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Allocation of Capacity for aFRR Exchange on NordLink

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Submission date: June 2017
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Preface

This report is a product of the master thesis conducted spring of 2017. The thesis was written in cooperation with Statnett SF and finalizes the 5-year master of science program at NTNU.

First, I would like to thank my supervisor, Gerard Doorman, for continuous guidance and support and and my co-supervisor at Statnett, Finn Erik Ljåstad Pettersen, for help and input.

Further, I would like to thank Cecilie Seem for insights and interesting discussions on the topic, and Ivar Husevåg Døskeland at Statnett for help providing future data sets.

Trondheim, 2017-06-16
Ellen Dypvik Bogen

Summary

A growing share of intermittent power production leads to challenges in power system balancing and requires improvement of system regulation capability. Cross-zonal exchange of balancing services is a step towards harmonized European balancing markets and an instrument to meet these challenges. In order to exchange balancing services, reservation of cross-zonal capacity(CZC) should be executed. The allocation of CZC for exchange of balancing services should maximize social surplus.

A market-based reservation model is one of the methods, described by the Network Code on Electricity Balancing, in which socioeconomic efficiency of the reservation of CZC can be demonstrated. In a market-based reservation model the marginal value of the CZC in the different markets are compared, to decide on a reservation volume that maximizes social surplus.

Simulations with case studies in a marked-based reservation model was performed, with the aim of quantifying the possibility of cross-zonal automatic frequency restoration reserves(aFRR) capacity exchange. The simulations in the marked-based reservation model was performed with weekly auctions on aFRR.

Six different case studies were developed; three historical case studies and three future case studies. Each of the case studies was developed by generating aFRR bid curves, using a regression model and historical aFRR bid prices. Historical Day-ahead market(DAM) prices were used for the historical case studies, while the future case studies used DAM prices simulated in Samlast and BID.

Socioeconomic benefit was demonstrated for all the case studies when simulated in the market-based reservation model. Germany was the main provider of aFRR for all the case studies. The latter result contradicts the expectations provided in a qualitative analysis of the thesis, in which Norway was considered to have a competitive advantage in providing aFRR.

The main reason for the simulation results appear to be non-representative inputs of aFRR bids. The aFRR market designs in Norway and Germany are too different, resulting in the distribution of the cost of offering aFRR appears to be shifted in opposite direction between energy and capacity bids.

Therefore, a sensitivity analysis was conducted to study the effect of market development in the direction expected in the qualitative assessment. The results showed that if Norwegian aFRR capacity bids became cheaper than German aFRR capacity bids, increasing the price difference between the countries leads to an increasing socioeconomic benefit.

Sammendrag

En økende andel av varierende fornybar kraftproduksjon fører til utfordringer i balanseringen av kraftsystemet. Utveksling av balanseringstjenester på mellomlandsforbindelsene er et skritt mot harmoniserte europeiske balansemarkeder og et instrument for å møte disse utfordringene. For å utveksle balanseringstjenester bør overføringskapasitet reserveres på mellomlandsforbindelsen. Allokasjon av overføringskapasitet for utveksling av balanseringstjenester bør maksimere sosialt overskudd.

En markedsbasert reservasjonsmodell er en av metodene, beskrevet i "the Network code for electricity balancing", som kan brukes for å demonstrere samfunnsøkonomisk effektivitet av reservasjonen på mellomlandsforbindelsene. I en markedsbasert reservasjonsmodell sammenlignes den marginale verdien av overføringskapasiteten for de ulike markedene, for å bestemme et reserveringsvolum som maksimerer det samfunnsøknomiske overskuddet.

Simuleringer med casestudier i en markertbasert reservasjonsmodell ble utført med det formål å kvantifisere muligheten for utveksling av aFRR. Seks forskjellige casestudier ble utviklet; Tre historiske casestudier og tre fremtidige casestudier. Hvert av casestudiene ble utviklet ved å generere aFRR-budkurver på kapasitet, ved hjelp av en regresjonsmodell og historiske aFRR-buds priser. Historiske spotpriser ble brukt til de historiske case-studiene, mens fremtidige case-studier brukte spotpriser simulert i Samlast og BID.

Samfunnsøkonomisk gevinst ble demonstrert for alle case-studier simulert i den markedsbaserte reservasjonsmodellen. Tyskland var hovedleverandør av aFRR for alle casestudier. Sistnevnte resultat står i motsetning til forventningene gitt i en kvalitativ analyse i oppgaven, der Norge ble ansett å ha konkurransefortrinn ved å levere aFRR.

Hovedårsaken til simuleringsresultatene ser ut til å være ikke-representative input på priser for aFRR-bud. Analysen indikerer at de ulike aFRR markedsdesignene i Norge og Tyskland bidrar til at kostnadene ved å tilby aFRR fordeles i motsatt retning mellom aFRR aktiveringsbud og aFRR kapasitetsbud.

Tilslutt, ble en sensitivitetsanalyse utført for å studere effekten av en markedsutvikling i den retningen som forventes i den kvalitative analysen. Resultatene viste at dersom norske aFRR bud ble billigere enn tyske aFRR bud leder dette til en økende samfunnsøkonomisk.

Abbreviations

TSO: Transmission system operator
ENTSOE: European network of transmission system operators for electricity
NCEB: Network code on electricity balancing
CZC: Cross zonal capacity
DAM: Day-ahead market
BM: Balancing market
BE: Balancing energy
BC: Balancing capacity
MV: Marginal value
BSP : Balancing service provider
BRP : Balancing Responsible party FCR: Frequency containment reserves
FRR: Frequency restoration reserves
aFRR: automatic Frequency restoration reserves
mFRR: manual Frequency restoration reserves
RR: Replacement reserves PCR: Price coupling regions
NWE: North-western European

Contents

Part I

Background

Chapter 1

Introduction

This chapter provides a motivation for the master thesis, presents the project formulation, briefly reviews previous analysis on the topic, and describes the structure of the thesis.

1.1 Motivation

Electricity cannot be stored, therefore, there must be an instantaneous balance between production and consumption. Yet, there will inevitably be deviations between real-time supply and demand of electricity, due to changes in weather conditions and unforeseen events. These imbalances are today handled by the Transmission system operator(TSO), responsible of maintaining secure and reliable operation, by procuring and activating balancing services.

An increasing share of intermittent renewable resources, such as wind and solar power, are today challenging real time balancing. These resources depend on conditions that are difficult to forecast and can hence result in unexpected changes on the production side. This, in addition to changes on the demand side, can result in an imbalance between power demand and supply in the system.

A possible way to handle the increasing challenges related to system balancing is through exchange of balancing services between countries. The different production mixes of the European countries provide different balancing capabilities. Norway, with a high share of flexible electric hydro power, has an advantage in offering balancing services. For exchange of balancing services to take place, capacity on the interconnector has to be allocated. The allocation of cross-zonal capacity(CZC) should be socioeconomic beneficial. Today, balancing services are mainly procured nationally through different market solutions that vary throughout Europe. In order to allocate capacity in a socioeconomic sufficient way, integration of the balancing markets are an important factor.

The NordLink cable is currently being built between Norway and Germany and the project is to be completed by 2019. The cable will have a transmission capacity of 1400 MW and, according to present agreements, up to 300 MW of the capacity, can be reserved for balancing services if socioeconomic efficiency is proven [1]. The Network code on electricity balancing(NCEB), developed by ENTSO-E, describes the methodology by which socioeconomic efficiency can be demonstrated.

1.2 Project formulation

The aim of the thesis is to quantify the possibility of cross-border exchange of automatic frequency restoration reserves (aFRR) capacity on the NordLink cable. The quantification is executed by performing simulations with case studies in a market-based reservation model.

Scope

The balancing service studied in this thesis is automatic frequency reservation reserves(aFRR), and thus CZC can only be reserved for aFRR in the market-based reservation model.

The methodology applied, marked-based reservation of cross-zonal capacity, is developed based on the definitions and requirements set out by the NCEB. In a market-based reservation model the value of the capacity of the different electricity markets is estimated and compared to identify the optimal allocation of the CZC.

The aFRR markets in Germany and Norway are today based on weekly auctions. Since the data provided are weekly, and scaling the bid curves to daily bid curves proved to be difficult to quantify in the preliminary specialization project [2], only weekly curves are used herein. The market-based reservation model will be simulated in two parts, for both day and night time.

Six different case studies will be developed; three historical case studies and three future case studies. Simulations with a market-based reservation model with different scenarios will be performed for each of these case studies.

The different case studies will be developed based on historical aFRR bids and simulated in the market-based reservation model using either historical DAM prices or future simulated DAM prices. aFRR bid curves will be generated for all case studies in both countries.

Objectives

The main objectives of this thesis are hence:

1. Develop a methodology to generate weekly bid curves for aFRR from Norwegian and German market players. The methodology should be based on existing historical aFRR bids. The generation should have a stochastic element, so it should be possible to generate an unlimited number of aFRR bid curves based for each case study.

2. Develop a market-based reservation model for simulation of the case studies. The model will be implemented in Excel Visual Basics.

3. Perform simulations with the model for the case studies with many sets of generated aFRR bid curves.

4. Perform sensitivity analysis on aFRR capacity prices.

1.3 Review of previous analysis

Today, 110 MW is reserved for exchange on balancing services on the Skagerrak 4 cable between Norway and Denmark with long term contracts, 10 MW for FCR and 100 MW for aFRR [3]. The yearly socioeconomic benefit for the 100 MW capacity reserved for aFRR on the Skagerrak 4 cable was calculated to be around 64-78 million DKK/year for Norway and Denmark together [4].

The application for concession for power transmission from Norway to Germany and Great Britain(Søknad om konsesjon for tilrettelegging av kraftutveksling med Tyskland og Storbritannia) [1] from 2013 estimates the the value of the reservation of the 300 MW for balancing services exchange to be 100 MNOK/year. The model is based on a dynamic model were the 300 MW can be allocated continuously. The estimation is based on empirical analysis and knowledge about theoretical relationships. The analysis includes both the aFRR energy market and the aFRR capacity market. The reader is directed to [1] for further description of the methodology behind the estimations.

In Statnetts' value creation report 2016(Verdiskapningsrapporten 2016) [3] Statnett provides a result of an analysis on the NordLink cable resulting in 150 MNOK/year in socioeconomic benefit for exchange of balancing services. This result is for both Germany and Norway. The report states that the analysis is based on empiric analysis and expectations of the market development. Further description of the methodology behind this estimation is not official. Yet, a brief description was provided in an email correspondence with Cecilie Seem in Statnett [5], rendered here. The analysis is based on historic market data for 2012 and 2013. The analysis is assumes dynamic allocation between 50 MW to 300 MW and includes activation, capacity and imbalance netting. The result is based both on quantitative analysis and qualitative assessment. The highest value was found in activation of balancing energy and with Norway as the balancing service provider.

1.4 Thesis Structure

The thesis is divided into three parts. In the first part the necessary theoretical background is given. In the second part the methods on which the thesis is based are described. Results and discussion are provided in the last part.

Part 1: Background

This parts is heavily based on a specialization project [2] done the fall of 2016, a preliminary study prior to this thesis. The thesis first establishes the fundamental theoretical concepts in chapter 2. Further in chapter 3 more specific characteristics of the two countries, Norway and Germany, are presented. Chapter 4 goes deeper into the socioeconomic theory behind allocation of cross-zonal capacity.

Part 2: Methods

Chapter 5 describes the reservation model applied in this thesis. In chapter 6 the methodology behind generation of aFRR bid curves is presented and in chapter 7 the case studies and the basis data set are described.

Part 3: Analysis

Chapter 8 provides a qualitative analysis of the input data to the reservation model. In chapter 9 the result from the generation of aFRR bid curves are presented. Chapter 10 presents and discusses the simulation results in the reservation model. Finally, a conclusion is provided in chapter 11.

Chapter 2

Theoretical Concepts

This chapter introduces to the theoretical concepts behind the master thesis and the electricity markets involved.

2.1 Day-ahead market

In the Day-ahead Market(DAM) the contracts between seller and buyer for delivery of power are made for the next day. Bids are submitted every hour, with the deadline being at noon. The DAM price is calculated hourly based on an advanced algorithm. The price should be set at the market cross between the supply and the demand bid curves.

[6] [7]

2.1.1 Capacity auctions

Power transmission capacity is a scarce resource since the possible amount of power transferred on a line is limited. Hence, adequate handling is needed for an optimal allocation of the capacity. Transmission capacity can be reserved either through an explicit or an implicit auction. An explicit auction is when the transmission capacity is auctioned to the market separately from the auction for electrical energy. An implicit auction i when the transmission capacity auction is included in the electrical energy auction. Interconnector reservation is done for both directions of the line separately. [8]

2.1.2 Congestion rent

Due to congestion between different bidding areas the DAM price calculation can give different prices in different areas, providing a possibility for arbitrage trade. This trade surplus, called congestion rent, is collected by Nord Pool and goes to the Transmission System Operators(TSO). If there are several TSO managing the interconnector, the congestion rent is split between them. Figure 2.1 shows the congestion rent between a surplus area (exporting area), A, and a deficit (importing area) area, B. The congestion rent on the interconnector from area A to area B can hence be calculated by equation 2.1. [7]

$$Congestion\ rent = P_{A,B} \cdot (p^{B}_{DAM} - p^{A}_{DAM}) \tag{2.1}$$

Where:

- $P_{A,B}$: Power transfer from A to B
- p^{A}_{DAM}: DAM price in area A
- p^{B}_{DAM}: DAM price in area B

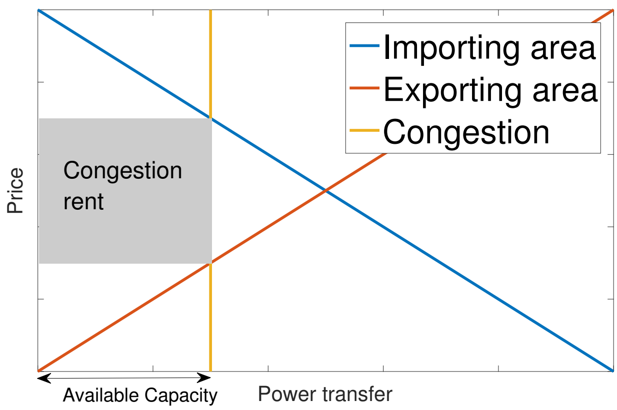

Figure 2.1: The figure illustrates the congestion rent between two areas, depict by the grey rectangle [7].

2.2 Balancing services and balancing markets

As described above electricity cannot be stored and hence there should be an instantaneous balance between supply and demand of electricity. In case of a power surplus or deficit, the stored rotational kinetic energy in certain turbines will compensate for this deviation to balance the system [9]. A change in rotational kinetic energy in the turbines affects the nominal system power frequency, which is 50 Hz. Hence, a power imbalance can be observed through a frequency deviation from 50 Hz. [10]

The day-ahead schedule will follow the principle of balance between production and consumption of electricity. However, a deviation from the day-ahead plan is inevitable [10]. Subsequently, there will be a need to have back up reserves in order to get the power system back in balance and maintain satisfying system quality [7].

