricity sources has risen and will keep on rising in the Nordic electricity system, which will increase the need of balancing power in the Nordics. The previously developed concept of balancing contributions is used to look at the historic contribution of different power sources to the balancing on the grid. Three different time scales are taken into account: Daily variations, (bi-)weekly variations, and seasonal/yearly variations. This will aid in the understanding of the synergy of different sources on the grid, which, together with a deeper knowledge of the electricity market, might make it possible in the future to quantify the potential for balancing of sources within the Nordic grid.

As a method to analyse the balancing contributions, a previously set-up online visualisation tool was used as an example, and this existing tool was revamped with a new software back-end using a database and automatic data collection. This allows one to be able to use a larger dataset, and for more functionality in the future, such as real-time updates and easier implementation of additional visualisations. Production and consumption data was gathered from Entso-e and SvK: the former has issues with data quality and the latter publishes data with a three-week delay which can only be obtained manually.

The results from the previous research have been replicated, and a bigger dataset has been used to do the calculations, encompassing the years 2015-2018. The overall results show great similarity to that of the previous work. For the first time it was possible to plot the intrayear balancing contributions as a time series, which showed especially that the contributions of hydro power and electricity trade have changed over the period 2015-2018. There is a difference in hydro power balancing contributions based on geographical location, where Finnish hydro power is mainly a daily and—to a lesser extent—weekly regulator, Swedish hydro and especially Norwegian hydro have larger contributions on a yearly basis as well. There are even differences within countries, as the balancing contribution of hydro in bidding area SE2 has changed much more over time than hydro in SE1, for example. Other examples of interesting situations on the grid have also been highlighted using the online visualisation tool.
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Chapter 1

Introduction

Nearly all people living in the world today are to some degree dependent on electricity for their daily needs. Electricity is used for simple household devices such as fridges and mobile phones—which have become more and more ubiquitous—but also drive complex industrial processes, important for the economic welfare of many countries. Electricity can be produced for self-use, but most consumers are connected to the electricity grid, where production and consumption of electricity is distributed over a region, country, or even larger areas.

The operation of the electricity grid is not a trivial task, since there needs to be a balance between the production and consumption of electricity at all times. If this balance is not upheld, the electricity grid loses stable operation. For example, there are inherent uncertainties associated with the consumption of electricity. Therefore, the production side needs to be somewhat flexible, to make sure the consumption is always exactly fulfilled.

This balancing of the electric grid is most technically challenging on the short term: if an imbalance suddenly occurs, the production side needs to react quickly, often within seconds, to restore and maintain the grid balance. But there also needs to be a balance on longer time-scales: variations between day and night, weekdays and weekends, and longer variations because of the seasons all need to be met.

The share of weather-based and variable renewable electricity production has also increased over the years, and will keep on rising steadily, in an attempt to adhere to national and international climate agreements that try to limit climate change due to human-emitted greenhouse gasses, such as the Paris agreement of 2015. Since most of these production sources are non-controllable and intermittent, the need for balancing power will increase even further as time progresses.

1.1 Previous research

In an attempt to quantify how different power stations contribute to the balancing of the electric grid, earlier work by Lönnberg & Bladh at Vattenfall [1] developed and coined the concept of balancing contributions (which will be theoretically explained in chapter 3). Lönnberg & Bladh also applied the concept to Swedish hydro power stations, to categorize them according to which time scale they are balancing most on. Furthermore, the measure has been taken up by Energimyndigheten (Swedish Government Energy Agency), the Swedish transmission system operator (TSO) Svenska Kraftnät (SvK), and Havs- och vattenmyndigheten to once more assess the balancing capabilities of the Swedish hydro power fleet, and which value hydro power provides for the Swedish electricity system [2].

The research on which this thesis is based, a Vattenfall-issued report by Scharff, published in 2018 [3], has taken the concept of balancing contributions and tried to expand the working range, by not only looking at hydro power stations in Sweden, but taking into account all electricity production in the whole Nordic synchronous area. The thought behind this is that balancing happens not on a country level, but in a whole synchronous area at once. It is therefore more useful and insightful to take into account the whole Nordic electricity system, instead of just Sweden. Two online tools were produced, with the aim of visualising electricity production and consumption data for the year 2015 or 2016, as well as the balancing contributions for different electricity production sources. It also considers import and export of electricity as a production type, so that the balancing contribution of electricity trade can be quantified.
as well. The two tools from the original research by Scharff [3] can be found in that publication. For readers of a digital version of this report, the two web-pages are linked below:

1. Production and consumption data (Indata) [Link]
2. Relative balancing contributions [Link]

1.2 Aims

From this previous research focusing on balancing contributions, a few key points for improvement were identified, both in the balancing contribution method and in the current online analysis tools [3].

Automated data collection and visualisation in online tool This makes the job easier for one who wishes to do analysis on balancing contributions, and allows one to identify interesting situations that might have happened on the electricity market and in the grid in near-real time.

Bigger and more complete dataset The previous dataset consisted of the years 2015 and 2016, but were separated internally. To get a more complete picture, and to be able to compare the current situation of the grid with what it was four years ago, the dataset should be enlarged to encompass all available data until now. This also allows for visualisation of intrayear balancing contributions, which was not possible with the "disconnected" years.

Critical evaluation of the balancing contribution concept (and how it is calculated) At present, balancing contributions are expressed as a relative measure calculated against a certain base (which is explained in more detail in chapter 3). Is this the best way to present balancing contributions as a measure? What can possibly be taken as base signals?

Use the updated tools to provide insight in some interesting situations The newly created online tool will provide many possibilities to do further research on balancing contributions. Some examples of challenging situations on the electric grid can be highlighted.

1.3 Research questions

To guide the research, and in an effort to achieve the last aim in particular, the following research questions are the central focus of this thesis. The questions which are going to be answered are:

1. How have the balancing contributions of the Nordic grid changed over the period 2015-2018? If there is a change, could it be attributed to a changing electricity generation mix?

2. What is the usual interplay between variable sources (mainly wind, little solar), dispatchables (hydro), and net import/export? How could this change in the future, and what effects does that have on the Nordic resp. continental European grid?

3. Is there a significant difference in the way that Swedish, Norwegian, and Finnish hydro power contribute to balancing?

1.4 Scope

The scope of this project contains everything that is needed to achieve the aims described in section 1.2: Working with the existing tool and upgrading it, adding more functionality to the existing tool, selecting appropriate data sources and getting familiar with them, implementing a new way of data handling and storage, doing analysis on production, consumption, and balancing contribution data, and delving deeper into factors that affect the balancing contribution, fully trying to understand the method behind it.

What is not included is to change the calculation method, to go into detail outside the Nordic synchronous area, or to be concerned with the classification of individual plants (as has been done in 1), nor to go into further detail on the level of individual river systems or generation units. But all these topics could in theory be expanded upon in further work.
1.5 Limitations

Hourly data is used in this research, so even though balancing has to be done on all timescales, the realm of balancing on scales less than an hour cannot be assessed here. Usually this is short-term regulation, if it concerns changes the operators have to make during the hour, or even frekvensreglering (frequency control) which happens automatically and takes care of time spans from seconds to minutes.

Described here is the generally agreed upon difference between reglering (regulation) and balansering (balancing) [4]. Even though the term regulation is not often used in English, the definition below will be used throughout this thesis:

**Regulation** happens within the hour, and can be a physical effect (system inertia, see section 2.3), or can be employed automatically or manually.

**Balancing** happens on time scales of an hour or longer, and is manual. Since the decisions of people are involved here, this could be considered planning.

The method of balancing contributions is not able to distinguish cause and effect. If one production type is providing balancing and another is providing counter-balancing, it is impossible to tell if the "helping" source had to be activated to balance the "non-helping" source, or if some "anti-balancing" was needed because one source was balancing "too much" in the right direction.

1.6 Report structure

This thesis starts with a short introduction into the previous work, the aims, and lists the research questions in chapter 1. Chapter 2 discusses some relevant background on the Nordic electricity system and market, which is required to place the research into its broader context. Then, chapter 3 lays out the groundwork of the balancing contribution concepts, and the theory behind it, as well as how the calculations are going to be done. Chapter 4 follows up on that by describing the used methodology, and explains some of the more technical background behind the online tool that was used for the analysis. The results are discussed in chapter 5, where some general observations are made regarding production, consumption, and balancing contributions. Additionally, some examples and insights into interesting situations are discussed in more detail. Finally, the thesis is concluded by listing and discussing some considerations, answering the research questions, and giving recommendations for further research on this topic. This is done in chapter 6.
Chapter 2

Background

This chapter will describe the background for the research that is carried out in this thesis, in order to give the reader a sense of the context of the work, which might clarify the choices made while conducting the research. Three main points will be dealt with: The electricity system in the Nordic countries in general, how the electricity market functions from a Nordic perspective, and the concept of grid stability on multiple time scales.

2.1 The Nordic electricity system

The countries that are considered in the Nordic electricity system are Finland, Norway, Sweden, and the eastern part of Denmark (administrative regions Sjælland and Hovedstaden, encompassing the islands of Sjælland and Lolland). There are many connections to other synchronous grids: to the Russian and Baltic grids, as well as to the continental European synchronous grid. Due to the geographically outstretched nature of Norway, Sweden, and Finland, the relatively low population density, and the abundance of lakes and rivers, hydro power has traditionally been the main source of electricity. With the advent of nuclear power, Sweden and Finland started enhancing their electricity production capacities with nuclear reactors, while Denmark and Norway have not employed nuclear energy at all in their country’s history [5].

Bidding areas

Concerning electricity production and trade, a country can be divided into different electricity market zones, otherwise known as bidding areas. A map of these bidding areas in the Nordics, along with their respective codes, is displayed in figure 2.1. As will be explained later in section 2.2, electricity prices can vary in the different bidding areas, which depends on the production capability in the area, the consumption in the area, and the transmission possibilities to other areas. For example, there are a lot of big hydro power stations in the north of Sweden, but not many people live there, so the consumption will be fairly low. In southern Sweden, the situation is opposite. So power will flow from north to south in Sweden (from SE1 and SE2 to SE3 and SE4). If the transfer capacity is sufficient for the amount of power that needs to be transported, the electricity price will harmonize across the bidding areas. But if at any point a transmission bottleneck occurs, the price on the deprived side of the bottleneck will increase, while it will decrease on the other side. These price differences then act as incentives for local power producers and consumers to make sure there still exists a balance on the system.

Sweden

In Sweden electricity is mainly coming from nuclear and hydro power, both providing about 40% of the total energy. The rest is coming in about equal parts from wind and small thermal power [7]. Since the majority of large hydro power is in the north of Sweden, and the main population areas in the south, there is a big southward transfer of electricity within the country itself. Next to that, Sweden exports electricity to Finland, Denmark, and Lithuania. There are also connections to Germany and Poland.
Background

E.R.A. Overmaat

Figure 2.1: Bidding areas for electricity in the Nordic electric grid, adapted from [6]. Note that only the eastern part of Denmark is synchronously connected with the Nordics. The western part of Denmark is synchronized with the continental European grid.

Norway Hydro power is the only major source of electricity in the Norwegian mix, providing some 95% of the yearly energy demand [8] [7]. There are small amounts of wind power along Norway’s coastal areas (NO3 and NO4), and some conventional thermal power [9].

Norway is a net exporter of electricity, mainly to western Denmark (DK1), the south of Sweden (SE3), and the Netherlands.

Finland Finland has a varied mix of electricity sources. The main sources are nuclear and thermal power (mainly coal and biofuels), and to a lesser extent hydro power. There is also some wind power and thermal gas [7]. Finland is not divided into bidding zones.

Next to that there exists a strong connection to Russia, where Finland is a big importer of electricity. Also Finland imports electricity through the north of Sweden, and from SE3 through the Åland DC interconnector.

Eastern Denmark The whole of Denmark is characterized by high wind power penetration, and so is eastern Denmark, where wind power provides one-fourth to one-fifth of the yearly energy [7]. Offshore and onshore wind is present in roughly equal amounts. Denmark has an extensive district heating system where the heat often comes from CHP plants (combined heat and power), fuelled mainly by biomass and coal. Eastern Denmark is, together with SE4, the only bidding area in the Nordics where there is a non-negligible amount of solar power installed, although this will surely change over the coming years.

The rest of the electricity demand is met by imports, which can reach significant levels. Imports originate from southern Sweden, Germany, and western Denmark. The DC connection between the east and west of Denmark is particularly important.

2.2 The Nordic electricity market

This section is intended to give the reader an understanding of how the Nordic electricity marketplace functions, and how choices are made regarding electricity production in the Nordic grid system. In the
Nordics, there is one electricity market. *Nord Pool* operates this market and is the central authority. Nord Pool is jointly owned by the TSOs of Norway, Sweden, Finland, and Denmark.

Keeping balance is not the primary concern of many electricity producers, but is instead the responsibility of the TSO. It needs to be understood that there are many outside factors, such as prognoses, electricity price, and the rules and laws of the country, that influence how electricity is going to be produced. For example, there are strict regulations on water management (vattendomar in Swedish), that dictate maximum and minimum water levels in Swedish river systems, which will directly affect the way that hydro power can and will be used. The electricity market serves then as a platform where the TSO and power producers and consumers can communicate, and the market is set up in such a way that the balancing goal is an underlying principle of its operation.

### 2.2.1 Production planning

Electricity producers who own power stations have to plan their production. For them, the first priority is offsetting their cost of production, and make a profit on top of that. Production planning takes place to achieve this goal.

#### Price forecasting

From the beginning, a forecast about the electricity price is made, and forecasts are made a very long time in advance. However, what counts for any forecast is that the further away a prognosis is made, the higher the inaccuracy of that prognosis will be. So the forecasts are continually updated depending on the latest situation. The price is dependent on supply and demand, and a price forecast is made for each bidding area individually, depending on the distribution of supply and demand. How the price is determined exactly is discussed in section 2.2.2.

On the demand side, electricity is mainly consumed by industry, services/transport, and residential users. Therefore, the demand of electricity depends on the time of day and the kind of day it is. Demand will be higher during the day than in the night, and less electricity is used in the weekend compared to weekdays. Temperature also has a large effect on the electricity demand. In the winter, lower temperature means more electricity use for heating purposes.

On the supply side, the weather again plays a big role: wind and solar sources are directly dependent on the wind speed and available sunlight, and hydro power is dependent on the amount of water that is available within a river system. For non-weather based sources, the price of fuel can influence at what price power producers will bid in their production, which has an effect on the final market price.

The more connected a bidding area is, the bigger role imports and exports play. Then price prognoses for neighbouring areas play an important role as well.

#### Planning and bidding

Using a previously generated price forecast, production planners then determine at what price certain resources should be bid in. They take into account at what cost generating electricity using a certain plant is profitable, and place a bid on the Nord Pool spot market at that price.

For hydro power bidding, there is more to bidding than cost of operation. The water levels in the hydro reservoirs have to be managed well, as the water has a certain value to producers. Should the turbines be run now, or should water be saved until the electricity price is higher and more can be earned using that same water? Additionally, government regulations describe maximum and minimum water levels in reservoirs, as well as maxima to the rate of change of water level, all from an environmental perspective. These are strict rules, so the hydro power stations have to be operated in quite a tight regime.

#### Dispatch

Then, while electricity is being produced under the current hour, sometimes unexpected things are happening, or some last-minute adjustments need to be made. SvK is the party that keeps track of the overall status on the grid, and who can contact individual operators of power plants in case of need. Even though the production planning was made, the bidding was done, and the price was set, SvK can ask individual producers to do something which is different from the plan, for the stability of the grid.
2.2.2 How the electricity price is determined

All producers of electricity make bids to the spot market, as described above. Electricity consumers and retailers also make bids for purchasing electricity. Then, the overarching organization in charge of the power exchange (in this case that is Nord pool) has a forecast on consumption, and matches up consumption and production bids until the expected demand is met. The cheapest bids are taken first, and from the cheapest side, all bids are added up. The price of the final bid that meets the demand, will be the electricity price for that hour. All producers will be paid that price, even if they placed a lower bid for their production. This is called the "price cross", and is illustrated in figure 2.2.

There is a difference in operating cost between the different production types, which usually means that some production types with low operational costs (hydro, wind, solar, nuclear) will be able to bid in at a low price, and so they will always deliver their power to the grid. Other sources which might be more expensive to run, like thermal plants, therefore only get "activated" at times of higher demand (and thus, only at higher prices). This is referred to as the merit order.

![Illustration of how the electricity price is determined from bids made on the electricity market.](image)

Figure 2.2: Illustration of how the electricity price is determined from bids made on the electricity market. Adapted from [10].

2.3 How to keep the grid stable: balancing on different time scales

At any point in time, there needs to be a balance in the grid between the production and consumption of electricity. As a matter of fact, there will always be a balance between production and consumption, firstly governed by the inertial response of all the synchronously connected generators in the system, which is captured in the Swing Equation, which is displayed in (2.1).

\[ J \omega \frac{d\omega}{dt} = P_{produced} - P_{consumed} \]  

(2.1)
This indicates that the power difference $P_{\text{produced}} - P_{\text{consumed}}$ between production and consumption will be provided by a change $\frac{dω}{dt}$ in the rotational energy of all grid-connected rotating inertia. The total energy stored in that grid-connected inertia is equal to $Jω$. Overproduction means all rotating masses will take up energy, and thus their speed increases, resulting in a higher grid frequency. Vice versa, underproduction will take energy from the rotating masses, and their speed will go down, leading to a reduced grid frequency.