After liberalization of the electricity markets, the TSOs received the responsibility of secure operation and maintaining a reliable supply of electricity[9]. This includes, always ensuring balance between power production and consumption.

Players

The main players in the balancing markets are the Balancing Service Providers(BSP's), the TSO and the Balancing Responsibility Party(BRP's). As the names suggest, a BSP's provide balancing service to a market, the TSO further procures and employs these balancing services in order to restore real-time balance in the system [9]. The BRP's submits their operational plan, power production and consumption, to the TSO, prior to real-time operation. In the event of any deviation from the plan the BRP's will be charged by the TSO. Imbalance settlement and the role of the BRP's will not be a focus in this thesis, and is therefore not further described. [9]

Balancing energy and Balancing capacity

The Network code on electricity balancing(NCEB) introduces the concept of balancing energy(BE) as the energy delivered by the BSP's. This energy can be provided by different technologies, both on the supply and demand side, and is activated by the TSO. The balancing energy is procured through the balancing energy market, sometime also referred to as the activation market. The TSO faces a risk related to not having enough available balancing energy. Procuring a sufficient amount balancing capacity(BC) in advance will hedge this risk [11]. This procurement is done by the TSO in the balancing Capacity Market.

To sum up, the TSO activates the balancing energy either through offers in the balancing energy market from the BSPs or through reserve capacity already procured in the balancing capacity market submitted by the BSPs. If the BSP offers capacity in the BCM it will be remunerated for capacity and, in case of utilization of the reserve, remunerated for the balancing energy. [9]

Regulation directions

If the frequency drops below 50 Hz, there is a power deficit on the production side in the system, and the TSO has to activate more power in the system in order to stabilize the frequency. The power increase is usually on the producer side, but there is also a possibility of lowering power demand on the consumer side. Regulation in this direction is called "up-regulation". On the other side, if there is a power surplus in the system, the frequency will increase and the TSO require a deactivation of power in the system. The TSO is procuring "down-regulation". [10]

National obligation volume

The sufficient amount of balancing capacity procured for each area is defined by the TSO in that area [11]. In this thesis this procurement volume is referred to as the national obligation volume of balancing capacity. The required reserve is determined by local requirements, network bottlenecks and fault tolerance [9]. The national obligation volume can be seen as the TSO's demand for balancing services. It is this feature together with the bid curve from the producers, the supply of aFRR, that sets the price of balancing services.

2.2.1 Type of Balancing Services

Different balancing service definitions and arrangements are used by the TSOs throughout Europe, partly due to different generation portfolios [9]. Procurement of the different balancing services is done through various market solutions and different solutions are found among the European TSOs[12]. Hence, there are different terminologies and definitions of balancing products.

Balancing services are traditionally divided into three; Primary, secondary and tertiary reserves [7]. Figure 2.2 , illustrates how the different balancing services are operated. Momentary imbalances will first be handled by the rotating mass in the system, inertia, converting to electrical energy [13]. Then, regulated primary reserves will be activated automatically within 2 minutes. If the frequency deviation persists, the secondary reserves will be activated automatically and release the primary reserves. This should happen within 15 minutes. If the deviation continues tertiary reserves is activated manually. [12]

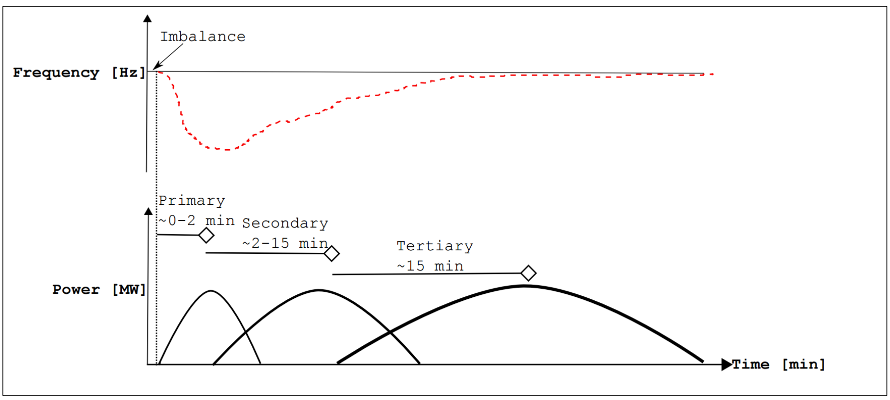

Figure 2.2: Balancing services. Figure collected from [14].

Since the NCEB strives to harmonize the European balancing markets, so that the objective of a common balancing market can be achieved, the NCEB lists standard characteristics as a minimum set of features that defines balancing products. The NCEB defines three types of balancing services:

1. *Frequency containment reserve* (FCR)
2. *Frequency restoration reserve* (FRR)
   These can be both automatic(a) and manual(m) reserves
3. *Replacement reserves*(RR)

[15]

The characteristics and features listed for the balancing products in the NC EB will not be further described in this thesis, since it is the current product design in the countries involved that is of interest. In chapter three the characteristics of these types of balancing services in Norway and Germany are presented.

2.2.2 Balancing capacity pricing

The theory behind balancing capacity pricing is here presented, in addition to reasoning applied in the modelling.

There are two scenarios that will be studied. One in which the DAM price is above the marginal costs, and hence the power producer will want to produce electricity in the DAM. In the other scenario the DAM price is below the marginal cost of operation and thus the power producer will not want to produce in the DAM.

The model depicted in this section is based on a simple model described in the the book "Power System Economics-the Nordic Electricity Market", [7]. For the latter scenario, the capacity pricing derivation provided involves the authors, and supervisors, own reasoning.

This is a rather simplified model with several underlying assumptions:

- The power producer can only choose between producing in the DAM or the balancing market, no other electricity markets are considered.
- Costs and restrictions for start and stop of the power plants are disregarded.
- Constant marginal operating cost (either zero or full). Hence, there are no best point of operation, i.e. production volume with lowest marginal operating costs.
- The power grid is disregarded.
- A large number of competing power plants is assumed.

Marginal cost of operation below DAM price

Equation 2.2 shows the price of offering balancing capacity per MW for up-regulation, when the marginal cost of the plant is below the DAM price. The producers have to produce less than optimal in the DAM, and hence, there is an alternative cost of offering up-regulation balancing capacity that is increasing as the DAM prices increase. For down-regulation, the production volume is assumed to be above minimum production in addition to the regulating volume offered, and therefore the price of offering balancing capacity is zero, 2.3.

$MC < p_{DAM}$:

$$p_{BC}^{UP} = p_{DAM} - MC_{plant} \tag{2.2}$$

$$p_{BC}^{DOWN} = 0 \tag{2.3}$$

Where:

- p_{BC}^{UP} = Price of offering up-regulation balancing capacity
- p_{BC}^{DOWN} = Price of offering down-regulation balancing capacity
- p_{DAM} = DAM price
- MC_{plant} = Marginal cost of plant

The cost of offering the balancing capacity is the price times the balancing capacity volume offered by the plant.

Marginal cost of operation above DAM price
To offer balancing capacity the power plant has to be able to react within the agreed time frame. aFRR is a spinning reserve [16] ant therefore the power plant must be producing in order to offer aFRR. Since aFRR is the balancing service studied in this thesis, it is of interest to look at the capacity pricing of a spinning reserve.

With a DAM price less than the marginal cost of the plant, the plant would not be producing in the DAM market. To offer aFRR the plant will have to produce the at least the minimum production volume. And, for down-regulation, the regulating capacity volume offered needs to be produced in addition. Thus, for lower DAM prices, the price of aFRR will decrease as the spot price increases. This increase in aFRR price as the DAM price decreases can also be explain for a hydro power dominated system with a high inflow. If the hydro plant must produce at the maximum production capacity, to avoid spilling, decreasing the production, to offer up-regulation capacity will have a high cost. Offering down-regulation capacity will also be expensive, because if the capacity is activated the plant will have to lower its production and increase the risk of spilling. In this case the power plant is producing, even though the DAM price is below the marginal cost of operation, since the cost of spilling is much higher than the alternative cost of production.

Equation 2.4 and 2.5 shows the price of spinning offering balancing capacity per MW, with the reasoning described above.

$MC > p_{DAM}$:

$$p_{BC}^{UP} = MC_{plant} - p_{DAM} \tag{2.4}$$

$$p_{BC}^{DOWN} = MC_{plant} - p_{DAM} \tag{2.5}$$

Where:

- p_{BC}^{UP} = Price of offering up-regulation balancing capacity
- p_{BC}^{DOWN} = Price of offering down-regulation balancing capacity
- p_{DAM} = DAM price
- MC_{plant} = Marginal cost for plant

The cost of offering the balancing capacity is the price times the production volume of the plant. For up-regulation the production volume is at least equal to the minimum production, while for down-regulation it is at least equal to the minimum production in addition to the regulating volume.

Chapter 3

The German and Norwegian Power Markets

The market design for balancing services plays a crucial role in the underlying assumptions of the method being used in this thesis. Therefore, the market design and solutions of the relevant countries, Norway and Germany will be briefly described in this chapter. First, a brief overview over the important features of the power system in the two countries will be provided. Then the relevant markets for the thesis, the day-ahead market(DAM) and balancing market(BM), is presented. In light of the scope of this thesis, the focus will be on the balancing market design for aFRR.

3.1 General comparison of the power systems

Table 3.1 gives an overview over some main indicators of the power system in Germany and Norway. The relationship between electricity consumption and production and population in Germany is much lower than in Norway.

Table 3.1: Population, electricity production and consumption in Norway and Germany.

	Norway	**Germany**
Population(millions)	5,14	80,98
Electricity Production(TWh)	142	628
Electricity consumption(TWh)	118	570

The power mix in Norway consists of 96 % Hydro power generation in 2014 [17]. The German power mix is more varied. In 2014 the power mix was dominated by thermal power, whereas 45% coal, 10% gas and 16% Nuclear. There were 9% wind generation and 6% photovoltaic energy generation. An overview of the power production mixes of Norway and Germany are given in figure 3.1. There has been an increasing trend on installation of wind and photo voltaic energy in the German power system [9].

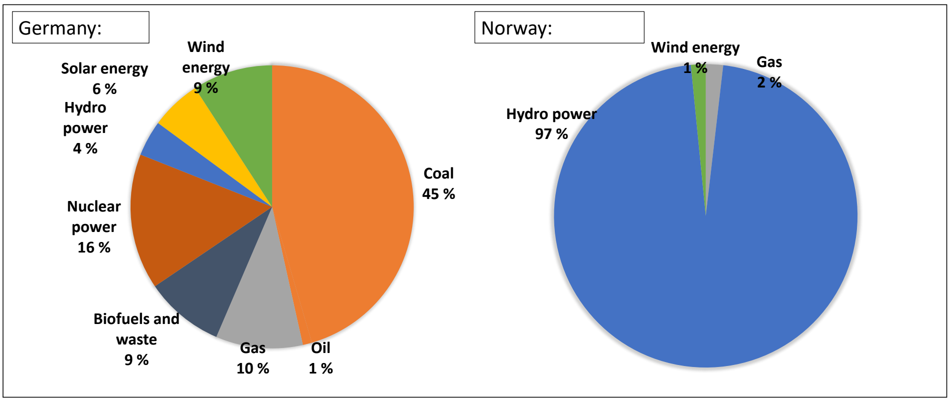

Figure 3.1: Power production mixes in 2014 for Norway and Germany [17].

Norway and Germany are non-synchronized countries. Norway is synchronized with the Nordic countries, while Germany is a part of the continental Europe synchronous system [9]. The countries are today connected indirectly through the HVDC links to other countries in the continental European synchronous system, like Denmark and the Netherlands. Yet, the NordLink cable will be the first direct HVDC link between the two countries.

The Nordic system is divided in four national control areas: Norway, Sweden, Denmark and Finland. Each control area has a different TSO [9]. Since the focus of this thesis is on exchange from Norway to Germany only the Norwegian TSO, Statnett, and its arrangements will be in described. There are four TSOs operating in Germany: TenneT TSO GMbH, Ampiron GmbH, EnBW Transportnetze AG and 50Hertz Transmission GmbH [18] [9]. TenneT is responsible for the control zone connected to NordLink [9].

3.2 Day-ahead market

Nord Pool provides the only common market place for physical trade in the Nordic power system [7]. Nord Pool operates the DAM, in addition to the Intraday market, which will not be further described here [19]. The Nordic power system is divided into several bidding areas, due to congestion on the transmission lines. Figure 3.2 shows the bidding areas in the Nordic power system. The Norwegian bidding area of special interest in this thesis is NO2. An area price is calculated for every bidding area [19]. Today Nord Pool uses implicit auction for the interconnector capacities in the DAM price calculation [19].

There are different day-ahead market places in continental Europe. EPEX spot is the power exchange for Germany, as well as for France, Germany, Austria, Luxembourg and Switzerland [9]. Today, Germany is covered by one bidding area in Germany [20].

Price coupling of regions(PCR) is the initiative of seven European TSOs to harmonize the European electricity markets by developing a single price coupling algorithm, Euphemia, to be used to calculate electricity prices across Europe on a day-ahead basis[21]. North-western European price coupling(NWE) is a project that coupled the day-ahead markets across Central Western Europe, Great Britain, the Nordic countries and the Baltic countries using the PCR solution [22]. The price coupling implies that the DAM prices in the NWE area are comparable.

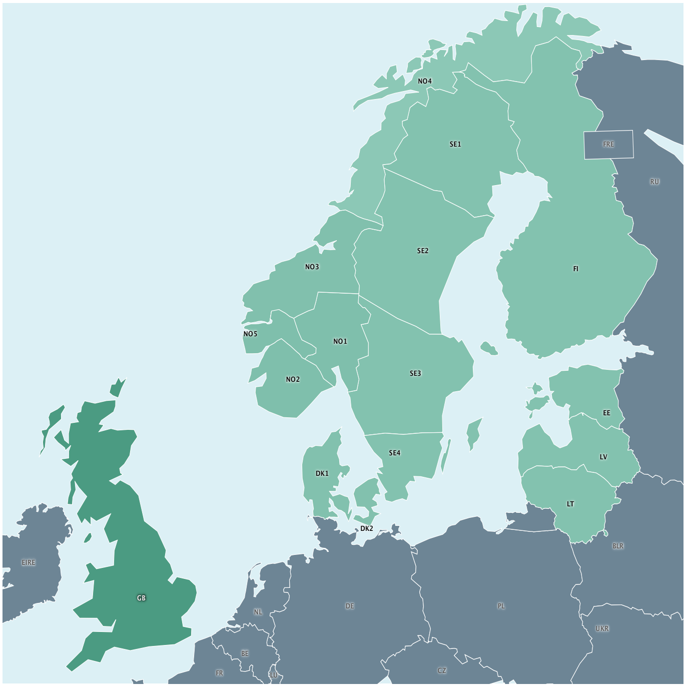

Figure 3.2: Nordic bidding areas. Figure collected from [23].