Small and unexpected variations in production and consumption are taken care of by the frequency regulation reserves, which happens very fast, with a response time in the order of seconds. When imbalances of production occur in relation to the forecasted consumption, a TSO can decide to call in additional reserves to keep a balance on the current hour (since power producers bid in their production on an hourly basis in the electricity spot market of Nord pool). Once again, this all falls under regulation, because it happens within the hour, and generally speaking power producers do not have a say in what happens here.

Because the electricity price is determined by demand and supply (see section 2.2.2), the variations on longer time scales are taken care of by the electricity market, and is here referred to as planning or, more generally, balancing.

Producers bid in their generation at a certain price, based on the expected total demand, the costs of operation etc. But some electricity sources, such as wind power and solar power, cannot control at which power level they will produce, it simply depends on the available solar irradiation or the wind speed. They are intermittent, and thus the potential difference between the forecasted generation and the actual generation is bigger than for dispatchable sources. Wind power forecasting is still a topic on which much research is being done, since one will want to obtain a grid operation with less uncertainties [11].

Based on the electricity price (which is usually dependent on the time of day, see 2.2.1), the grid is also balanced on a daily basis: there is going to be more production during the day when demand (and price) is high, and conversely, in the night, prices are lower which leads to less production.

These variations based on bidding and price happen on even longer time scales as well. Weekends know lower demands than weekdays, so production is naturally lower there. In the Nordics, the winter is cold, and knows a higher electricity demand driven by heating. On average, more electricity is produced there. These are the kinds of variations that are often not thought on when speaking about the balancing of the electric grid, but are the main focus of this thesis.
Chapter 3

Theory

In this chapter, the concept of balancing contributions is theoretically and mathematically explained and defined, and it is shown how the results are going to be calculated. Furthermore, the method for separating patterns using time horizons is explained, and new horizons for enhanced analysis are proposed. Readers are referred to the Vattenfall reports by Lönberg & Bladh [1] and Scharff [3] for a more thorough and in-depth theoretical background on balancing contributions and time horizons.

3.1 The balancing contribution concept

In order to find out how much a certain area or production type has contributed to the total balancing of the Nordic grid, in essence one needs to quantify how well two time series have followed each other. If data is available on the total consumption and on production of a power plant, one can see how much that power production goes up when the consumption goes up, and vice versa. If a power plant is following the consumption well, it is "helping out" with keeping the balance, and has a positive balancing contribution. If the plant reduces power when more electricity is needed (output goes down while consumption goes up), it has a negative balancing contribution.

3.1.1 Bases

In this report, the base means which timeseries we are calculating the balancing contribution against. In other words: what does one actually want to balance out? The description before used the consumption as an example, but one can calculate balancing contributions on any two time series. Since the balancing of the grid occurs in a whole synchronous area at once, all bases are calculated for the whole Nordic synchronous grid. In this research, three bases have been considered, and that is reflected in the choices one can make in the online tool (discussed in section 4.1):

Consumption is the sum of the consumption of all bidding areas. Under normal operation, production always needs to be and always will be equal to consumption, as explained in section 2.3.

Residual load also called net load is the total sum of consumption, minus the total generation of intermittent sources—in the Nordic case, wind and solar power. This is the load that has to be supplied by dispatchable power sources such as hydro, nuclear, and thermal power.

Wind is the total wind power generation in the Nordic synchronous area, both onshore and offshore. Since wind is the predominant intermittent renewable source in the Nordic synchronous area, it might be interesting to see which other sources have done a good job of working together with wind power, and which ones did not have such synergy.

In this report, the base that is used, unless otherwise stated, is the residual load. The reason for this is that it provides the most insight. In the end, what needs to be balanced is the total consumption, but since the intermittent sources are not at our control, what needs to be "actively balanced" by dispatchable sources that one has control over—which is the responsibility of the TSO—is the residual load.
3.1.2 Balancing contribution definition

The balancing contribution definition has been set up before in the work of Lönnberg & Bladh [1], where the relative balancing contribution of a production source that has produced $P_{\text{prod}}$ to the base $P_{\text{base}}$, is defined as:

$$C_{\text{rel,prod}} = \frac{\text{cov}(P_{\text{prod}}, -P_{\text{base}})}{\text{var}(-P_{\text{base}})}$$  \hspace{1cm} (3.1)

or, when the production and base consist of a timeseries of $n$ elements

$$C_{\text{rel,prod}}\{n\} = \frac{\text{cov}(P_{\text{prod}}\{n\}, -P_{\text{base}}\{n\})}{\text{var}(-P_{\text{base}}\{n\})}$$  \hspace{1cm} (3.2)

The covariance term gives a measure of how well the production and the base timeseries are correlated, and by dividing by the variance of the base timeseries, the final value is normalized to the base. This means that a production timeseries that by itself completely balances out the base timeseries, will have a relative balancing contribution of 1.

3.1.3 Balancing contribution properties

Using the above mentioned definition, the calculated balancing contributions have some interesting and noteworthy properties:

**Linearity** The balancing contributions of different plants together is equal to the sum of their balancing contributions. In this way, the balancing contribution for a production type in a bidding area is simply the sum of the individual plants of that type in that area. In a similar manner, the balancing contribution of a production type in the Nordic grid is simply the sum of the balancing contributions of that production type in all bidding areas.

**Sum to 1** Per definition, since the electricity system is (under normal operation) always in balance, the balancing contributions of all production types under a certain time period will always sum to 1. The base will always have a balancing contribution of -1, since $\frac{\text{cov}(P, -P)}{\text{var}(-P)} = 1$.

**Express in percent** A balancing contribution of 1 is equivalent to 100%. In the results, all balancing contributions are displayed using percent.

3.2 Calculation

3.2.1 Time series data

This research works with data as time series. Section 4.3 will describe in-depth where the data comes from exactly, but for now it is enough to know that the used data has an hourly resolution, so that we have a value of production or consumption or power flow for every hour. This is the resolution of our times series, and thus one is able to look on differences that occur from hour to hour. Since bids are made on whole hours on the spot market, and anything that occurs within the hour is (usually) a deviation from planning, this is likely the reason why TSOs publish production and consumption data on an hourly basis.

Some countries within ENTSO-E have already moved to providing data with half-hour resolution or even with 15 minutes resolution. This also reflects the faster market working in these countries, where operators are able to bid on 15 minute time slots instead of hours [12].

3.2.2 Calculation process

One calculates a balancing contribution using a predefined Resolution and Time window. For every individual combination of production type and bidding area, a balancing contribution is calculated for a certain subset of the entire dataset that falls within the specified time window. This will yield one value, which is saved at a timestamp in the middle of the window. Then, the window is moved by the resolution size, and the same procedure is applied again.
An example is given in figure 3.1, where the window size is 24 hours, and the resolution is 1 hour. The balancing contribution is calculated for the data within the time window. Referring back to (3.2), this timeseries thus consists of 24 entries \((n = 24)\). The result is one single value, which is saved in the middle of the time window.

### 3.3 Time horizons

As has been explained in 2.2.1 on production planning, there are several obvious electricity production and consumption patterns, the three most obvious of which are:

1. Diurnal variations due to day and night
2. Weekly variations between weekdays and weekend
3. Yearly variations between the seasons

When calculating balancing contributions though, there is an additional consideration. By choosing a smart resolution and window size of the balancing contribution calculation, one can segregate these three variation frequencies from each other. For example, if one calculates for every day an average value of the production and consumption, then the daily variations (morning, evening, night) don’t show up here, and the only difference will be the changes that happen over the days. In a similar fashion, if one takes production and consumption averages of every week, the variations within the week will not be visible, only differences that exist between individual weeks can be seen. The residual load is at the moment still dominated by the consumption pattern, so it will have the same sort of variations as the consumption. So also when calculating balancing contributions against the residual load, the method described above seems to be reasonable.

Most production types are dispatchable, and are operated to follow the demand of electricity. Therefore, they too will possess for a large degree the same variation patterns. Solar power has an obvious 24-hour pattern, as well as a seasonal pattern. These properties will clearly surface when one looks at the total average balancing contributions. These are presented in section 5.2 and are similar to the results presented in the original methodology by Lönnberg & Bladh [1] and in the previous research by Scharff [3]. The three time horizons with their respective resolutions and window sizes are tabulated in table 3.1.
Table 3.1: Existing time horizons for separating the different consumption patterns, as proposed and used in the previous research by Scharff [3]

<table>
<thead>
<tr>
<th>Name</th>
<th>Resolution (h)</th>
<th>Window size (h)</th>
<th>Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intraday</td>
<td>1</td>
<td>24 (1 day)</td>
<td>Diurnal variations</td>
</tr>
<tr>
<td>Intraweek</td>
<td>24 (1 day)</td>
<td>336 (2 weeks)</td>
<td>Variations from day to day, and in a week</td>
</tr>
<tr>
<td>Intrayear</td>
<td>336 (2 weeks)</td>
<td>8736 (~1 year)</td>
<td>Seasonal variations</td>
</tr>
</tbody>
</table>

However, besides these three obvious variations, there might be other frequencies that are worth considering. For example, within the day, there are periods of relative stability (night, midday), while there are other periods which showcase more ramping behaviour.

Additionally, wind power variations do in some degree follow the three aforementioned cycles (usually more wind in the winter than summer, there can be diurnal variations too), but there are also other frequencies in the wind, ranging from variations of a few hours within the day (strong ramps), variations of 4-8 days (multi-diurnal), up to multi-week/monthly variations [11, 13, 14]. So in addition to the previously defined three time horizons, a new proposal is made to try to "catch" other types of variations as well, and properly express their balancing contributions, since their true effect might now be hidden because of the choice of time horizon. The division of these time horizons is somewhat arbitrary, and many different divisions have been used in literature. The new set of proposed time horizons is tabulated in table 3.2.

Table 3.2: Newly proposed time horizons for capturing different patterns related to renewable electricity generation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Resolution (h)</th>
<th>Window size (h)</th>
<th>Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramps</td>
<td>1</td>
<td>3</td>
<td>Quick ramps</td>
</tr>
<tr>
<td>DayPart</td>
<td>3</td>
<td>24 (1 day)</td>
<td>Sections of the day</td>
</tr>
<tr>
<td>MultiDiurnal</td>
<td>24 (1 day)</td>
<td>168 (1 week)</td>
<td>4-8 day wind variations</td>
</tr>
<tr>
<td>Seasonal</td>
<td>168 (1 week)</td>
<td>8736 (~1 year)</td>
<td>Seasonal variations with higher resolution</td>
</tr>
</tbody>
</table>
Chapter 4

Methods for data visualisation

This chapter will describe the proposed methods for obtaining balancing contribution results. It involves creating a software platform where data is gathered and visualised, so that the analysis process is made easy. The data collection and processing is described, as well as the different sources of data. A note is made on data quality, and instructions are given to the reader about the created software, so that any results in this report may be replicated.

4.1 Software tools

In the previous work by Scharff [3], two public online tools were created which allowed one to delve deeper into data on production and consumption in the Nordics, as well as balancing contributions in the Nordics. These visualisations tools were made using the Microsoft PowerBI software suite, which were manually fed with calculated data. In this work, as an attempt to automate that whole process, the previously created visualisation tools will be used as a baseline. They will be recreated and improved upon.

Implementation of software goals

To be able to make an electronic platform where one can go in and take a look at indata and visualisations of balancing contributions, first it needs to be clear what the goals are of such a platform or tool. The tool that is going to be created for this thesis needs to have the following requirements:

- Automatic data collection and calculations. With the press of a button, a specified amount of data needs to be retrieved, and all necessary calculations need to be done on it. In order to immediately save the data that is obtained, to do the calculations, and to visualise afterwards, a database system will be used. To be able to get the latest data, a program needs to continually read the database to check what is the most recent data, and what is still missing compared to now.

- Flexible interface, and the ability to do in-depth analysis on balancing contributions. Most of the analysis part will be done in the visualisation software (Microsoft Power BI). The visualisation can be tweaked, and ideally have the same or more analysis functionality as the previous tools.

4.2 Data flow

Data on the electricity market and on consumption and production is available online. The data sources used in this research will be elaborated upon in section 4.3. An overview of the whole data flow chain is visualised in figure 4.1. To achieve an automatic process, it is required that data from the data sources is obtained at regular intervals. This data needs to be formatted and then stored in a database. Readers who are interested in the exact storage structure in the database are referred to figure A.1 in the appendix. An overview of the whole data flow chain is visualised in figure 4.1. This constitutes the raw data, which has an hourly resolution. Data can be missing: either entries are missing in the middle of an existing time series, or the beginning or end of a time series might not be available. Raw data includes:
• Production data for all bidding areas
• Consumption data for all bidding areas
• Data on the physical flow of electricity between all bidding areas

After that, some calculations need to be done on the data. This goes in the following order:

1. From the physical flow data, the net import or export for every bidding area is calculated by taking the sum of all flows in and out of that area.

2. From the total production in an area (all production types plus/minus any transfers) minus the total consumption in that area, the amount of "missing" production is calculated. This is a measure for data quality, as the electricity balance should always be upheld in reality (as explained in section 2.3). Missing simply quantifies how much production should be added or subtracted to make the electricity balance correct.

3. Then, the base timeseries are calculated. At every hour the three bases are calculated for the whole Nordic system by adding up all relevant values from all the bidding areas: consumption, wind, or consumption minus wind and solar in case of the residual load base.

4. Next are the averages: averages of all production types, transfers, consumption, and averages of the base timeseries. Depending on the time horizon that is to be calculated, averages should be taken on resolution size. For this research, that means that daily averages (of 24 hours) and two-weekly averages (of 336 hours) are calculated.

5. Last but not least are the calculations of the balancing contributions, which are calculated per base and time horizon separately, as described in section 3.2.

All these constitute calculated data, which has hourly resolution or larger (in case of the averages), but where one is sure that there are no gaps in the timeseries. If certain entries are not present in the raw data, then it will be covered either by the missing production type, or if further calculations rely on missing raw values, they are calculated using a zero instead of the missing value. To sum up, the calculated data includes:

• Net electricity exchange (import/export) for all bidding areas
• Missing production type for all bidding areas
• Timeseries for all bases
• All non-hourly averaged timeseries
• All balancing contributions timeseries

4.3 Data sources

To allow for a full calculation of the balancing contributions in the Nordics, data is needed on production, consumption, and trade of electricity in the Nordic region. In this thesis, two main data sources are used:

1. ENTSO-E, European Network of Transmission System Operators for Electricity: ENTSO-E has a transparency platform [15] where all member TSOs have to report electricity figures. From here, the following data are obtained:
   • consumption data for all Nordic bidding areas
   • production data for all production types in all bidding areas in Norway, Finland, and Denmark
   • production data for wind power in all bidding areas in Sweden
   • production data for nuclear power in bidding area SE3
   • physical flow data for electricity exchange between all bidding areas inside the Nordic synchronous system, as well as any trade via high voltage direct current (HVDC) cables to outside regions in Europe

2. SvK, Svenska Kraftnät (Swedish TSO): SvK publishes statistics on production, consumption, exchange, and more [16]. From SvK we get the remaining production data for Sweden which is not available from ENTSO-E: hydro power, thermal/other generation, and solar production for all bidding areas in Sweden.
4.3.1 Entso-e

**Publishing** Data on the ENTSO-E transparency platform is published very close to real time. This goes for consumption, production, and physical flow data. The data of a certain time slot is usually published within an hour (and often quicker) after the end of the period of delivery. For Norway, the data regularly lags behind one or two hours.

Figures can be updated at a later point in time by the TSOs as well, for example when slower but more accurate measured data replaces estimated values.

**Reliability** In the previous version of the online tool, exchange data was not taken from ENTSO-E but from Nordpool instead, and consumption data was also taken from SvK. There is a difference in the way that SvK reports consumption data compared to how it is reported on ENTSO-E. For example, are transmission losses counted as part of the consumption? Different actors use different conventions, and this can be the cause of discrepancies between different data sources. This will affect both consumption values as well as physical flow values. Some examples on physical flow data and the differences between ENTSO-E and Nordpool are included in appendix B.1. The data quality of ENTSO-E is commented on in section 4.4.

4.3.2 Svenska Kraftnät

**Publishing** SvK publishes production data for the whole of Sweden on ENTSO-E’s transparency platform, but does not distinguish for bidding areas there. They only publish data on production per bidding area on their own website. Here, it is possible to download an excel file with this production data. Data for the current month is published approximately three weeks after the end of that month, which constitutes a major lag in data from Swedish sources.

For a near-real-time visualisation, this would mean that there is no data on the Swedish bidding areas regarding hydro power, solar power, and other generation, since these are the production types that SvK’s data is used for. In order to still give the user of the tool a visualisation, these three production types will automatically be included in the **Missing** production type. This is a non-ideal solution, but is the best solution while Swedish production data is not yet published on ENTSO-E’s transparency platform per bidding area in an hourly fashion.

**Reliability** Once the spreadsheets of consumption and production have been published on the website of SvK, they are no longer changed. These are SvK’s final published figures, so they are as accurate as
it gets according to SvK.