3.3 Balancing markets

Unlike the DAM, the Norwegian and German balancing markets are not harmonized. In this section the balancing markets design of the different countries will thus be presented separately.

3.3.1 Norway

Some of the Nordic balancing markets are not yet harmonized. Nordic markets for tertiary reserves are integrated, the Nordic TSOs are preparing for a integrated secondary reserves market. [12] [24]

Statnett procures frequency containment reserves (FCR, primary reserves), automatic restoration reserves (aFRR, secondary reserves) and manual frequency restoration reserves (mFRR, tertiary reserves). RR is not procured by Statnett.

Further description of the aFRR market

aFRR was implemented in the Nordic countries in 2013. In the Nordic countries aFRR is used to handle frequency deviation. The national obligation volume is decided on, jointly, by all the Nordic TSO, but is procured on national markets with somewhat different design. [24]

aFRR capacity is procured by Statnett with weekly auctions. Minimum bid size is 5 MW and maximum bid size is 35 MW, the volume has to be dividable by five. Each accepted bid with equal product will get the same price per MW in the same price area, and is set by the highest accepted bid, that is marginal and uniform pricing. The capacity bids are accepted as a whole, parts of the bid volume will not be accepted. The scoring rule and hence acceptance of bids, is based on minimizing the total cost of procuring aFRR. The producers are restricted by location of the reported aFRR providing station group. [16]

The price of the activation energy is set pro-rata in the mFRR activation market in the regulating direction, this will be uniform pricing. Time slots of when aFRR capacity is procured (provision blocks) vary in the Norwegian aFRR market, and should be announced by Statnett 2 weeks prior to operation. [16]

The Nordic TSO are preparing for a common Nordic aFRR market by 2018. The aFRR will be procured on a daily based, two days prior to operation day. Time period and total need for procurement is decided based on the whole systems needs. The pricing methodology will be pay-as-bid. First, price of activation will be set by the mFRR energy market, pro-rata, like it is done now. At a later stage a balancing energy market for aFRR, with a common merit order list, will be implemented. [25]

3.3.2 Germany

Since there are four TSOs operating in Germany, the procurement of balancing power is organized through a public procurement auction [18]. The same balancing markets are used as in Norway; primary, secondary and tertiary control. Primary and secondary reserves have weekly auctions and is implemented on a national level [9]. The auctions include both capacity and energy [9]. The tertiary reserves are procured with four hour increments [9], the auctions are held each weekday. The balancing market is cleared four times an hour [9].

Further description of the aFRR market

In Germany aFRR is used both for frequency deviation and to handle deviation with power flows between countries [24].

In contrast to the Norwegian aFRR market design, the German aFRR bids consists of two parts; the energy bid and the capacity bid. The capacity bids are first chosen through the pay-as-bid rule. A capacity bid can be accepted in parts. An accepted capacity bid can lead to profits if the energy is activated, with the price set equal to the energy bid. The lowest energy bid will first be accepted and so on. [18] There are, today, two weekly time slots for provision of aFRR, 8am-8pm and 8pm-8am, with weekly auctions. [26] The bids does not have to be accepted as a whole, and can be accepted with a resolution below 5 MW. Germany has portfolio-based bidding, meaning that the producers bid on aFRR capacity and energy with a portfolio of different power plants. [27]

3.3.3 Comparison of aFRR market design

Table 3.2 summarizes the most important design differences between the Norwegian and the German aFRR market described above.

Table 3.2: Overview of market solution for aFRR in Norway and Germany [9], [27] , [16], [26].

Feature	**Norway**	**Germany**
Capacity market	Yes	Yes
Pricing mechanism capacity market	Marginal pricing	Pay-as-bid
Bid volume accepted	Bid volume accepted as a whole	Bid volume can be accepted in parts
Energy market	No	Yes
Pricing mechanism activation	Pro-rata	Pay-as-bid
Complete bid consists of	Power offer, power bid	Power offer, power bid, energy bid
Location flexibility	Station group	Portfolio based

Since the application of aFRR is different in the two countries, the ways in which the two countries distribute the procurement of balancing capacity is also different, see figure 3.3 showing the relative share of balancing capacity in 2015 and 2016. This illustrates how the different objectives in each of the countries results in a different procurement volume. As one can see, a much higher share of the balancing capacity procured in Germany is aFRR than the balancing capacity procured in Norway [28]. Moreover, as seen in figure 3.4, Germany has an even higher share, compared to Norway, of activated aFRR(aFRR energy). The German activated FCR volume is not included. The German activated FCR volume is so small that it is not reported in [28]. Norway has a much higher share of activated FCR compared to Germany.

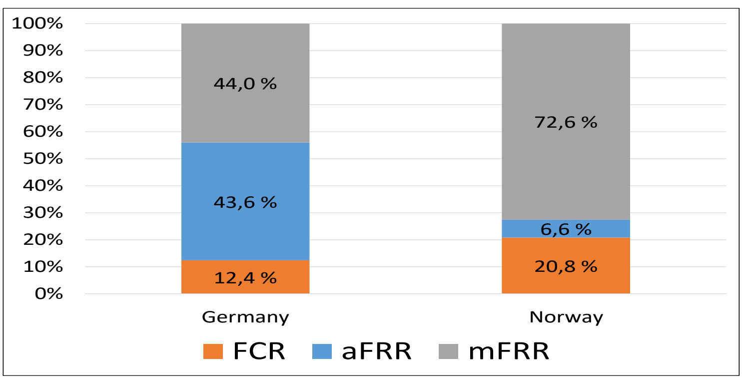

Figure 3.3: The relative procurement of balancing capacity for Germany and Norway [28].

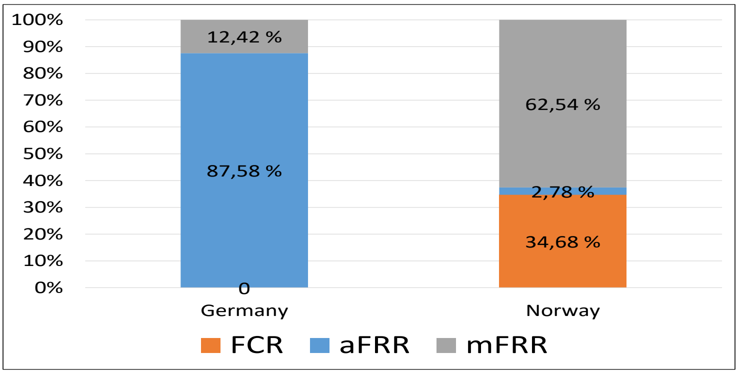

Figure 3.4: The relative procurement of balancing energy for Germany and Norway [28].

Chapter 4

Allocation of Cross-zonal Capacity

To enable exchange of balancing services reservation of cross-zonal capacity(CZC) is needed to ensure that the balancing service can be instantly delivered. In this chapter the socioeconomic theory behind exchange of balancing services and allocation of CZC will be described. In addition, the chapter presents the models in which socioeconomic efficiency can be proven, stated in the Network code for electricity balancing(NCEB). Finally, there is a brief description of the methodology applied in a former project on exchange of aFRR capacity, the Hasle pilot.

4.1 Allocation of cross-zonal capacity

The theory presented in this section has the following assumptions:

- Only two interconnected countries
- Implicit auction for allocation of the CZC in the Day-ahead market(DAM)
- Fixed power demand in both countries
- Balancing capacity is procured in both countries
- CZC may be reserved for both the DAM and balancing market(BM)

[29]

4.1.1 Optimal allocation of CZC

Reservation of CZC for the BM implies less capacity available for the DAM. Hence, there will be an alternative cost of reserving the capacity for the BM. To estimate how the optimal allocation of CZC between the different markets involved, the true market values of the CZC in both markets must be known. The optimal allocation will further be in the intersection between the two marginal value(MV) curves of the CZC in the two markets, see figure 4.1. The social surplus will then be maximized. Since the DAM price and exchanges vary from hour to hour the optimal reservation volume will also change hourly. [29]

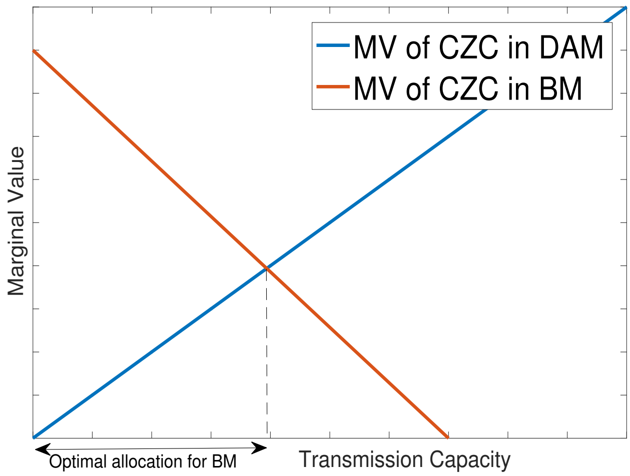

Figure 4.1: Optimal allocation of the CZC between the BM and the DAM. Figure collected from [29].

4.1.2 The market value of CZC in the DAM and BM

As stated above the market values of CZC for both markets must be known in order to find the optimal allocation of CZC. This section attempts to quantify the value of these two markets.

The DAM

The market value of the DAM is equal to the changes in price as a result of the reservation on both sides of the interconnector, in addition to the loss of congestion rent, see equation 4.1 [29]. Figure 4.2 shows the supply curves of the two countries on each side of the interconnector. The costs related to effects of the CZC reservation on the DAM price are shown in the green triangles, while the cost related to loss of congestion rent is shown in the yellow rectangle. As one can see, the size of the effect on the price depends on the slope of the supply curves.

$$\text{Value of DAM} = \text{Price effects} + \text{Congestion rent} \tag{4.1}$$

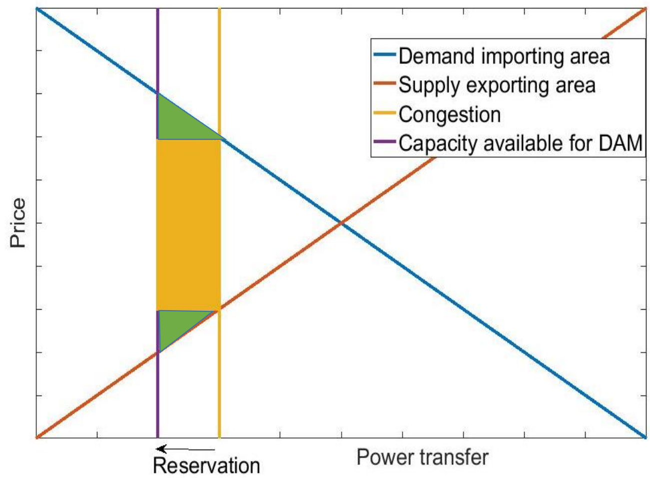

Figure 4.2: Cost of reservation of the CZC for the BM. Figure inspired by [29]

The marginal value of the DAM will change with reservation volume, due to changes in congestion that will affect the prices in both countries.

The BM

Based on the assumptions above, that both countries procure balancing capacity, the market value in each country of balancing capacity(BC) will be known prior to operation. The price in each country is set by the bid curve from the producers and the national obligation volume decided on by the TSO.

The market value of balancing energy(BE), on the other side, will only be known after real-time operation, because then it is known what balancing volume was activated. Therefore, the market value of CZC in the BM will always be uncertain [29]. If we assume that both the balancing capacity and balancing energy price are known, the market value of the CZC in BM will be:

- The producer surplus will increase in one country, the low cost BC country. While in the high cost BC country the consumer surplus will increase. This leads to overall socioeconomic surplus equal to the price difference between the BC price in addition to the price difference between the BE price (activated).
- There is also a value related to exchange resulting in less BC having to be procured in the two countries in total.

[29]

Ideally for exchange of balancing services to take place, there should be a harmonization of the electricity markets of the countries involved, so that the prices in each country can either be compared or utilized through a common merit order list.

One CZC reservation direction will give the possibility of export of up- regulation for one country and export of down-regulation for the other country. E.g. if the CZC is reserved from country A to country B, country A can provide up-regulation balancing services to country B, while country B can provide down-regulation balancing services to country A.

4.2 Models for reservation of cross-zonal capacity for exchange of balancing capacity

As stated above, for an optimal allocation of capacity, both the true market value of the CZC in the DAM and BM should be known. This should also be known in order to identify the CZC reservation volume that will be socioeconomic efficient, but not necessary be the optimal CZC reservation volume.

However, as it is not possible to know the true market value of the markets involved, the NCEB states three different models that can be used to prove socioeconomic efficiency of the CZC reservation for balancing capacity:

1. Co-optimization process
2. Market-based reservation
3. Reservation based of economic efficiency analysis

[11]

The methods will set a price for the CZC. If the TSO decides to reserve CZC it must pay this price [11]. Only model 1.) and 2.) will be further described here, as model 3.) is an irrelevant analysis for this thesis.

4.2.1 Co-optimization process

In this process the TSOs participate in a CZC auction simultaneously as the auction for balancing capacity. The auction can either be implicit, with the DAM auction, or explicit. For the explicit auction the market participants will bid on the CZC with regards to what market value they expect of the CZC. For an optimal allocation to take place a implicit auction is needed. The CZC auction is then cleared and the reservation volume is set by the market values of the different markets. The implicit and explicit co-optimization process are shown in figure 4.3. [11][29]

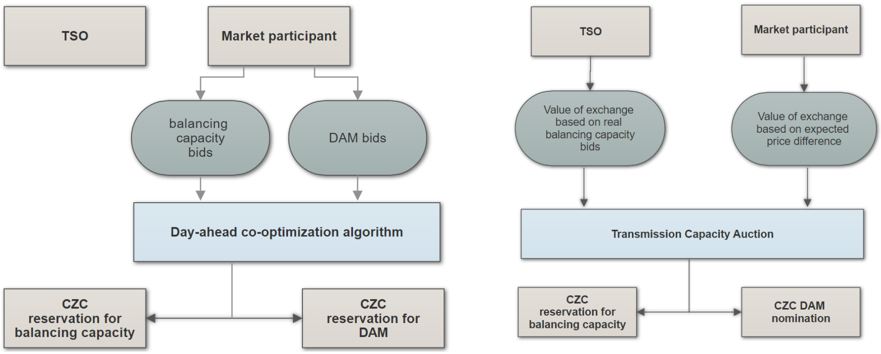

Figure 4.3: Flow chart of a co-optimization model with an implicit(left) and explicit(right) auction. The figure is based on [29].