## 4.4 Data Quality

As mentioned in the previous section, the two providers of data, ENTSO-E and SvK, each have their own publishing schedule and data reliability. While SvK greatly hinders the implementation of a real-time data system because of the slow and cumbersome publication, ENTSO-E has serious issues with random and unexplained missing entries, which can range from a single hour to several days. Usually, the data gets better over time, but there are still many gaps. Section 5.4 will describe a bit more how these data quality issues affect the balancing contribution results, while this section tries to quantify and make the reader aware of what issues there exist with the data. As an example, figure 4.2 shows the period of Saturday the 17th of October to Tuesday the 3rd of November, 2015, for the Norwegian bidding areas. The first big red block shows approximately two days for which production data for all sources is missing. It is not possible to see the difference between the consumption and the residual load, because at this time, there is no wind or solar power, so the residual load is equal to the consumption. In the middle of the figure, an unexpected spike is visible. During this hour, it seems that both the production and the consumption value are approximately double of what they are supposed to be. The next hour, production values are missing completely. This seems as if two values were summed up and saved on the same hour. The daylight saving time change in 2015 actually happened on the 25th of October, which doesn’t seem a coincidence. The second bar of missing data, three hours after the unexpected peak, is due to automatic daylight saving time adjustment in the visualisation software PowerBI, and has nothing to do with missing data. Finally, the big red block on the right is a complete lack of consumption data, hence the negative values for Missing. The yellow line indicating consumption is still visible, but it is simply connecting the two existing points on either side of the gap.

## 4.5 Overview and use of the online tool

The version of the tool that has been used to produce the results presented in this report, can be found under the following link:

https://app.powerbi.com/view?r=eyJrIjoiYmJlYWJlMzItYWUxNi00ZDFiLTliODktOTU5NGIwMGViYmViIiwidCI6IyY4YmUxOGE2LjYWY2NDgtN0E0Ny1iZTczLTgwY2NNMjA0ZCI1mH0j9
This links to a web page which contains all visualisations. On the bottom, one can choose between six different pages:

- Page 1 shows only indata. No balancing contributions have been calculated here. One can select what kind of average is displayed (hourly values, daily average, or two-weekly averages), as well as filter on bidding area, country, and/or production type.

- Page 2 displays an overall visualisation of balancing contributions. The same selectors as in page 1 are present, and one can also select against which base the balancing contribution is calculated. In the lower right corner a table is shown with the total average balancing contributions of all production types over the whole dataset period (2015-2018), calculated against the currently selected base.

- Page 3 displays a similar table as on page 2, the total average balancing contributions over 2015-2018 against the chosen base, but now the contributions are split up per country.

  Electricity exchange (called "net import" in the online tool) are the only production type that do not adhere very well to the balancing contribution linearity. Even though summed it still checks out, one should be careful to draw conclusions from the net import values listed per country, since they can include transfers and loop flows. Balance is kept in the whole synchronous area, so a transfer of electricity from one area to another area in the Nordics does not help the balancing, even though it will show up in the tables here.

- Page 4 has similar tables as page 3, but on even greater detail, as the balancing contributions per bidding area are displayed. The same considerations on the balancing contributions of net imports apply.

- Page 5 allows the user to compare balancing contributions of two different points in time.

- Page 6 contains the total average balancing contributions for 2015-2018 (the same as on page 2), and allows for a comparison against a chosen time window.

Use instructions for the online tool

To be able to let the reader of this report explore the online tool, and to make it easier to arrive at the same results and/or visualisations as have been used in this report, every table or figure in this thesis is labelled in the caption with a set of instructions to replicate the result on screen for the user. For instance, the following instructions

☑ Page=1, AverageType=intraday, Country=EasternDenmark, BiddingArea=DK2, ProductionType=Other+Wind+Solar+NetImport, DateSelect=2018-08-09/2018-08-12, DisplayOptions=Don'tShowAnyTotals

means one should look at the first page (which shows the production and consumption data), with the intraday average type of (which entails hourly resolution), with only Eastern Denmark selected, only visualising the production types other, wind, solar, and net import (electricity exchange). The requested time window for visualisation is from the 9th of August 2018 up to and including the 12th of August 2018, and the display options should be set to not display the total consumption or the total residual load.
Chapter 5

Results and analysis

The results that are obtained using the software tool that was described previously will be discussed in this chapter. General results and continuations of the previous research by Scharff [3] will be presented first, for both the indata and the balancing contributions. After that, a few examples are highlighted and more in-depth analysis is done on the balancing contributions. Finally, a sensitivity analysis is performed.

5.1 Observations with regards to indata

In figure 5.1 the whole overview of available data is visualised for the intraweek horizon, and in figure 5.2 for the intrayear horizon. The intraday horizon is left out, as it will not be detailed enough to distinguish from the intraweek plot on this image resolution used for this report. All production types in all areas for the entirety of the available time span (2015-2018) are displayed, and this is thus the most complete picture of the production and consumption data that can be obtained. Using this visualisation, we can make at first glance some immediate observations, the most obvious but non-trivial of which:

• The overall operation of the Nordic grid has not changed much in four years.

This might be a no-brainer, but it is important to realise that there have been no major overhauls in the Nordic electric system over the last year that have caused issues. This is important since any analysis that is done on this dataset is assuming the same baseline.

Some further immediate observations:

• Data quality has improved over the years, with 2018 being the year with the least number of missing events
• The years 2016 and 2018 show a similar trend in summer: export of electricity from the Nordics almost stops in the middle of summer, and total hydro production is slightly lower here than in 2015 or 2017.

5.2 Observations with regards to balancing contributions overall

Now the results of the balancing contribution calculations will be discussed.

5.2.1 Average total balancing contributions

Table 5.1 shows the average relative balancing contributions of the whole dataset. In this table, balancing contributions for all the different production types are displayed, for all three time horizons. All production types are listed as rows on the left, and the three different time horizons are listed as columns at the top. For example, it should be interpreted that wind power has a balancing contribution of -4 % on the intraday horizon, a balancing contribution of -21 % on the intraweek horizon, and a balancing contribution of 6 % on the intrayear horizon. The values are all displayed as whole numbers, but the
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Figure 5.1: Production and consumption data for the whole Nordic grid, showing all bidding areas and all production types, as well as net imports for 2015-2018 using an intraweek horizon.

Table is fed with decimal numbers, which are rounded. This can lead to a result of -0 % (solar power on the intraweek horizon, for example). This means that there was a small negative value there, but so small that it was rounded to zero. The size of a coloured bar next to a value is relative to the largest value in that column, so the size of a bars should not be used to compare results in different tables, or to compare results from different columns in the same table. The numbers should be used for all comparisons, the coloured bars merely serve as a visual aid. Remember that the sum of the balancing contribution values in one column always equals zero.

The overall picture looks similar as in the previous research by Scharff [3]. Comparing the 2015-2018 results with the original results from only 2016 from that same research [3], the following observations can be made:

- On the intraday time horizon, the numbers are almost exactly the same as in [3], give or take a few percent here and there.
- Hydro power’s balancing contribution has been reduced by approx. 10% on the intraweek time horizon, which has been almost entirely taken over by Missing’s 8% positive contribution.
- Looking at the values for intrayear, hydro has reduced somewhat, with a slight increase of nuclear and net imports. More in-depth analysis of the intrayear timeseries and possible explanations are given in 5.2.2.

5.2.2 Intrayear balancing contribution timeseries

With the current dataset, which covers four years of production and consumption data, it is now possible to visualise the balancing contribution timeseries for the intrayear horizon. This consists not only of a single value, which is the result that is obtained when calculating intrayear balancing contributions for a single year of data. Now, this intrayear timeseries of balancing contributions contains multiple values, which shows how the intrayear balancing contributions changes over time. It is displayed in figure 5.3.

When plotting balancing contribution timeseries, time is displayed on the x-axis, and magnitude of the relative balancing contribution is displayed on the y-axis. Once again, the sum of all relative balancing contribution on a certain hour is always zero. Also keep in mind that, even though the calculated...
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Figure 5.2: Production and consumption data for the whole Nordic grid, showing all bidding areas and all production types, as well as net imports for 2015-2018 using an intrayear horizon.

Table 5.1: Total balancing contributions for 2015-2018. The base is the residual load.

balancing contribution value is saved (and thus displayed) at a certain time point, this encompasses a whole window of data. Taking a look at figure 5.3, for example, the balancing contribution value that shows up for nuclear power on the 31st of December 2015 is 17.27%. This means that, on the intrayear time horizon, nuclear power balanced 17.27% of the total residual load over the time period 1st of July 2015 till 30th of June 2016 (the window for the intrayear time horizon is one year long).

What can be observed from figure 5.3 is that there has indeed been a change in the intrayear balancing contributions over the years 2015 to 2018. For example, while the previous research by Scharff saw very small relative balancing contributions from imports and exports of only 4% [3], it can be seen from figure 5.3 that in fact in 2015 and the beginning of 2016, imports and exports actually did play a significant part in intrayear balancing. In 2016, their contribution on average declined to almost zero, but rose again during 2017, only to decline again over 2018.