4.2.2 Market-based reservation

In a market-based reservation model the TSOs reserve CZC based on actual BM bids and on the TSOs forecasted DAM prices, see figure 4.4. An analysis is done comparing both these values and the reservation will depend on the price difference between them. [11][29]

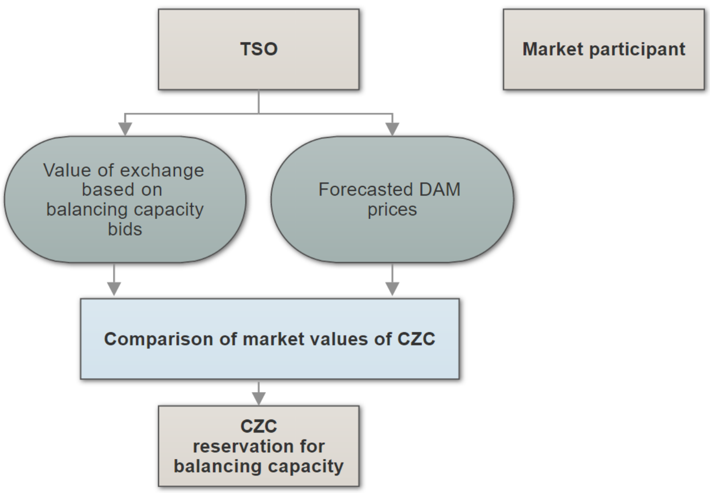

Figure 4.4: Flow chart of a market-based reservation model. The figure is based on [29].

The NCEB states that: "If no transmission capacity auction is available for the relevant time frame for procurement of balancing capacity the TSOs can perform the market-based reservation process or a finer granularity than available is needed to make efficient CZC reservation". [15]

Since aFRR is procured on a weekly basis, a market-based reservation model is the only analysis that can be done. When the auction granularity on aFRR is going to be daily, this will be two days ahead. Therefore, a market-based reservation model is still needed as the clearing of the DAM is done one day in advance. Hence, a market-based reservation model is applied in this thesis.

4.3 The Hasle pilot

The Hasle Pilot was a project on the main interconnector between Norway and Sweden (NO1-SE3) during fall 2014. The aim of the project was evaluating the market-based reservation model for aFRR, as a way of achieving socioeconomic benefit [30]. The Hasle pilot was a conservative model. The purpose was not a reservation of the optimal amount, but rather a smaller reservation volume for aFRR.

In order to exchange balancing capacity from Norway to Sweden cross zonal capacity was also reserved internally between the bidding zones in Norway.

The Hasle pilot methodology consists of two steps.

1. Decision on reservation volume based on a socioeconomic analysis using a market-based reservation model

2. Checking the predefined criteria

The first step, decision on reservation volume based on a socioeconomic analysis, determines the exchange volume that is socioeconomic beneficial. The next step, checking the predefined criteria, verifies that additional criteria are met in order to executed the reservation.

The market-based reservation model used in this thesis is heavily based on the methodology used in the Hasle pilot presented in [31]. The curious reader is encourage to read the Hasle report [30] or method description [31] for a more thorough description of the methodology.

Part II

Methods

Chapter 5

The Market-based Reservation Model

This chapter describes the Market-based reservation model applied in the thesis. It is heavily based on the model used in the Hasle pilot and should fulfill the requirements set by the Network code on electricity balancing (NCEB). The reservation model was implemented as a script in Excel Visual Basics.

First, the underlying assumptions of the model are described. Further, a presentation of the method for determining the marginal value (MV) of cross-zonal capacity (CZC) in the balancing market (BM) and in the Day-ahead market (DAM) is provided. Since the balancing market of interest in this thesis is the aFRR market, this is from now on the only balancing market considered. The end of the chapter provides a description of the determination of the reservation volume and calculating the socioeconomic benefit.

5.1 Assumptions

The assumptions of the market-based reservation model are as follows:

- **Exchange volume with 5 MW increments**
  This is chosen because the Norwegian aFRR bids today are accepted with 5 MW increments.
- **Internal bottlenecks in the Norwegian system are disregarded**
  The model only considers the DAM price in NO2 and does not take into account the capacity reservation that must be done internally in the system due to bottlenecks. If the aFRR capacity provided is from another bidding zone than NO2, capacity has to be reserved internally in addition to the CZC. This will affect the value of the CZC reservation.
- **The balancing energy market is disregarded**
  The impact of the aFRR energy market on estimating the marginal value of

the CZC for aFRR is neglected. This means that the value of the exchange of aFRR energy between the countries, i.e. the activated aFRR, is not included in the model. This is done due to aim of the thesis and the nature of the marked-based reservation model applied. Impacts of this assumption will be further discussed in chapter 8.

- **The aFRR capacity bid curves of the two countries are comparable**
  The aFRR capacity bid curves applied in the market-based reservation model are comparable, meaning that they represents the true market value of the capacity in both countries. The underlying assumptions of considering the aFRR bid curves to be comparable are presented in chapter 7.

- **The effect of the CZC reservation on the DAM prices is disregarded**
  Less available capacity for the DAM may lead to a higher DAM price gap between the two countries. Excluding the effect of the CZC reservation on the DAM prices might give a too small marginal value of DAM and cost of reservation.

- **Disregarding exchange between other countries**
  aFRR capacity can only be sold between Norway and Germany. Exchange between other countries is not included in the model.

- **Reservation of CZC for other electricity markets are disregarded**
  Only the DAM and the aFRR market is considered.

- **aFRR capacity can be provided both by Norway and by Germany**

- **Weekly auctions**
  CZC for aFRR capacity is reserved for one week. The methodology described below are for calculation of reservation of CZC for one given week.

- **Provision of aFRR capacity is only on weekdays**
  aFRR capacity is only provided on weekdays within the reservation period.

5.2 Determining the MV of the CZC in the DAM

Because the aFRR auction is prior to the DAM gate closure time the MV of the CZC in the DAM has to be estimated based on forecasted prices.

The forecast method for the MV of the CZC in the DAM should be transparent, because the TSO is a monopoly and is thus heavily regulated and should not make a profit of the reservation. The power producers should be able to understand the forecasting method easily. In this thesis the DAM prices from the week before is used as a forecast.

Since the effect of the reservation on the DAM prices is disregarded, the MV of the CZC in the DAM price is assumed to be reflected in the possible congestion rent on the cable. Therefore, the MV of the CZC in DAM can be estimated as the expected loss of congestion rent per MW CZC reserved for aFRR capacity, based on the forecasted DAM prices. For one given hour the MV of the CZC in the DAM per MW will be as shown in equation 5.1 and 5.2.

In direction Norway to Germany($NO \rightarrow GE$):

$$MV_{DAM} = p_{DAM}^{GE} - p_{DAM}^{NO} \tag{5.1}$$

In direction Germany to Norway($GE \rightarrow NO$):

$$MV_{DAM} = p_{DAM}^{NO} - p_{DAM}^{GE} \tag{5.2}$$

Where:

- MV_{DAM} = MV of CZC in the DAM per MW CZC reserved for the given hour [EUR/MWh]
- p_{DAM}^{NO} = DAM price in Norway for the given hour [EUR/MWh]
- p_{DAM}^{GE} = DAM price in Germany for the given hour [EUR/MWh]

The MV of CZC in the DAM can thus be calculated for each hour individually. The MV of the CZC in the DAM in the power flow direction will have a positive MV, while the MV will be negative in the opposite direction. Because there will be no "negative" loss of congestion rent per MW in the opposite of the flow direction (there is no power flow in that direction), this value is set equal to zero.

aFRR is reserved on a weekly basis. That is, there will be weekly aFRR bid curves. Thus, the MV for the DAM should also have the same time frame. One MV of the CZC in DAM for a whole week needs to be estimated, since the MV of the CZC in DAM is different for every hour. In this thesis the average of the MV for every hour of the week before is applied as a forecast.

Estimation of one MV of CZC in the DAM(MV_{DAM}) for a week is hence calculated in the following way in the market-based reservation model:

- MV_{DAM} in opposite flow direction is set equal to zero.
- Since aFRR capacity is only provided on weekdays, the MV_{DAM} is calculated for weekdays and it is only the weekday DAM prices that is applied in the estimation.
- The average MV_{DAM} in one flow direction within all the provision hours of the week is set as the MV_{DAM} for the whole week.

5.3 Determining the marginal value curves of CZC for aFRR capacity

The MV of CZC in the aFRR capacity market can be calculated as the difference between the aFRR capacity prices between Norway and Germany for the exchange volume, assuming that one has comparable capacity bid curves.

The providing country will have to procure the exchange volume, in addition to the national obligation volume. The acquiring country will on the other side procure the national obligation volume subtracted the exchange volume. This volume is in this thesis called the total national procurement volume. The marginal price of the exchange volume is set at the national procurement volume. The marginal price of the a certain exchange volume is compared for the two countries. This gives a MV curve of the CZC for aFRR capacity depending on exchange volume.

There are four possible exchanges of aFRR capacity; either Norway can be the aFRR capacity provider or Germany can be the aFRR capacity provider. The providing country can again offer both up- and down-regulation. The MV curve is the aFRR prices difference between the two countries for different exchange volume.

As there are different aFRR bid curves for up- and down regulation, there will be one MV curve of the CZC for aFRR capacity for each of the four possible exchanges. Hence, one will end up with four marginal value curves for the CZC in aFRR market: up-regulation provided by Norway (UP_{NO}), down-regulation provided by Norway ($DOWN_{NO}$), up-regulation provided by Germany(UP_{GE}), down-regulation provided by Germany($DOWN_{GE}$). The calculation of the MV curves for the four possible exchanges is shown in table 5.1 with nomenclature described below. The nomenclature is given for one of the four possible exchanges.

Table 5.1: Calculation of the MV curve of CZC for aFRR capacity for the four possible aFRR capacity exchanges.

	$\boldsymbol{UP_{NO}}$	$\boldsymbol{DOWN_{NO}}$	$\boldsymbol{UP_{GE}}$	$\boldsymbol{DOWN_{GE}}$
$\boldsymbol{P_{GE}^{tot}}$=	$P_{GE}^{nat} - P_{exch}$	$P_{GE}^{nat} - P_{exch}$	$P_{GE}^{nat} + P_{exch}$	$P_{GE}^{nat} + P_{exch}$
$\boldsymbol{P_{NO}^{tot}}$=	$P_{NO}^{nat} + P_{exch}$	$P_{NO}^{nat} + P_{exch}$	$P_{NO}^{nat} - P_{exch}$	$P_{NO}^{nat} - P_{exch}$
$\boldsymbol{MV_{aFRR}}$ $\boldsymbol{(P_{exch})}$=	$p(P_{GE}^{tot}) - p(P_{NO}^{tot})$	$p(P_{GE}^{tot}) - p(P_{NO}^{tot})$	$p(P_{NO}^{tot}) - p(P_{GE}^{tot})$	$p(P_{NO}^{tot}) - p(P_{GE}^{tot})$
Reservation direction:	$NO \to GE$	$GE \to NO$	$GE \to NO$	$NO \to GE$

Nomenclature in table 5.1:

- $NO \to GE$, $GE \to NO$ = CZC reservation direction
- P_{GE}^{nat} = National obligation volume Germany [MW]
- P_{NO}^{nat} = National obligation volume Norway [MW]
- P_{exch} = Exchange aFRR volume [MW]
- P_{GE}^{tot} = Total procurement volume Germany [MW]
- P_{NO}^{tot} = Total procurement volume Norway [MW]
- $p(P_{GE}^{tot})$ = Bid price of a German procurement volume, P_{GE}^{tot} [EUR/MW]
- $p(P_{NO}^{tot})$ = Bid price of a Norwegian procurement volume, P_{NO}^{tot} [EUR/MW]
- $MV_{aFRR}(P_{exch})$ = Marginal value of CZC for aFRR capacity for exchange volume, P_{exch} [EUR/MW]

Two of the MV curves will be negative, and are of course disregarded because no reservation will take place. Consequently, reservation of CZC will only be executed in one reservation direction for each regulation direction(up-/down-regulation). Thus, there will be one reservation volume in the $NO \rightarrow GE$ direction, either for up-regulation from Norway or down-regulation from Germany, and one reservation in $GE \rightarrow NO$ direction, either for down-regulation from Norway or up-regulation from Germany.

5.4 Determining the CZC reservation volume

The marginal values are now compared for each exchange volume, with a step of 5 MW. The reservation volume is set at the intersection between the MV curve of the CZC for aFRR capacity($MV_{aFRR}(P_{exch})$) and the estimated MV of the CZC in the DAM for the respective week,(MV_{DAM}), as long as it does not exceed 300 MW, see figure 5.1 and equation 5.3.

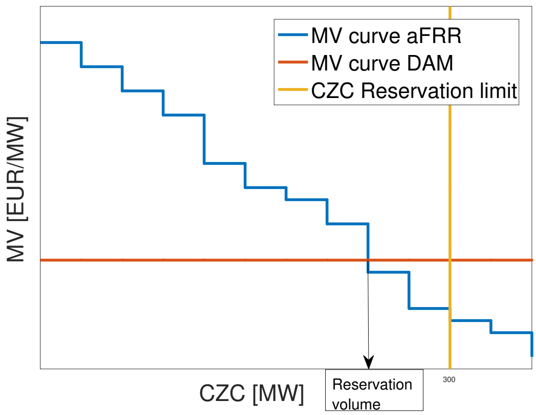

Figure 5.1: Example of reservation of CZC on NordLink. Collected from method figure in [31].

$$MV_{aFRR,week}(P^*_{exch}) = MV_{DAM,week} \tag{5.3}$$

Where P^*_{exch} is the CZC reservation volume.

5.5 Socioeconomic benefit of the CZC reservation

The socioeconomic benefit of the reservation is calculated as follows for a given week and CZC reservation volume P^*_{exch}:

$$\text{Socioeconomic benefit} = \text{Value of reservation} - \text{Cost of reservation} \tag{5.4}$$

$$\text{Value of reservation} = D \cdot H_B \cdot \int_{P_{exch}=0}^{P^*_{exch}} MV_{aFRR}(P_{exch}, W)dP_{exch} \tag{5.5}$$

$$\text{Cost of reservation } = P^*_{exch} \cdot \textstyle\sum_{d \in W} \sum_{h_d \in B} MV_{DAM}(h_d) \qquad (5.6)$$

Where:

- B = Provision block
- W = Reservation week
- d = Weekday
- h_d = Hour h in day d
- H_B = Nr of block hours in block B
- D = Number of provision days in week
- P^*_{exch} = CZC reservation volume
- P_{exch} = Exchange volumes
- $MV_{DAM}(h_d)$ = MV of CZC in DAM for hour h_d
- $MV_{aFRR}(P_{exch}, W)$ = MV of CZC for aFRR for exchange volume P_{exch} for week W

The value of the reservation is calculated as the integral of the marginal value curve for the CZC in aFRR up to the reservation volume, P^*_{exch}. Since the aFRR prices are given per hour the integral is timed with the number of hours of provision that week, equal to the block hours each day, H_B, times the number of weekdays, D, see equation 5.5.

The actual cost of reservation is calculated ex post and is the true loss in congestion rent. It will be equal for every exchange volume, but different each hour of provision of aFRR. Thus, to calculate the cost of reservation the DAM price difference between the two countries are added up for every provision hour, $MV_{DAM}(h_d)$, of the week and then timed by the CZC reservation volume, P^*_{exch}.

Chapter 6

Generation of aFRR Capacity Bid Curves

In this chapter the methodology behind generation of the aFRR bid curves to be applied as input in the market-based reservation model will be described. The objective is to generate many representative random aFRR bid curves, both German and Norwegian, for the different case study periods to conduct further analysis in the market-based reservation model.