Looking at the other production types, nuclear power clearly has had a higher balancing contribution at the end of 2016 and during 2017 than before and after this time period. Taking a look back at the production data for the intrayear horizon (figure 5.2), it seems that refuelling of the nuclear power stations usually happens gradually over summer, and in 2018 there was a slight increase in nuclear power just as the yearly minimum demand was reached. Wind power production seems to be at a minimum at that point too. These result can be explained by the extraordinarily dry summer of 2018 in the Nordics, which

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has an influence on the timing of the spring flood and reservoir water levels for hydro power, and also has ramifications for wind power production.

Also, wind power and thermal power have had a slightly higher balancing contribution during the same period as nuclear had a higher balancing contribution. The question arises though: did hydro power have a lower balancing contribution under this period because the other sources were "naturally" helping with balancing on the intrayear horizon (hydro had to do less), or did the other sources have to help out with the balancing, because hydro power was not able to achieve better intrayear balancing under that period?

Figure 5.3: Balancing contributions timeseries for the full set of indata, using intrayear time horizon and the residual load as base.

Page=2, AverageType=intrayear, Base=residualload, Country=SelectAll, BiddingArea=SelectAll, ProductionType=SelectAll, DateSelect=2015-01-01/2018-12-31

5.2.3 Comparison of different countries and areas

In the previous research by Scharff [3], a quantitative comparison was made between the balancing contributions from the different countries and bidding areas in the Nordics. There, the conclusions that could be drawn from the year 2016 were:

- On the intraday horizon, Swedish and Norwegian hydro power perform similarly.
- On the longer time horizons, Norwegian hydro power has higher (intraweek) or much higher (intrayear) balancing contributions than Swedish hydro power.

The proposed explanation for this is that Norwegian river systems are much shorter, with larger reservoirs, which allows for more flexible operation, but also for better seasonal storage [3].
Comparing these findings with the new average total balancing contributions that were obtained per country for 2015-2018 (displayed in Table 5.2), the following observations can be made:

- Norwegian hydro power still gives larger balancing contributions on intrayear and intraweek horizons, but also it seems to have contributed more on intraday as well (12% more than Sweden).
- It seems Swedish nuclear power is solely responsible for the slightly increased nuclear contribution on the intrayear horizon. Finnish nuclear power has seen virtually no change in its intrayear balancing contribution.
- Give or take a percent or two, all other raw production types (except the ones mentioned above) are exactly the same.

Going in deeper on the level of the individual bidding areas (which are not visualised in this thesis, readers are referred to Page 4, Base = residual load), the following difference between the previous research by Scharff [3] and the current visualisations can be noted:

Table 5.2: Total relative balancing contributions for 2015-2018, for each individual country within the Nordic asynchronous area. Again, note that the coloured bars are sized relative to the maximum value in the respective column and table.

- The reduction in balancing contribution from Swedish hydro power is for the largest part attributable to bidding area SE2. The other Swedish bidding areas show only a marginal decrease in hydro power balancing contribution.
- The Norwegian bidding areas show very similar numbers for hydro power and for the other production types, where all have either gained or lost a few percent. NO3 shows the biggest differences.
- Only hydro and nuclear power show any significant differences.

5.3 Examples

This section goes more into detail on a few specifically highlighted situations, which are examples of challenging situations for the electricity system, or which provide an interesting insight in the operation of the grid. They also provide an insight in the current status of the Nordic electricity system.
5.3.1 Normal operation

To get an idea of the usual working of the Nordic electricity system as a baseline, a look can be taken at the total picture of production and consumption in the Nordic synchronous area. This could explain some of the more general balancing contribution results, for example the ones tabulated in table 5.1. Additionally, the analysis can be broken down per country. In this way a good image can be obtained which production types contribute in which country, and what the interplay is between different production sources, the total demand, and electricity trade.

To start, a time period was chosen in which no unexpected patterns occur, as well as where no large patches of data were missing. It was chosen to look at Wednesday the 24th of January to Monday the 29th of January, 2018. That is six days of continuous data. In this time period, which falls in the winter, a clear morning and evening consumption peak can be seen in electricity demand, and the time period also encompasses weekdays and a weekend. In this time span, wind power is abundant at the beginning, declines over time, and increase again at the end. Figure 5.4 shows the visualisations for all four countries encompassed in the Nordic synchronous area.

- Hydro in Norway strongly reacts on the total residual load patterns, where there seems to exist an almost perfect match between hydro power production and imports/exports: At low residual load, hydro power production goes down and exports decrease/imports rise, and vice versa. This can be seen especially well on Monday the 24th and Tuesday the 25th. This happens on the intraday horizon, but also on the intraweek horizon (not well visible in the figure. Change the average type to intraweek in the online tool to see this). This strong anti-correlation is not so clearly visible in Sweden, where exports seem to more closely follow the total Nordic consumption instead of the residual load.

- At the same time, Eastern Denmark is very reliant on variable imports to meet any daily variations not met by wind power. This reliance on electricity exchange will occasionally lead to exports at times of low residual load. From figure 5.4 it could be observed that on the occasions where DK2 is exporting electricity, Norway is a net importer. Such differences in export level can’t be seen in Sweden, even though there exists a trading link between SE4 and DK2. One reason for this, apart from the earlier observation that the Norwegian hydro power fleet is situated in shorter river systems with larger reservoirs, is the fact that the installed wind capacity in Norway is small compared to its other generation sources. This reduces the need for balancing domestically, and so Norway can balance for other areas. In Eastern Denmark, there is a relatively high percentage of installed wind capacity, but energy volumes are small. In comparison, Swedish production of wind power is four- or five-fold that of Norway, which might explain why Norway takes on the previously described role instead of Sweden.

- In Finland, hydro power takes care of the daily variations, but seems not to react to the level of the total or local residual load. In this example, thermal generation takes care of the intraday variations and part of the intraweek variations (again, switch to intraweek average in the online tool to properly see this). It seems imports are the main adjustment tool for balancing out variations in wind power. It remains unclear whether these imports come from Sweden or from Russia. This is a nice example of how balancing on the different time horizons is taken up by different production types, and as well that one production type works mainly with consumption, while another tackles imbalances caused by wind. Together then they can balance the local residual load, but it is obvious that there are two different mechanisms at play here.

The observations listed above are well reflected in the average total balancing contributions per country, which are displayed in table 5.2.

5.3.2 The Duck

In systems with a high penetration of intermittent renewable power, especially with high solar PV generation, a phenomenon called the duck can occur. First coined in California (which is seeing an ever-increasing share of solar PV generation), the duck occurs when solar irradiation is high and demand is low during the day, giving a low residual load. In the evening, as the sun goes down, peak demand occurs, and thus a huge ramp in the residual load is observed. This residual load pattern is displayed in figure...
Figure 5.4: Indata plots for the four countries within the Nordic synchronous area.

Page=1, AverageType=intraday, ProductionType=SelectAll, DateSelect=2018-01-24/2018-01-29, DisplayOptions=ShowBothTotalConsumptionAndTotalResidualLoad
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(c) Finland

(d) Eastern Denmark

(e) Eastern Denmark (scaled differently on the Y-axis and without total consumption and residual load visualised)
5.5. The problem is that the level of the "base load generation" (usually provided by conventional power stations) decreases, but the demand peak is still as high as before, which increases the evening power ramp [17]. Obviously, the share of installed solar PV generation is much higher in California than in the Nordics, which can be explained by the higher potential yield these panels can get at lower latitudes. Regardless, some bidding areas in the Nordics have a significant share of renewables, and especially wind. Even though wind power does not show the same patterns as solar power, it might be interesting to observe if wind power and solar power together cause a similar problem. As an example, bidding area DK2 is highlighted, since DK2 has the highest relative installed capacity of wind and solar compared to its average consumption.

In figure 5.6, the production and consumption for DK2 is shown for a few days in August. Some interesting operational patterns occur, three of which have been marked in the figure.

1. On the morning of the 9th, before the sun rises, wind power production reaches almost zero. Presumably DK2 is now already at maximum import capacity, since thermal power has to deliver around 150 MW of extra power for a few hours to meet the morning ramp and the demand thereafter.

2. Less than 24 hours later, the wind has picked up considerably and wind power is now providing upwards of 900 MW of power. Just after midnight on the 10th, the residual load drops under the base load generation (in DK2 provided by the production type other), and DK2 has to export power to keep the balance.

3. That same day (10th of August) in the evening, as the sun sets and the wind speed drops, there is a residual load ramp of about 440 MW in two hours. This is not extravagant compared to the regular morning ramp of consumption, but is quite steep and is solely caused by the reduction of intermittent generation.