The methodology has several steps. First, the historical aFRR bids are developed into bid curves. These historical bid curves are then applied in a regression model, to generate regression coefficients. The regression results are further used together with explanatory variables and a stochastic variable to generate an average value for the aFRR price. Finally, aFRR bid curves are developed based on the shapes of the historical bid curves.

A data set containing historical aFRR bid curves should be provided. In addition the data sets for the explanatory variables, both historical and future, should be provided for the case studies. These data sets are further referred to as the basis data sets and will be described in chapter 7.

6.1 Developing aFRR bid curves from bids

Historical aFRR bids curves are developed from aFRR bids. The bids must be sorted based on different provision time slots(blocks) an regulating direction (up- or down-regulation).

The bid curves for the two exchanging countries have to be developed in such a way that they are considered to be comparable. The specifics and assumptions which the development of bid curves for Norway and Germany are based on are further described in chapter 7. For now, let us assume the aFRR bids are developed into comparable bid curves.

6.2 Regression model

The goal of the regression model is to find a correlation between historical aFRR bids and other market variables, to generate average aFRR bid prices for the case studies.

The simplest linear model states that the true mean of the dependent variable has a linear relationship with the explanatory variables. When developing a regression model the relationship is identified between the true mean of the dependent variable and the explanatory variable. Further, the deviation of the observations of the dependent variable is considered by adding a stochastic variable, see equation 6.1 for the simplest form of linear regression with one explanatory variable. [32]

$$Y_i = \beta_0 + \beta_1 \cdot X_i + \epsilon_i \tag{6.1}$$

Where:

- i = The particular observation unit
- Y_i = The dependent variable
- β_0 = The intercept
- β_1 = Slope of the line
- X_i = The explanatory variable
- ϵ_i = The random error

The random errors ϵ_i have zero mean and are assumed to have a common variance.

The average bid price for each week during the historical data set period is set as the dependent variable. Several explanatory variables should be tested to find the regression models that fit best with the basis data set. The regression is done in Excel's multiple regression analysis.

Several explanatory variables are tested to find an adequate reservation model. There are different indicators to consider when deciding whether the reservation model is adequate. The coefficient of determination, R^2, can be interpreted as the variation in the dependent variable that is "explained by" the linear relationship with the explanatory variable . This must however be treated carefully as there could be reasons for associations in the observed data, which are not explained by causality. [32]

The most common hypothesis is that the value of the true mean of the dependent variable is zero. That is that there is no slop of then curve, consequently no identified relationship with the explanatory variable. This is referred to as the null hypothesis [32]. The p-value is the probability of the observed data when the null hypothesis is true [33]. Hence one would want a low p-value for the estimated regression coefficients. The theory behind regression analysis will not be further described in this thesis. The curious reader is directed to literature on the subject, for example [32], for further insight.

If the regression result is adequate the regression coefficients can be used as part of the method to generate bid curves. If not, further specification of the regression model is needed, and other explanatory variables may be included in the regression model.

There will be two different regression models, one for Norway and one for Germany. Further, there will be different regression results (coefficients) for up- and down-regulation.

6.3 Generation of aFRR bid curves

The method behind the generation of aFRR capacity bid curves consists of three steps:

1. Finding the average aFRR bid price by using the regression model.
2. Adding a stochastic variable, random error, to the average aFRR bid price.
3. Using one of the original bid curves from the basis data set to develop a bid curve.

Below is a description of each step.

1.) Finding the average aFRR price
First, an average aFRR bid price is generated for a particular week using the regression coefficients and explanatory variables. The explanatory variables will either be historical explanatory variables or future forecasted explanatory variables, depending on which case study is being developed. It is important to emphasize that, for the future case studies, forecasted values of the explanatory variables have to be available.

2.) Adding a stochastic variable
The stochastic variable, ϵ, is added to the average aFRR bid price, yielding $\overline{p}^{gen}_{aFRR}$, in order to generate several different bid curves and capture of the volatility. A new ϵ is generated for every average aFRR price generated in each direction. Hence, it will be different in each direction and will be different in both regulation directions.

ϵ is generated by a random number generator in Excel, with the standard deviation collected from the regression model and a normal distribution around zero.

3.) Developing a bid curve
The average aFRR bid price for a particular week (historical or future) can further be applied to develop a bid curve. This is done by using one of the already existing original bid curves from the basis data set. The bid curve for a particular week is adjusted with regards to the average bid price estimated for that week, see equation 6.2.

$$p^{gen}_{aFRR}(P) = p^{rand}_{aFRR}(P) + (\overline{p}^{gen}_{aFRR} - \overline{p}^{rand}_{aFRR}) \tag{6.2}$$

Where:

- $p_{aFRR}^{gen}(P)$ = aFRR bid price for a certain procurement volume, P, of the generation week [EUR/MW]
- $p_{aFRR}^{rand}(P)$ = aFRR bid price for a certain procurement volume, P, of randomly week drawn [EUR/MW]
- $\overline{p}_{aFRR}^{gen}$ = Average aFRR bid price for randomly week drawn [EUR/MW]
- $\overline{p}_{aFRR}^{rand}$ = Average aFRR bid price for the generation week [EUR/MW]

The original bid curve is chosen by a random number generator in Excel. All the weeks in the basis data set have the same probability of being drawn. A new random week is generated for each generated curve, but the week drawn is equal in both regulating directions. This also contributes to a random development of bid curves and captures the variety in the shape of the bid curves.

Chapter 7

Case Studies

In this chapter the case studies are presented. The objective of the chapter is to give the reader an understanding of the basis of the case studies being simulated in the reservation model.

The chapter starts with a description of the basis data sets used in the thesis and modification of the basis data sets. Each of the six case studies, three historical and three future, are then described. The simulation scenarios for the market-based reservation model is presented at the end of the chapter.

7.1 The basis data sets

The basis data sets contain:

- Explanatory variables for input in the regression model
- Norwegian and German aFRR bid prices
- Norwegian and German Day-ahead market(DAM) prices

The historical basis data sets include aFRR bids, explanatory variables and the NO2 and German DAM prices. The future data sets only include the explanatory variables and Norwegian and German DAM price prognosis. Below is a description of the historical and the future data sets separately.

7.1.1 Historical basis data sets

The historical data sets applied in this thesis contains historical aFRR prices gathered from Statnett Norway and Tennet Germany for 2014 to 2017. The Norwegian DAM prices are collected from Nord pool, while the German DAM prices are provided by Statnett. German wind power production and consumption, used as explanatory variables which will be further introduced in chapter 9, are gathered from Statnett. Table 7.1, shows the basis historical data sets and where they have been collected.

Table 7.1: The historical basis data sets.

Data sets	Collected from
Norwegian aFRR prices	Statnett SF
German aFRR prices	Tennet
Norwegian DAM prices	Nord pool
German DAM prices	Statnett SF
German wind and consumption (Explanatory variables)	Statnett

Not all weeks are included in the Norwegian basis aFRR data set due to aFRR not being offered in certain weeks, see table A.1 in appendix A. The basis German aFRR data set includes all weeks.

As described in chapter 3, the Nordic and German aFRR market designs have some significant differences. This can be observed in the aFRR data set by different lengths and resolution for the time slots(provision blocks) where aFRR is offered. In addition, the German aFRR data set includes the balancing energy price, since there is also an auction on aFRR balancing energy.

A Modifications and assumptions of the historical basis aFRR data set

Modifications and assumptions on the aFRR data set are needed to develop aFRR bid curves that are assumed to be comparable between the two countries, in order to conduct simulations in the market-based reservation model. Here, each modification or assumption is further described. A more thorough discussion of the impact of the most important modifications and assumptions is provided in chapter 8.

Dependencies between balancing energy and balancing capacity
The difference in market design with regards to auctions on balancing energy and balancing capacity, as described in chapter 3, is disregarded. Only balancing capacity bid curves are applied in the market-based reservation model. The balancing capacity pricing in each country is assumed to reflect the true cost of balancing capacity within the country, and it is assumed that the price of the balancing capacity and balancing energy are independent of each other. This is a simplification, and it is important to emphasize that this assumption has a significant impact on the results. This will be further discussed in a qualitative assessment in chapter 8.

Exchange of aFRR only between Norway and Germany
It is assumed that exchange of aFRR capacity only will take place between Norway and Germany, all other exchanges are disregarded. Therefore, only the Norwegian aFRR prices are considered in this thesis, not the Nordic prices. The Norwegian aFRR bids collected are from all the bidding zones, however bids from the zones NO2 and NO5 represents the major shares.

Auction time frame
Today aFRR is procured by weekly auctions, and therefore the data set has a weekly time frame. The generated aFRR bid curves will accordingly be weekly. It

is assumed that aFRR is only procured on weekdays in both countries.

Pricing mechanism of balancing capacity
The two countries have a different pricing mechanism for accepting balancing capacity bids; Pay-as-bid in Germany and marginal pricing in Norway. Different pricing mechanism give different optimal bidding strategies in the two countries, and hence different bid curve structures. This difference is however disregarded, as it is difficult to quantify what impact it has on the bid curves.

Bid volume accepted
The Norwegian aFRR bids are only accepted as a whole(with 5 MW increments), see chapter 3. This feature is disregarded, and it is assumed that a bid can be partly accepted at the bid price. The exchange volume accepted will be with 5 MW increments.

Provision block design
To achieve comparable bid curves, the design of the provision blocks should be equal. The Norwegian block design varies through the basis data sets period. Thus there are different lengths and resolution of the Norwegian aFRR provision blocks. The German provision blocks are constant, and the same as described in chapter 3, that is one night block and one day block.

There is only one Norwegian block that is constant throughout the whole basis period; the block from 5am to 8am. Since the Norwegian aFRR bid curves in the basis data set contained many different time frames it was time consuming and cumbersome to sort and identify day and night blocks, in addition to finding an adequate method to weight the different provision blocks. For this reason, only bid prices from the Norwegian from 5am to 8am block was applied.

Since the Norwegian provision block from 5am to 8am is within the German night block, it is assumed that the Norwegian price would be the same for the whole night as from 5 am to 8 am. This Norwegian provision block was also used for simulations of the day time with the German day block, assuming that 5 am to 8 am provision blocks also contains some day time features, since it is in the beginning of the day.

The bid prices were given per hour and therefore the price given for the different blocks did not have to be adjusted based on the block size. Exchange of aFRR on NordLink will hence be studied for two provision blocks; day and night block with the same time frame as in Germany. The blocks that will be compared are hence be as shown in table 7.2. The possible impact of this simplification on the results is further discussed in chapter 8.

Table 7.2: aFRR capacity provision blocks in Norway(NO) and Germany(GE) applied in the case studies.

Provision Block	Original NO time frame	Original GE time frame
Day(8am - 8pm)	5am- 8am	8am - 8pm
Night(8pm - 8am)	5am - 8am	8pm - 8am

7.1.2 Future basis data sets

Future data sets are needed for the explanatory variables in the regression model, to generate aFRR bid curves for the desired future case studies, and as an input to the reservation model when simulating the future case studies. The future data sets applied in the thesis are provided by the department of Market analysis at Statnett. The prices have been collected from simulation in market models; Norwegian prices from the Samlast model, German prices, German wind production and consumption from the BID model.

In briefs, the Samlast model is best suited for the Nordic hydro dominated power market and applies the prices from the BID model to represent the continental Europe [34]. Since these models are not used directly in this thesis the theory behind will not be further described The curious reader is encourage to confer with the long term market analysis [34] for underlying predictions and assumptions.

The price areas are divided differently in the Samlast model, than the Nordic bidding areas described in chapter 3. Some price areas in the Samlast model are merged and used to calculate the NO2 price, applied in the market-based reservation model. This is done based on geographical location. The following price areas from the Samlast model are merged to represent NO2: "Norge Syd", "Telemark", "SKL" and "Vestsyd".

7.2 Presentation of the case studies

Six case studies are developed for simulations in the market-based reservation model. The method described in chapter 6 is applied, together with the basis data sets, to generated 50 bid curves for each week for the case studies. The result of the generation of bid curves is presented in chapter 9. The resulting bid curves for the case studies are then applied, together with the DAM price from the basis data sets, to perform simulations in the market-based reservation model described in chapter 5.

An overview of the cases is to be found in table 7.3. There are two groups of case studies; one containing historical years and one containing future cases. The characteristics of the future years giving the case study name, will be described further down in this section.

Table 7.3: Case studies.

	Cases	**Data set collected from**
Future case studies	2025 (wet)	Samlast, BID (Statnett SF)
	2025 (Dry)	Samlast, BID (Statnett SF)
	2025 (Normal)	Samlast, BID (Statnett SF)
Historical case studies	2014	Nord Pool, Statnett SF
	2015	Nord Pool, Statnett SF
	2016	Nord Pool, Statnett SF

The aFRR bid curves are generated for the years 2014, 2015 and 2016 using historical prices. In addition, bid curves should be generated for future scenarios, one low DAM price year, one normal DAM price year and one high DAM price year, with the basis year of 2025 in the Samlast model.

For the historical case studies the aFRR bid curves are generated based on the whole basis data set and the year in which the bid curves are to be generated, compared to the historical aFRR prices, does not matter. Since the object is to develop case studies and not conduct a historical analysis, bid curves are generated for all the German historical years, even though historical aFRR curves are presented for the whole period.

Precipitation years in the Samlast model
2025 is used as a base year in the Samlast model. This means that the input to the Samlast model are based on assumptions and expectations for this year. This year is chosen because the NorLink cable is to be completed by 2019, hence studying the possibility of cross-zonal aFRR exchange with expected and forecasted market conditions in 2025 is of interest.

Norwegian precipitation years are chosen for each future case study, based on the desired precipitation characteristic. In the Samlast model a wet year results in the lower DAM price, compared to a dry year. This is a result of more water in the Norwegian hydro reservoirs.

A wet, normal and dry case study is chosen for this basis year(2025) and represents the low, normal and high DAM price year respectively. This is done because it is interesting to look at different DAM price scenarios for the year of 2025. See table 7.4 for the future scenarios related precipitation year and total yearly precipitation.

Table 7.4: Precipitation in future case studies.

Case Study	Precipitation year	Total precipitation [GWh]
2025 (Dry)	1996	101293
2025 (Normal)	2004	137450
2025 (Wet)	2011	169729

7.2.1 Brief observation of the Day-ahead market price

Observations of the DAM prices in the case studies are briefly presented below. There will not be a deeper analysis on the market conditions behind the DAM prices applied in this thesis than the observations given here. The average weekly DAM prices applied in the observations are found in appendix A.

Figure A.1 provides the historical Norwegian DAM price, the prices depict are the average weekly prices for of all the Norwegian bid zones. 2014 is an overall higher DAM price year than 2015 and 2016. A dry summer resulted in low reservoir filling and lead to high DAM prices [35]. The figure shows that 2015 is a low price year, especially during the summer. There were high reservoir filling due to high precipitation and warm weather [36]. This was further one factor leading to low prices. In 2016 high hydro power production in addition to a dry fall lead to low reservoir levels and hence higher DAM prices was observed at the end of the year [37]. Figure A.2 shows that there are not much difference between the German historical years.

Following are some of the main future expectations collected from Statnetts' long term market analysis [34] on the German and Nordic prices for the year 2020 to 2025. The general expectations in the long term market analysis is that the share of renewable energy will increase, the coal power phases out and a power market that strives to achieve less CO2 emission. The prices are expected to increase towards 2030 in all of Europe due to increased gas prices, higher CO2-prices and phasing out of nuclear and coal. Increasing prices towards 2030 on the European continent gives higher Nordic DAM prices. Volatile short term prices are expected after 2020, due to an increasing share of variable renewable resources. [34]

7.3 Simulation scenarios

In this section the simulation scenarios will be described. A simulation scenario defines the conditions in which the simulations in the market-based reservation model are performed. Simulations will be done on one base scenario. In addition, a sensitivity study will be conducted with three different scenarios. The scenarios will be simulated for all case studies. NO2 is used as the Norwegian DAM price for all scenarios.

Base scenario

Table 7.5 shows the conditions of the base scenario. The national obligation volume is set equal to 2000 MW for Germany and 100 MW for Norway, based on observations in the basis data sets. 300 MW of cross-zonal capacity(CZC) can be reserved for aFRR with Norway as the providing country, 100 MW restriction applies to Germany. This restriction is due to the national obligation volume being 100 MW in Norway. The simulations are performed for both day and night blocks given in table 7.2.

Table 7.5: Simulation conditions for the base scenario.

Nation obligation volume Germany:	2000 MW
Nation obligation volume Norway:	100 MW
CZC reservation limit NO-GE:	300 MW
CZC reservation limit GE-NO:	100 MW
aFRR proving country:	Both
German provision blocks:	Night/Day
Norwegian provision blocks:	5am to 8am
Forecasting strategy	Average week before

Sensitivity studies on aFRR bid curves

The simulation scenarios that are simulated in the market-based reservation model for the sensitivity study is here presenter. Yet, the arguments in which these scenarios are developed will first be described in chapter 8 and 9.

The Norwegian aFRR bid curves are extended by an approach described in chapter 9. The same simulation conditions as in table 7.5 is applied, with some modification described in chapter 10. The German and Norwegian aFRR bids are then scaled in three different ways creating three simulation scenarios, see table 7.6. In sensitivity scenario 1 the German bid prices are increased by 10% and the Norwegian prices are decreased by by 10%. In sensitivity scenario 2 the German bid prices are increased by 20% and the Norwegian prices are decreased by by 20%. In sensitivity scenario 3 the German bid prices are increased by 30% and the Norwegian prices are decreased by by 30%.

Table 7.6: Sensitivity scenarios.

Scenario	NO scaled	GE scaling percentage
Sensitivity scenario 1	-10%	+10%
Sensitivity scenario 2	-20%	+20%
Sensitivity scenario 3	-30%	+30%

Forecast strategy for the MV of the CZC in the DAM

The base scenarios will be simulated in the reservation model with the forecast strategy applying the average MV of the CZC in DAM from the week before as forecast. In addition, the base scenario is simulated in the reservation model with perfect foresight. The Hasle pilot applied the maximum of the CZC in the DAM from the week before as a forecasting strategy. This was a conservative approach [30], and has shown to be a conservative approach in test simulations performed in this project. Consequently, the average MV of the CZC in DAM was chosen as a forecast strategy, since the aim of the thesis is to quantify the possibility of cross-border exchange of aFRR capacity and not aiming at finding a forecast strategy suitable for operation.

Since DAM prices from the week before is used as forecast the first week of all the case studies is not included in the simulation, as there has to be values of the DAM price from the week before available. This could have been handled by including the DAM prices from the last week of the year before in the simulations. Yet, due to the data set provided and time limitations, the first week is not included. Hence, the total yearly socioeconomic benefit estimated can be different than with one extra week. The first week is not included for all case studies, due to comparability, in spite of that for the case studies 2015 and 2016 the DAM prices from the week before would have been available.

Part III

Analysis

Chapter 8

Qualitative Analysis of the Basis Data Sets

This chapter contains a qualitative analysis of the basis data sets. This analysis is provided to support the analysis of the results conducted in chapter 9 and 10.

First, is an analysis of the Norwegian and German aFRR capacity market today, based on the aFRR capacity bid curves provided in the basis data sets. It is followed by a discussion of additional values of the reservation the market-based reservation model does not cover. Finally, there is a brief discussion of the Day-ahead market(DAM) price as input in both the regression model and reservation model.

8.1 The aFRR capacity bid curves

Presented are some observations of different features in the aFRR bids provided in the basis data sets. Possible causes for the observations are then highlighted in the following subsections.

8.1.1 Observations of the aFRR capacity bid curves

Price level at national obligation volume

Table 8.1 gives the average bid price at the national obligation volume for each year in the basis data set. Since no aFRR exchange between the countries is currently executed, the price at the national obligation volume is today marginal price. Therefore, this bid price is chosen for comparison.

The Norwegian producers are expected to have a competitive advantage of offering balancing capacity, due to the high hydro share and the regulating capability of hydro power. However, the Norwegian aFRR capacity prices in the basis data set are overall higher than the German aFRR capacity prices, indicating that the true cost of offering aFRR capacity is not reflected in the bid prices.

The average Norwegian aFRR price for the long-term reservation on the SK4 cable is 7,2 EUR/MW for both up- and down-regulation[4]. The distribution between up- and down-regulation is not provided in the citation. Since the Norwegian price on the SK4 cable is distributed between up- and down-regulation it will be much smaller than the average Norwegian aFRR price at the national obligation volume provided in table 8.1. The SK4 aFRR prices are long-term contracts, and thus not completely comparable with the aFRR prices from weekly auctions. However, this indicates that the Norwegian aFRR prices from the weekly auctions might not reflect the cost of offering aFRR capacity.

The difference between the down-regulation and up-regulation price is greater in Germany and for the day block the down-regulation prices are particularly low. This is further discussed under "Correlation between the up-and down-regulation bids".

Another interesting observation is that the prices in the earlier provision years, 2014 and 2015 are higher than the more recent years. One possible cause of this trend is described in the next section.

Table 8.1: Average aFRR bid price [EUR/MW] for at the national obligation volume for the years provided in the basis data sets.

Year	Regulation direction	Norway	Germany night	Germany day
2014	Up	10,81	11,44	6,66
	Down	10,45	5,59	6,99
2015	Up	11,18	9,05	5,43
	Down	10,47	5,16	1,15
2016	Up	7,06	6,67	4,20
	Down	6,52	2,13	0,42
2017	Up	5,50	3,60	3,97
	Down	5,40	2,14	0,12

Shape of the bid curves

Figure 8.1 shows the Norwegian aFRR bid curves provided in the data sets. The Norwegian bids have a different shape than the German night block aFRR bid curves, shown in figure 8.2. The Norwegian bid curves show an exponential growth at the end of the curve, while the German bid curves are more flat. One reason for this may simply be the way the curves are developed in this thesis. As explained, the Norwegian aFRR market is much smaller, compared to the power system, than the German aFRR market. Hence, all the historical Norwegian bids have been included in the analysis in order to provide a great enough volume to study the exchange of aFRR capacity. The German bid volume were, on the other side, much greater and it was not necessary to include all the bids when developing the bid curves.

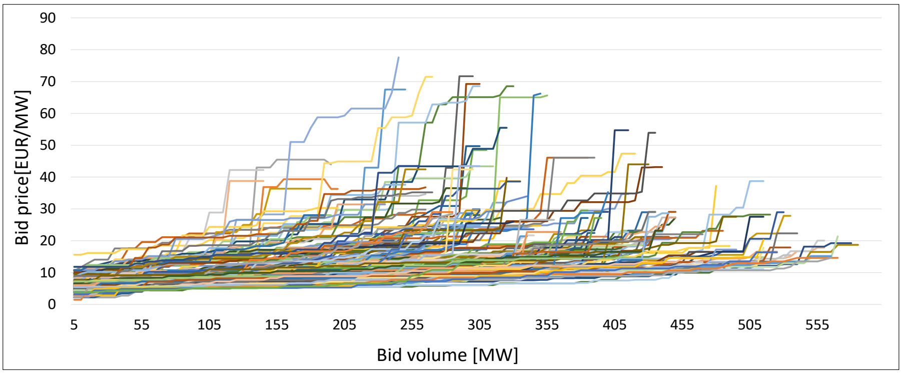

Figure 8.1: Historical Norwegian aFRR capacity bid curves from the basis data set. The bid curves are developed from bids in provision block from 5am to 8am.

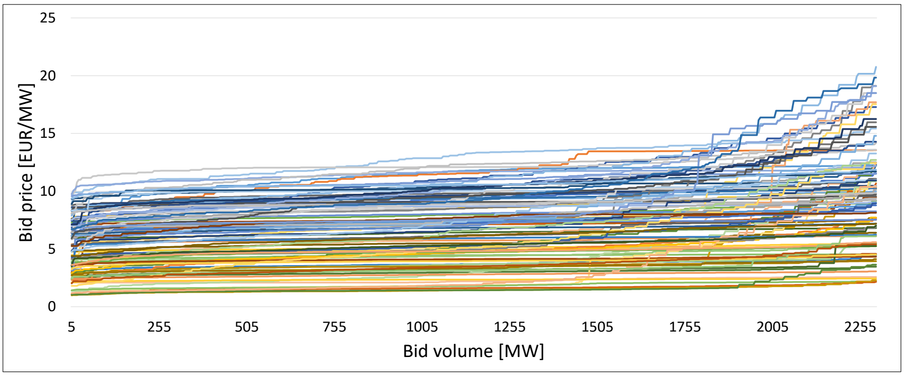

Figure 8.2: Historical German aFRR capacity bid curves from the basis data set. The bid curves shown are from the night provision block.

Correlation between the up- and down-regulation bids

Both the German and the Norwegian aFRR bid curves show correlation between up- and down-regulating aFRR prices, see figure 8.3, 8.4 and 8.5, demonstrating the weekly average aFRR bid prices for the Norwegian block, the German night block and the German day block. In Norway, the up- and down-regulating prices correlate especially much. This appears to be a contradiction to market expectations; up- and down-regulation are expected to have somewhat different bid prices for different market situations, according to the theory described in chapter 2. This feature may indicate that the Norwegian aFRR capacity bids do not show the true cost of offering aFRR balancing capacity. The down-regulation prices are overall lower than the up-regulation prices in Germany, but the prices are observed to correlate.

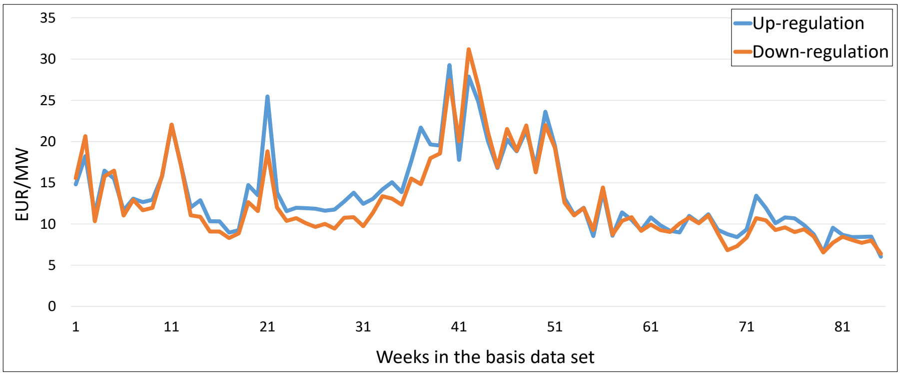

Figure 8.3: Correlation between up- and down-regulation prices for the Norwegian block from 5am to 8am. The prices are the average aFRR capacity bid price for every week in the basis data set.

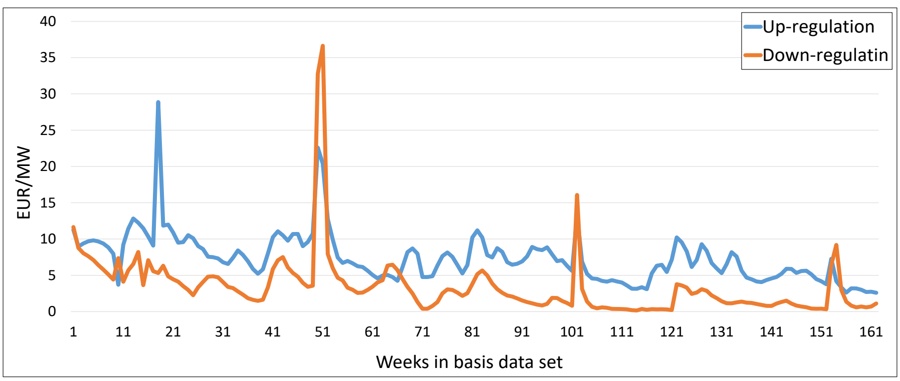

Figure 8.4: Correlation between up- and down-regulation prices for the German night block. The prices are the average aFRR capacity bid price for every week in the basis data set.

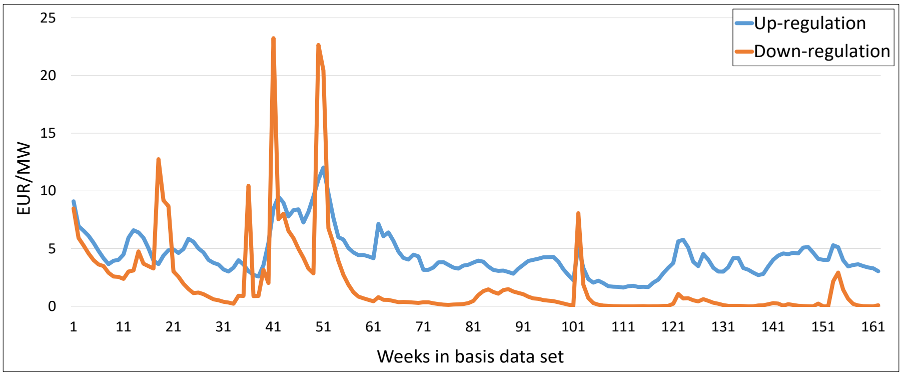

Figure 8.5: Correlation between up- and down-regulation prices for German day block. The prices are the average aFRR capacity bid price for every week in the basis data set.

One could expect higher up-regulation prices than down-regulation prices, based on the theory presented in chapter 2. In figure 8.3, 8.4 and 8.5 the up-regulation price is overall higher than the down-regulation price. One reason that the Norwegian up-regulation price is not that much higher than the Norwegian down-regulation price may be explained by the following reasoning. The theory presented in chapter 2 assumed a constant marginal cost of the plant, and implied that if the DAM prices are higher than the marginal cost of the plant, the cost of offering up-regulation balancing capacity will increase with the DAM price. However, the marginal cost varies for different type of power generating and is often non-linear [7]. That is, varies with the production volume. The best point, optimal production volume, will not all ways be the maximum production volume. Hence, if the plant is already producing electricity, and best point is below maximum production, offering aFRR up-regulation may also be cheap.