Now the "duck problem" is not so relevant in the Nordics as a whole: DK2 represents only a twentieth of the whole Nordic synchronous area in terms of production/consumption. But a bidding area within a synchronous system is only as good as its interconnections to that system, and if the assumption that DK2 was at maximum import capacity was correct, then it begs the question what could provide fast regulation (apart from imports) if residual load ramps become even steeper. If the trend of intermittent renewable expansion continues, grid operators should always take into account that fast down-ramps of wind power can coincide with the sun setting, coinciding with the evening consumption peak. If one spots
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5.3.3 Most recent data: the year 2018

The most recent data in the existing dataset is the year 2018, which is the best bet for analyzing the current situation in the system. The resulting average relative balancing contributions for 2018 are displayed in table 5.3. What can be noticed here is that hydro power is contributing more to the balancing of the residual load than compared to the 2015-2018 results, which are shown in table 5.1. Especially significant is the nearly 15% increase on the intrayear horizon compared to previously. This shows that hydro power has actually been able to provide a larger share of balancing on all three horizons, than has previously been shown. Again, it is not known if these values are the result of a higher required need for hydro power balancing the previous year, or if it is just a coincidence of the situation of operation. What can be noted though, is that compared to the four-year average (table 5.1), the contribution of wind to the residual load has increased, only ever so slightly, and not nearly as much as the increase in hydro power balancing. Nuclear generation, other generation, and Missing are all reduced somewhat (with Missing now carrying a negative contribution instead of a slightly positive one).

One note that has to be placed with this result is that, because the data reaches only until the end of 2018, only the intrayear balancing contributions until July of 2018 are obtained. So any contribution to the intrayear balancing that happened in the second half of 2018 is underrepresented in this result.

5.4 Sensitivity analysis of balancing contribution calculation

Because of the data quality issues that are present, which are described in section 4.4, it is desirable to know how sensitive the results are to errors in the indata, so that one is able to understand how accurate the results are and how much trust can be put in the results that are visualised in the tool.
Results and analysis

Table 5.3: Average relative balancing contributions for the year 2018. The base is the residual load

<table>
<thead>
<tr>
<th>Production Type</th>
<th>Intrayear</th>
<th>Intraday</th>
<th>Intraweek</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nuclear</td>
<td>15 %</td>
<td>-0 %</td>
<td>-1 %</td>
</tr>
<tr>
<td>2 Other</td>
<td>22 %</td>
<td>6 %</td>
<td>13 %</td>
</tr>
<tr>
<td>3 Wind</td>
<td>4 %</td>
<td>-5 %</td>
<td>-27 %</td>
</tr>
<tr>
<td>4 Solar</td>
<td>-0 %</td>
<td>1 %</td>
<td>0 %</td>
</tr>
<tr>
<td>5 Hydro</td>
<td>63 %</td>
<td>123 %</td>
<td>107 %</td>
</tr>
<tr>
<td>6 Net import</td>
<td>4 %</td>
<td>-29 %</td>
<td>-19 %</td>
</tr>
<tr>
<td>7 Missing</td>
<td>-3 %</td>
<td>1 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Consumption</td>
<td>-104 %</td>
<td>-96 %</td>
<td>-73 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0 %</strong></td>
<td><strong>-0 %</strong></td>
<td><strong>0 %</strong></td>
</tr>
</tbody>
</table>

5.4.1 Patterns and levels

What needs to be said first is that due to the method of calculation of the balancing contributions, only variations in production/consumption are reflected in the balancing contribution. The absolute level where these variations occur has no influence on the result. This might introduce problems for production types which are not measured centrally, e.g. the distributed generation. The changes in time for wind power, for example, can be hard to estimate immediately after operation, which could lead to less accurate timeseries when it comes to the patterns. This is particularly relevant for data from ENTSO-E, as this data is updated regularly, as has been explained in section 4.3.1. Because of the troubles with estimation of wind power production, a slight time-shift might have been introduced to the data, which will yield vastly different results for the balancing contributions since the patterns of the wind production and the base are now shifted relative to each other.

5.4.2 Production type Missing

To get a bit of a better idea of how inaccurate production/consumption values can affect the balancing contribution result, the already existing production type Missing can be looked at. Usually Missing has a rather constant positive production value which constitutes a small percentage of total production. Under these conditions there is very little or no discernible pattern in this production type, and thus it has a very small balancing contribution. But on some occasions data is lacking. Either production data is not available for a certain time, or the consumption is zero. In those cases, Missing suddenly becomes very large positive or very large negative respectively. Taking a look back at the example given in section 4.3.1 and visualised in figure 4.2 there are three different events happening there. Production data is missing for a longer period, consumption data is missing for a longer period, and there is a single hour with unexpected values. How does this affect the balancing contributions?

On the intraday horizon, as the calculation window reaches the first value of Missing in one of the big blocks, there will be a huge balancing contribution, either positive or negative (depending on what the residualload is doing at that moment: rising or falling). The production types that are being replaced by Missing will have the opposite effect. When the calculation window only encompasses the missing data, its balancing contribution will simply be the sum of the balancing contributions of the sources it is replacing, without any extra magnified effect. Figure 5.7 visualises these balancing contributions. The two peaks can clearly be seen where the big block of Missing data enters and exits the calculation window. If only a single hour is missing, or only part of the data is missing, a pattern like in the middle of figure 5.7 will occur: while this single missing value is inside the calculation window, it will have a small but non-negligible balancing contribution. There are no big peaks, however, because the other production types are still present, and thus there is no big "step" in the time series.

On the intraweek horizon on the other hand, these two days have been averaged to a daily value which consists only of Missing. Therefore it will have a dominating and constant effect on any calculation window it is included in. This can be seen by the overwhelming balancing contributions of Missing in figure 5.8.
Results and analysis

E.R.A. Overmaat

Figure 5.7: Visualisation of an intraday balancing contribution timeseries, and how Missing influences this.

- Page=6, TimeHorizon=intraday, Base=residualload, Country=Norway, BiddingArea=NO1+NO2+NO3+NO4+NO5, ProductionType=SelectAll, DateSelect=2015-10-17/2015-11-03

Figure 5.8: Additional visualisation of an intraweek balancing contribution timeseries, and how Missing influences this.

- Page=6, TimeHorizon=intraweek, Base=residualload, Country=Norway, BiddingArea=NO1+NO2+NO3+NO4+NO5, ProductionType=SelectAll, DateSelect=2015-10-17/2015-11-03
On the intrayear horizon, one or two days of missing data (which are already averaged into a two-week resolution), with a window size of one year, is not going to make any big differences. Therefore, these few missing days of data will not make a significant impact on the intrayear balancing contribution. To compare the impact of the Missing balancing contribution on the results on the three different time horizons, table 5.4 lists the relative average balancing contributions in this time period of Saturday the 17th of October to Tuesday the 3rd of November.

Any errors in the indata for production, consumption, or electricity exchange will always be reflected through the Missing production type. It is therefore a strong indicator to which degree the current results can be trusted.

- When Missing has high values in the production and consumption visualisations, the user knows that there is a problem with the production or consumption data, and that care has to be taken.

- If, in addition, Missing also has a large balancing contribution value on some time horizon, the user should be very careful, since apparently some important pattern is captured by data that is now part of the Missing consumption type.

Table 5.4: Total relative balancing contributions for the time range 17th of October to 3rd of November, the time with blocks of missing data in Norway. Note: these results include all bidding zones, but still the Norwegian missing data has an extremely large impact on the intraweek balancing contributions.
Chapter 6

Discussion, conclusion, and recommendations

This chapter will round off the research. A few noteworthy points are discussed, after which the research questions will be answered. Finally, some recommendations are given which might guide further research in this topic.

6.1 Discussion

6.1.1 Data quality issues

Even though the data quality issues will not have severely influenced the results of the calculations presented in this report, one should always be careful when making an analysis on more recent data, especially concerning the to-be-implemented real-time visualisation. There, it is expected that data is missing at least on some Swedish production types, and ENTSO-E also keeps updating their data, so it is paramount that data are checked on a regular basis after they are obtained, and that they are updated if any changes occur.

6.1.2 Balancing contribution per installed capacity

In the previous research by Scharff [3], the balancing contribution relative to the estimated installed capacity was also calculated in an attempt to see which sources have good potential for balancing (in a relative sense). For example, even though there is only very little solar power installed, and the balancing contribution is still very low, taking a look at balancing contribution per installed capacity, it can be seen that solar power is doing a very good job on the balancing of the intraday horizon. In a similar way, one might be able to get an even better view of the "efficiency of balancing" of hydro power stations for example. If two stations with different nameplate capacities are balancing in a similar manner in relation to their installed capacity (e.g. regulating up and down 50% of installed capacity), the station with the larger installed capacity will have a higher balancing contribution. More in-depth analysis of different sources in certain bidding areas could make use of this concept.