Comparison of the German night and day block

Figure 8.6 indicates that the night and day up-regulation price correlate. German night prices are observed to be higher than German day prices. The down-regulation prices (not shown here) during the day are much lower than the up-regulation prices. The latter observation fits well with expectations; If the producers are already producing during the day, offering down-regulation aFRR capacity will have a low price if the producers bid a price higher than the expected DAM price in the aFRR energy market.

An explanation of the correlation between the night and the day block can simply be expectation of certain market condition of the week. Subsequently, the night and day block will vary together with the expectations of the overall market situations.

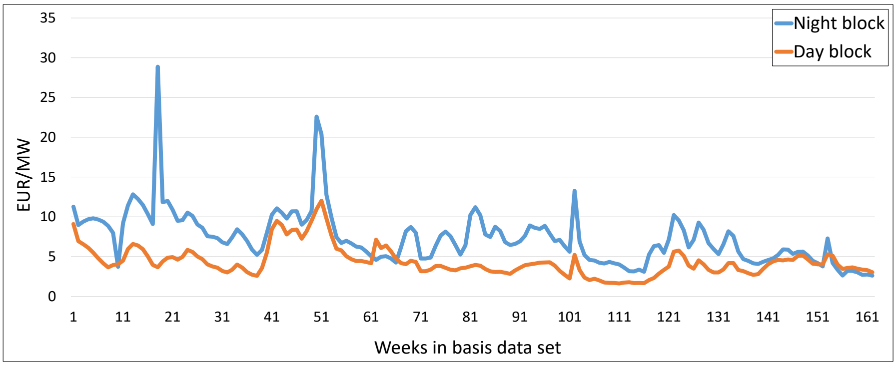

Figure 8.6: Correlation between average up-regulation aFRR prices for the German night and day block from the basis data set.

8.1.2 Discussion of the aFRR price structures

Following is a discussion of causes behind the different aFRR capacity price structures in Norway and Germany. The causes are highlighted separately.

Dependencies between balancing energy and balancing capacity
There will inevitably be dependencies between the balancing energy bids and the balancing capacity bids, due to the market design in each of the countries.

In Germany the producers bid in both balancing energy and balancing capacity at the same time. Observations in the basis data sets, where the balancing energy bids also were included, indicated that the German producers bid cheaper in the capacity market and higher prices in the balancing energy markets. Results of this observation is not provided in the thesis, due to bid sorting being time consuming and cumbersome. The basis data set indicates that the German cost of offering aFRR service, both capacity and energy, is unevenly distributed between the bids on balancing energy and balancing capacity. As the scoring rule on balancing capacity is purely based on the aFRR capacity bids, see chapter 3, the producers will have an incentive to lower there aFRR capacity bids. However, the power producer will not bid a too high aFRR energy bid, because the it will not be chosen to activate balancing energy.

The Norwegian aFRR energy price is set ex-post in the RK-market(see chapter 3). Since the aFRR energy price is set in another market, the Norwegian producers will can have an incentive to increase their aFRR capacity bid prices to mitigate the risk of receiving a to low aFRR energy price in the RK-market. Thus, the Norwegian producers have incentives to distribute the cost of offering aFRR between the balancing capacity and balancing energy in opposite direction than the German producers. Norwegian producers have incentives to increase their balancing capacity bids, while German producers have incentives to decrease their balancing capacity bids.

Different pricing mechanism
The different pricing mechanisms of the two countries can give a different optimal bidding strategy for the producers.

Literature on a pay-as-bid pricing mechanism, the pricing mechanism applied in Germany, indicates that if there are perfect competition there will be an equilibrium at the marginal price and all actors will bid the marginal cost of the marginal supplier [38]. However, in the case of imperfect information, uncertainties in the demand, the literature indicates that the producers will bid more aggressively [38]. Norwegian producers, with marginal bidding, will on the other side have incentives to bid their true cost of offering aFRR.

Different flexibility in location of the aFRR providing power plant
Portfolio based bidding in Germany increases flexibility for the producers and could for this reason lower the costs of offering aFRR capacity. Norway's arrangement involves less flexibility and this may lead to higher aFRR prices due to higher costs of offering aFRR capacity.

Different application of the aFRR markets
The share of procured aFRR is much higher in Germany, and the application of the aFRR capacity is different, see chapter 3. Figure 3.4 showed that the share of activated aFRR is much higher in Germany than in Norway. Consequently, the German producers may experience less risk when setting the aFRR capacity price due to the high chance of being activated, and hence receiving the aFRR energy prices.

Size and liquidity of the markets
The Norwegian aFRR market being small can imply less liquidity and fewer producer and lead to a sub optimal market condition. The aFRR capacity prices may for this reason not reflect the true costs.

An observation in the basis data set is that earlier years (2014,2015) have higher prices than the later years (2016,2017), indicating that the market is growing and becoming more liquid resulting in lower prices.

Different time frames of the provision blocks
The time frames of the provision blocks to be compared in this thesis are different. A longer provision block time frame can give less flexibility and contribute to higher aFRR prices. Yet, this reasoning contradicts the observations, as the German aFRR bid prices are cheaper than the Norwegian aFRR bid prices even though the German time frames of the provision blocks are greater.

If the power plant, on the other side, is not running and offering aFRR capacity, a shorter time frame of the provision block could be more expensive due to start- and stop-costs of the power plant.

8.1.3 Future aFRR markets

The common Nordic market, to be introduced by 2018, will be more similar to the German market than the current Norwegian market design, leading to the markets being more harmonized. Since the Norwegian market is assumed to have a competitive advantage, harmonization of the two aFRR markets and possibility of aFRR exchange between them may lead to lower Norwegian aFRR prices. The German producers will also adjust their prices as they will not want to sell their product more expensive than the other players.

Going from weekly to daily bids can lower the aFRR price further. This is due to mitigation of price risk and flexibility for the producers.

8.2 Additional value of the reservation

There are additional values of the reservation that the market-based reservation model does not cover. The impact of disregarding these values are briefly discussed below.

Activated balancing energy

The value of the activated balancing energy is not included in the market-based reservation model. The aim of the thesis is to quantify the exchange of aFRR capacity, but when comparing the result with previous analysis this must be kept in mind. Different cost of activation of aFRR are expected in the two countries and therefore there will be a value of the actual activation of aFRR.

Second, disregarding the activated balancing energy is likely to have an extra high impact for the simulations in this thesis. The reasons for this is the different dependencies in the two countries between balancing energy and balancing capacity. If balancing energy where to be included in the model, these dependencies would not have such a significant effect on the result.

Potential of reservation direction

Reserving aFRR for up-regulation with one country as the aFRR capacity provider opens up for the other country providing down-regulation. Therefore, there is an additional value of reserving cross-zonal capacity(CZC) for aFRR that is not captured by the model used in this thesis.

In the case of cheaper down-regulation in Germany the value of providing up-regulation from Norway will increase, because the CZC in direction NO-GE can provide both up-regulation from Norway and down-regulation from Germany. If the aFRR price difference between the two countries are stable, this value may be less because there will most likely not be beneficial to provide aFRR from the other country.

Imbalance Netting

There is also a value of using the reserved CZC for imbalance netting. Imbalance netting is explained in [39] is the agreement between TSOs that allows for the avoidance of simultaneous aFRR activation in opposite directions, meaning that instead of activating aFRR in opposite direction the power surplus in one country will be used to cover the power deficit in the other area.

Days not included

Only weekdays are included in the market-based reservation model and the first week of every case study not simulated. This may imply that the resulting socioeconomic benefit is less than without excluding these days.

Continuously allocation of CZC

Previous analysis has assumed that the CZC can be allocated continuously. Reserving capacity for one whole week at the time, gives higher cost of reservations and more sub optimal reservations. As the future aFRR market will have daily auctions there will be values of the reservation in a more dynamic allocation of the CZC.

8.3 Day-ahead market price dependencies in the models

The DAM price is important both with regards to the generation of bid curves and also for the reservation decision in the market-based reservation model. The DAM price effects the results in two ways. The first way is directly in the market-based reservation model, when estimating MV of the CZC in the DAM. The second way is when generating average aFRR prices in the regression model. Hence, it is important to consider both these effects when analyzing the simulation result.

The DAM price difference between Norway and Germany gives the MV of the CZC in DAM. Hence, the price level in the two countries does not affect the MV of the CZC in DAM. Yet, the price level will affect the average generated aFRR bids in the regression model.

Chapter 9

Results from Generation of aFRR Capacity Bid Curves

This chapter provides the result of generation of aFRR bid curves for the different case studies. First, results from the regression models for Norway and Germany are provided, then the resulting generated bid curves are described and discussed. The end of the chapter describes the modification of the bid curves for the sensitivity analysis.

9.1 Regression model results

Below is a presentation of the regression models that fitted best with the basis data set, and therefore, was used to generate the bid curves. The results for each country are presented separately. At the end of the section there is a description of general limitations of the regression models and how these have been handled, either in the regression model or prior to generation of bid curves.

The average aFRR bid price for each week during the data set period was set as the dependent variable, $\overline{p}_{aFRR}$, for both Norway and Germany. This is the average aFRR bid price for the whole bid curve.

9.1.1 Norway

Several explanatory variables have been tested. Among these were Norwegian consumption, but the result showed low significance with the basis data set. The explanatory variable that fitted best with the historical average aFRR bid price was the average Norwegian weekly Day-ahead market(DAM) price for the studied week, $\overline{p}_{DAM}$ in EURO/MWh, and this was the only explanatory variable used in the Norwegian regression model.

The relationship between the aFRR price and the DAM price is not linear, see theory presented in chapter 2. With higher DAM prices the aFRR price is assumed to decline with increasing DAM price, and opposite for lower DAM prices.

Therefore, a non-linear regression model was tested and this model fitted best with the observations. Excel's linear regression analysis have been applied, but some of the inputs ($\overline{p}_{DAM}$) were non-linear.

Equation 9.1 shows the non-linear regression model.

$$\overline{p}_{aFRR} = a + b \cdot \overline{p}_{DAM} + c \cdot \overline{p}_{DAM}^2 + d \cdot \overline{p}_{DAM}^3 \tag{9.1}$$

The Norwegian standard deviations was altered by deleting "extreme weeks", with the aim to achieve a lower standard error. Weeks in which the deviation between the actual historical average aFRR price and the average aFRR price estimated by the regression model is more than 5 EURO/MW was deleted and a new regression analysis was performed, with the same model (i.e. explanatory variables). The regression results that have been applied in the market-based reservation model are displayed in table 9.1.

Table 9.1: Results from the Norwegian regression models.

	Up-regulation	**Down-regulation**
a, intersection	46,544	56,179
b, ($\overline{p}_{DAM}$)	-2,673	-3,807
c, ($\overline{p}_{DAM}^2$)	0,0638	0,1031
d, ($\overline{p}_{DAM}^3$)	-0,000476	-0,000921
Standard deviation	2,454	2,180
R^2	0,689	0,791
Adjusted R^2	0,676	0,782
F-significance	$1,0810^{-18}$	$4,5310^{-25}$

The R^2-value is observed to have a tolerable level for both up- and down-regulation. The p-values for the regression coefficients is provided in appendix B, section B.1, and is not further discussed here.

Figure 9.1 shows the average aFRR bid prices estimated in the regression model as a function of the DAM prices. As one can see, the average aFRR bid price will decrease with increasing DAM price. This fits well with the theory presented in chapter 2. Assuming that the power plant is not producing when the DAM prices are low, and consequently, there is a high alternative cost of offering aFRR capacity, the aFRR prices will increase as the DAM prices decreases. The model suggests that the aFRR price will decrease more rapidly when the DAM prices are lower, and as the DAM price increases the aFRR price will be less affected.

The regression model is inadequate for higher DAM price, and the model could give negative aFRR prices. Figure 9.1 illustrates this issue. If the Norwegian DAM prices exceeds 55 EUR/MWh for down-regulation or 61 EUR/MWh for up-regulation the estimated average aFRR price will consequently be negative(disregarding the stochastic variable). This is not handled in any way and must be treated carefully when analyzing the high DAM price case studies.

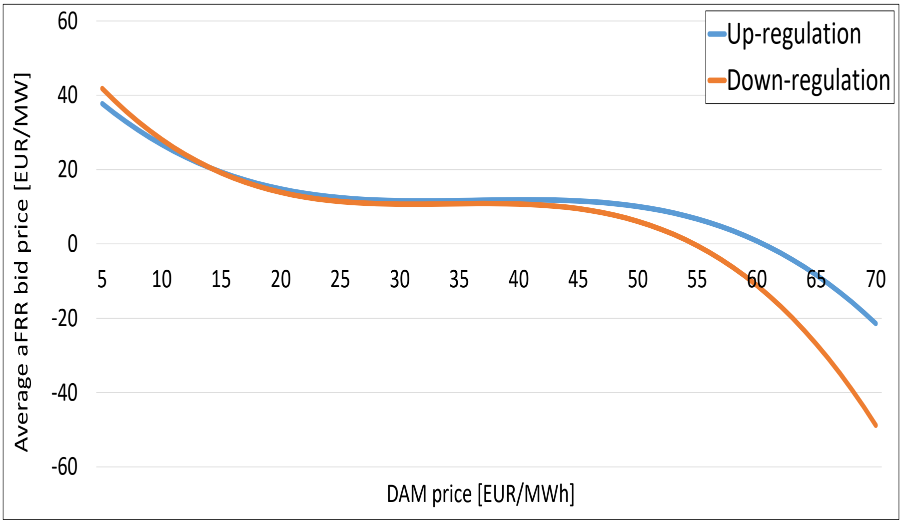

Figure 9.1: Average aFRR prices calculated with the Norwegian regression models for up- and down-regulation as a function of the DAM price.

9.1.2 Germany

Two different regression models should be implemented for Germany, one for the night block and one for the day block. There were difficulties in identifying significant explanatory variables for the German aFRR bid curves, especially for the day block, and therefore some alternative approaches were needed to generate representative German aFRR bid curves.

Night block

The best regression results were achieved when applying different explanatory variables for up- and down-regulation, i.e. two different regression models. Both models use a non-linear regression for the DAM price. The accumulated DAM price that fitted best with the historical data was the average night price, $\overline{p}_{DAM,night}$ in EUR/MWh.

The up-regulation regression model that fitted best with the basis data set includes the average night wind production, $\overline{P}_{wind,night}$ in MWh, as explanatory variable, while the down-regulation regression model that fitted best with the basis data set includes the average night consumption,$\overline{C}_{night}$ in GWh, as explanatory variable, see equation 9.2 and 9.3.

$$\overline{p}_{aFRR,up,night} = a+b\cdot\overline{p}_{DAM,night}+c\cdot\overline{p}^2_{DAM,night}+d\cdot\overline{p}^3_{DAM,night}+e\cdot\overline{P}_{wind,night} \quad (9.2)$$

$$\overline{p}_{aFRR,down,night} = a+b\cdot\overline{p}_{DAM,night}+c\cdot\overline{p}^2_{DAM,night}+d\cdot\overline{p}^3_{DAM,night}+e\cdot\overline{C}_{night} \quad (9.3)$$

Table 9.2: Results from the German regression models for the night block.