6.1.3 Balancing potential

What would be very useful for future system operators and production planners would be to know how much balancing capability is available or is possible from a certain power plant or, more generally, from a certain production type in a certain bidding area. Unfortunately, the presented methodology is not able to provide that. Apart from the fact that it would be extremely hard to predict the operation of plants in the future, since everything is dependent on uncertain forecasts of price, competitors, consumption, etc. (as explained in section 2.2.1 and 2.2.2), the current method uses historical data only, and thus is only able to make an assessment of historical balancing contributions. If the online tool is taking in data close to real time, it can still give an insight in the "current" status of the grid, which can help planners and operators make decisions, but it cannot see into the future.
6.1.4 Regarding results that concern the flexibility of the Nordic grid

What can the results say about the flexibility of operation of the electric system, and the stakeholders therein? As has been mentioned before, the method of balancing contributions is not able to distinguish cause and effect. Thus, a higher value of balancing contribution of a certain source might mean this source can provide more balancing power, or it might have been caused by an unusual situation on the grid. As time progresses however, and longer data sets are obtained, some patterns might reoccur, which signifies a changed operation of the grid. Also, historical production data could at least tell what the maximum operating parameters are of certain plants or production types. If some chain of operation events has occurred and yielded a certain balancing contribution, at least one knows that in technical terms this operation could likely be repeated if necessary.

6.2 Conclusions

Taking the results generated in this report and the discussion that came before, the research questions stated in the introduction can be answered.

How have the balancing contributions of the Nordic grid changed over the period 2015-2018? If there is a change, could it be attributed to a changing electricity generation mix?

Four years of data is not a lot when it concerns changes in the electricity system of a whole region, and it can be hard to notice differences. First and foremost, any changes that did happen over these years were not sudden, and didn’t stand out as such. Taking a look at the latest data for 2018, on average the balancing contribution of hydro power has increased on all three time horizons. Wind power’s negative balancing contribution on the intraweek horizon has become slightly more negative, and the same goes for net imports on the intraday horizon.

It is hard to say which effects are caused by a changing electricity mix. The changes in wind power balancing contributions are most likely to be caused by the increased installed capacity of wind power in the Nordic synchronous system, but the weather might have been just as important a factor as well. The changing needs on the continental European electricity market, where installed capacities of intermittent renewables are also rapidly growing, might have changed the way the Nordics export and import electricity, and that could be the biggest driver behind the changed intraday balancing contribution of electricity exchange.

What is the usual interplay between variable sources (mainly wind, little solar), dispatchables (hydro), and net import/export? How could this change in the future, and what effects has that on the Nordic resp. continental European grid? As can be seen by the balancing contributions overview, most of the daily variations in the consumption are captured by hydro power, which in addition levels out any short-term variations in wind power, and is the main regulating force when exporting at higher prices or importing at lower prices. Bidding areas with less hydro resources are more reliant on imports and exports for immediate balance keeping, for example DK2, SE3, SE4, and FI.

It looks like the share of intermittent renewables is going to keep increasing, so either the links in between bidding areas will have to be made stronger to facilitate larger volumes of electricity exchange, or there is going to be need for sources of balancing power in bidding areas with high installed levels of renewables. This could take on the form of electricity storage techniques, or more flexible generation plants. Note that "new" electricity storage techniques (such as batteries, flywheels, etc.) can only provide balancing power for short time horizons, because of the limited energy volumes they store.

Is there a significant difference in the way that Swedish, Norwegian, and Finnish hydro power contributes to balancing? Yes, there is a significant difference, not only per country but also per bidding area.

Finland Because of the relatively low share of hydro power in the overall Finnish mix, energy storage volumes are small. Therefore, Finnish hydro power mainly acts as a daily regulator and provides some balancing on weekly variations too. Seasonal contributions are negligible.
**Norway** Simpler and shorter river systems with bigger reservoirs give Norwegian hydro power large flexibility and great storage potential, giving good balancing contributions on all time horizons. There are even differences within the Norwegian bidding areas, with some contributing more to daily variations than seasonal variations, and others where it’s the other way around. It seems Norwegian hydro power is the main driver for electricity exchange between the Nordic and continental European grid, as a higher correlation between hydro power production and exports is seen in Norway than in the other countries.

**Sweden** Hydro power in SE1 and SE2 dominate the Swedish balancing contributions on the short and medium time scales. Seasonal balancing is taken up together with other sources. There are indications there may be a difference between SE1 and SE2 in the way that they develop themselves over time with respect to balancing on shorter and longer time scales.

### 6.3 Recommendations for further research

- Instead of relying on literature from other geographical locations and previous research to get an estimate which patterns and frequencies are present in e.g. wind power production, a Fourier analysis of the whole four-year timeseries of production and consumption could be done, to find the frequencies which are characteristic for each individual production type. This had been done in the previous research by Scharff [3], but more data usually means a better result, especially now that something can be said about periods which are longer than a year, which was not possible before.

- The new time horizons that have been described in section 3.3 which could be better suited to quantify the influence of wind and solar power (among other things) need to be implemented, and the appropriate averages and balancing contributions need to be calculated.

- Unfortunately, the author of this report, due to time constraints, was not able to implement the desired near real time data collection and visualisation. This is still a high priority to implement, as it will continuously expand the available dataset, and it allows users to track changes without requiring the publishers of the tool to be actively developing it.

- A few side-questions arose in the previous research, such as:
  1. The lack of 12- and 24-hour patterns in offshore wind as opposed to onshore generation
  2. The separation of data from traditional thermal power stations and biomass- and waste-fuelled combined heat-and-power, as a difference can be expected

  These could be answered. The current system of information storage allows one to define which production types fall in which category, as ENTSO-E has more than 20 different production types defined, most of which are currently aggregated under a single label. For example, in the current tool, run-of-the-river hydro power, “regular” reservoir hydro, and pumped hydro generation are all aggregated under **Hydro**.

- The current online tool could even be upgraded with an extra page that visualises balancing contributions per country or bidding area, but which is also responsive to the date selection. In that way, differences between bidding areas could be analyzed in time. The balancing contributions relative to installed capacity could also be visualised.

- For gaining a better understanding which effect electricity trade has on the balancing contribution, and what factors steer the exchange of electricity, a next version of the tool should, in addition to listing net import as a production type, display information where electricity is coming from and is going to. This information is already in the existing database, but an appropriate way of visualisation is required. In this way, it is possible to see if exchange is happening within the synchronous area or outside. It is also possible to identify the main routes for electricity trade. This too had already been done in the previous research by Scharff [3], but that was a manual task which produced a static figure. Having a responsive visualisation that updates automatically would give even more analysis power to the user of the online tool.
As has hopefully become clear in this report, keeping the system in balance is the prime objective of the TSO, while for most power producers, the primary objective is to make a return on investment. The way the electricity market functions, both objectives can be fulfilled, but the way in which this happens is perhaps not the best technical solution to the balancing question. If the method for balancing contribution calculation could be expanded, it is possible for example to take the electricity price as a base signal, and see how the production types react to that. Even though the electricity price is by a large part influenced by electricity demand and non-dispatchable generation, other factors play a role as well, which could yield interesting results.
Bibliography


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Appendix A

Database

A.1 Database structure

Figure A.1: Internal database structure. **Bold** attributes are primary keys in their respective table. Lines represent foreign-key relations between tables. The colour of an attribute signifies the data type: **Numbers**, **Date and Time**, or **Text**.
Appendix B

Physical flow comparisons

B.1 Comparison between Nordpool and Entso-e

This appendix includes a few plots that highlight the differences that exist in physical flow data (electricity trade) between the data on Nordpool and ENTSO-E. This research uses physical flow data from ENTSO-E, while the previous research by Scharff [3] used physical flow data from Nordpool.

The data from both sources was compared for the year 2018, to see what kind of discrepancies are in the data, and if there are any patterns that can be discovered.

B.1.1 Sweden

For connections within Sweden itself (for example between SE1 and SE2, from SE2 to SE3, etc.) and for the HVDC interconnection between Sweden and Lithuania, the values line up exactly between Nordpool and Entso-e. There are a few incidental missing values. Figure B.1 visualises this data. Between Sweden and Finland, there is a more constant discrepancy between Entso-e and Nordpool. This can be seen in figure B.2. This also shows a daily pattern in the level of power difference.

B.1.2 Norway

There always seems to exist a slight data difference when looking at the domestic connections within Norway, and on many occasions the power difference goes completely off the charts, with a discrepancy of more than 500 MW of power for multiple days, and even peaks of 3000 MW of power differences is not uncommon. This is visualised in figure B.3.

B.1.3 Denmark

There is constantly a small data difference of a few MW for the interconnector between DK2 and DK2. This can be seen in figure B.4.
Figure B.1: One year of data for Sweden. The domestic and Baltic connections are highlighted.
Figure B.2: Daily variations in Sweden. Connections to Finland and Norway are highlighted.
Figure B.3: Physical flows between bidding areas within Norway
Figure B.4: One year of data for the DK1-DK2 interconnector