	Up-regulation	**Down-regulation**
a, intersection	48,665	71,560
b, ($\overline{p}_{DAM,night}$)	-3,769	-6,869
c, ($\overline{p}^2_{DAM,night}$)	0,1198	0,2194
d, ($\overline{p}^3_{DAM,night}$)	-0,0012765	-0,00225981
e, ($\overline{P}_{wind,night}/\overline{C}_{night}$)	-0,000025934	0,017152
Standard deviation	3,14	3,71
R^2	0,180	0,281
Adjusted R-square	0,158	0,265
Significance F	$2,7110^{-6}$	$1,3310^{-10}$

Table 9.2 gives the results of the regression model.

The regression results indicate that the model is poor. The low R^2 value may imply that the data is not close to the fitted regression line. There is also quite low correlation between the explanatory variables and the dependent variable. The p-values are provided in appendix B, section B.1. The significance levels(F) are strong for both models.

The up-regulation regression model implies that as the wind production increase, the aFRR capacity price for up-regulation will decrease. When the consumption increases the estimated down-regulation aFRR capacity price will increase according to the regression model for down-regulation. It is difficult to find an intuitive explanation for this result. There are, most likely, better explanatory variables that have not been identified. These could for example be either production of other power sources like nuclear, coal or gas, availability of power plants or capacity restrictions within the German power systems. However, these explanatory variables were not tested, due to time limitation.

Although the regression results were poor, the models have been applied to generate the German night bids, and with certain modifications, described below, the curves are assumed to be satisfactory for the purpose of this thesis. Wind and consumption have been used as explanatory variables, since they improve the regression results, even though finding an intuitive explanation for the regression results of these two explanatory variables was difficult. Wind and consumption shows less significance than the DAM price, see appendix B. For this reason, graphs of the wind and consumption as explanatory variables are not included in the appendix.

Figure 9.2 shows that the regression models are not well suited for higher DAM prices. In the figure the wind production and consumption are held constant for up-regulation and down-regulation respectively and set equal to the average for the whole basis data set period. The high DAM price cases are not handled in any way and must be treated carefully when analyzing the result.

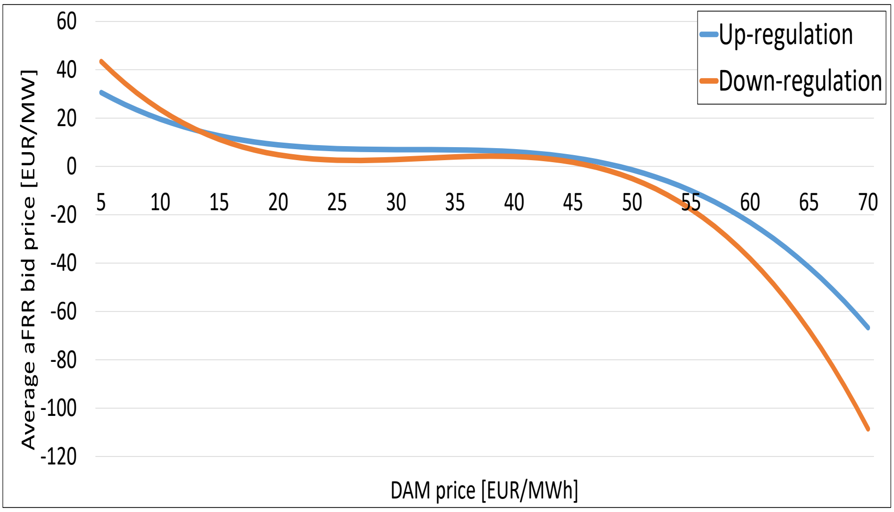

Figure 9.2: Average aFRR prices calculated with the German regression models for the night block and up- and down-regulation as a function of the DAM price.

Day block

There could not be identified any explanatory factors that correlated well enough with the historical aFRR capacity prices for the day block. Correlation between the average aFRR prices in the basis data set for night and day block have been observed, as illustrated in figure 8.6. Therefore, since no suited explanatory factors were identified, the generated night bid curves have been used to develop bid curves for the day block. It is important to emphasize the high uncertainties related to this approach, especially as there are already high uncertainties in the regression model for the night block.

For up-regulation, developing the day block bid curves was done in accordance with the observed correlation between the day and night blocks. The average price difference between the average aFRR price of the two blocks was used to adjust the generated night curves. The average price difference is equal to 2,86 EUR/MW, when deleting week 20 in 2014, where an abnormally high price difference was observed.

For down-regulation, the day prices were observed to be very low, in average equal to 1,95 EUR/MW. Excluding the higher aFRR down-regulation price year of 2014, the average aFRR price for down-regulation was 0,84 EUR/MW. Therefore, the German aFRR bid curves for down-regulation and the day blocks have been set equal to zero for all cases.

9.1.3 Limitations of the regression model

As described above several explanatory variables were tested, but there were problems in identifying variables with high correlation. Thus, it is important to consider the high uncertainty in the estimated average aFRR price when applying the result in the generation of bid curves and then further in the market-based reservation model.

An issue is that not much data with aFRR bids were provided, especially Norwegian bids. This can have contributed to the difficulty of finding explanatory variables, even though the regression result for Norway was adequate. In addition, trends that are not representative may have been captured by the model.

Careful treatment of the results is needed for the high DAM price case studies. E.g. the case study dry year 2025 has prices that exceed the recommended price level for application in the regression model, with a maximum Norwegian DAM price equal to 66 EUR/MWh and an average DAM price equal to 47,6 EUR/MWh, see figures A.3 in appendix A.

9.1.4 Handling the limitations of the regression model

The standard deviation for all the regression models are lowered to two when applying the standard variation when generating the stochastic variable epsilon. This reduces the span in variation of the generated average aFRR price, and limits the effect of extreme results in the reservation model.

50 bid curves have been generated for Germany and Norway each week in each case study. The 50 bid curves will all be simulated separately in the market-based reservation model. Hence, there will be 50 separate simulation results for each week. The average of the simulation results of these 50 bid curves will then be calculated for every week. This mitigates the uncertainty of one single results and is done to capture a wider variety of possible bid curves.

9.2 Generation of aFRR bid curves

This section starts by describing how a general characteristic of the generation approach, negative prices in the generated bid curves, is handled. Then the resulting generated bid curves are described. First, a presentation of the overall results is shown, then an example of generated bid curves for one week in each country is given.

9.2.1 Handling negative bid prices

As a result of the generation method, negative bid prices were observed in the first part of some bid curves. This have been handled by replacing negative prices in the bid curves by zero.

The alteration of the German bid curves may not have any significant effect on the result of simulation in the market-based reservation model. The marginal price of the exchange is set at a high bid volume. Hence, the alteration at the beginning of the German bid curves will not affect the prices at the end of the German bid curves, where the exchange price is set. An exception is for German bid curves that were especially low, where a greater part of the bid curve had negative prices.

For the Norwegian prices, this modification may give an effect when Germany is offering a high amount of aFRR (close to 100 MW) or the bid prices are especially low.

9.2.2 The generated bid curves

Figure, 9.3, shows the average aFRR price estimated with the regression model, including the stochastic variable epsilon. This is the average price prior to generating the bid curve and the effect of setting the Norwegian prices equal to zero is therefore not shown. The German bid curves from the night block are shown in the figure.

The case study 2015 has the highest average Norwegian aFRR price, this is due to low DAM prices during the summer, see chapter 8. The future case studies have low average German aFRR price. This is both due to higher DAM prices in the future DAM price data set and increasing share of wind production.

The down-regulation aFRR prices does not show the same difference between the historical and future case studies, and this can imply that it is the wind production, as explanatory variable, that decreases the average German aFRR price for the future case studies.

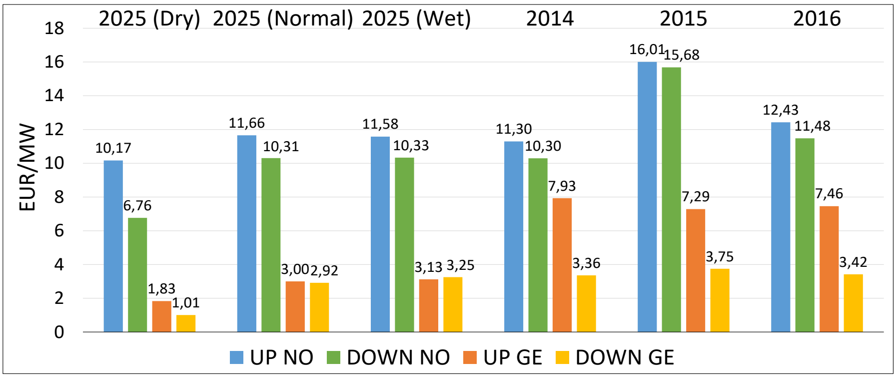

Figure 9.3: Average price of the up-(UP) and down-regulation(DOWN) aFRR bid curves for Germany(GE) and Norway(NO) for the different case studies. The German night block is shown.

The average bid price of the bid curves is, however, not a good indication of what the result would be in the reservation model. The reason for this is the different shape of the curves in each country and that the prices of the exchange is set on the marginal price of exchange. The marginal price of the exchange, set at the national procurement volume, is unknown before the reservation is decided on. However, as the maximum exchange volume is 300 MW (not considering the limit of 100 MW with Germany as the providing country) one knows that the national procurement volume is between 1700 MW to 2300 MW for Germany in the reservation model, and 0 to 400 MW in Norway. The average estimated aFRR price at the national obligation volume (2000MW and 100MW) is presented in figure 9.4 for each country and each case study. This better represents the potential value of the reservation than the average of the whole bid curve.

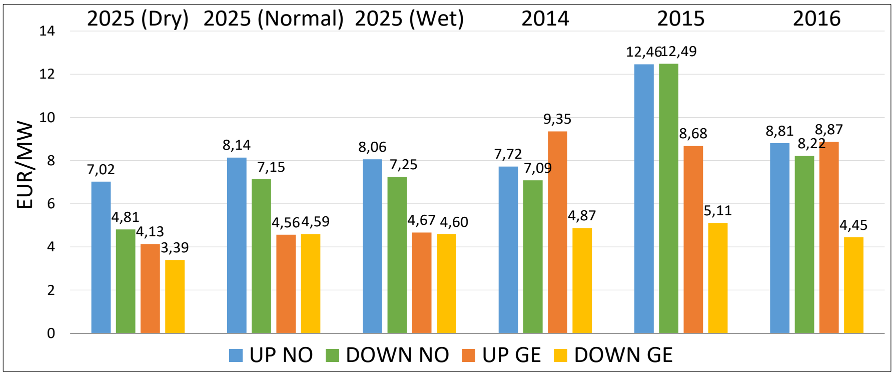

Figure 9.4: Average price at the national obligation volume for up-(UP) and down-regulation(DOWN) aFRR bid curves for Germany(GE) and Norway(NO) for the different case studies.

Example of Norwegian generated bid curves

Figure 9.5, shows the 50 bid curves generated for week 7 in year 2015. This week is chosen arbitrarily to display characteristics of the generated bid curves. As described in chapter 8 the Norwegian aFRR bid curves from the data set are not linear, and tend to have an exponential growth towards the end of the bid curve.

High price peaks are observed in the generated bid curves. These high price peaks come from the already existing high price peeks in the basis data set. The peaks will be restricted(not as high) when a lower standard deviation is used to generate epsilon. Yet, as high price peaks are observed in the data basis set, they will always be observed in some of the generated curves with the method described above. This is seen as representative and captures extreme situations.

Naturally, as there are different lengths of the aFRR bid curves in the basis data set, there will also be different lengths of the generated bid curves.

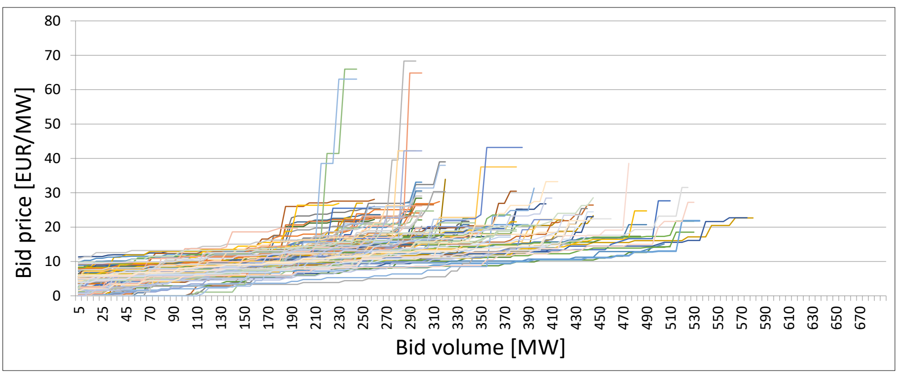

Figure 9.5: Generated aFRR bid curves for week 7 in 2015 Norway. Both up- and down-regulation curves are shown together.

Example of German generated bid curves

Figure 9.6, shows the 50 bid curves generated for week 7 in year 2015. This week is chosen arbitrarily to display characteristics of the bid curves. The German bid curves are flatter than the than Norwegian curves, and the bid curves are of the same length. The bid curve from week 20 in year 2014 was deleted from the basis data set due to an extreme bid price increase up to 340 EURO/MW.

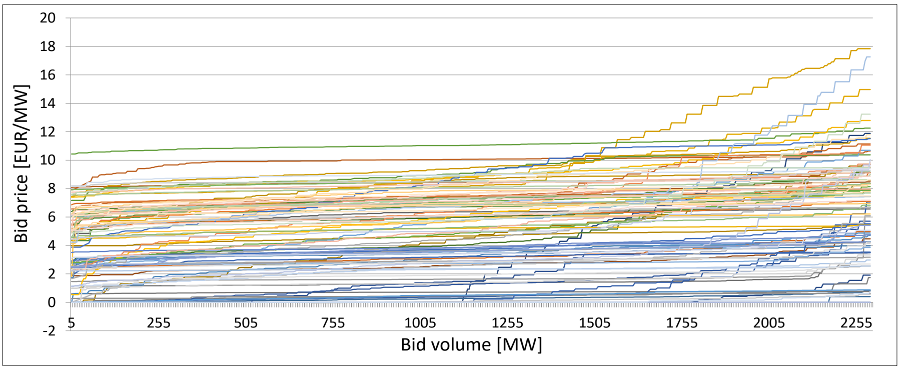

Figure 9.6: Generated aFRR bid curves for the German night block in week 7 in 2015. Both up- and down-regulation are shown together.

9.3 Modification of the bid curves for the sensitivity analysis

A sensitivity analysis has been conducted to study the expected effect of more harmonized aFRR markets. The sensitivity was set up in a way that tried to imitate the expectations of the real costs of aFRR capacity in the markets. Modifications of the generated aFRR bid curves are done in order to use them in the sensitivity analysis.

First, modification of the Norwegian bid curves is done to imitate that the Norwegian market is growing so that the 300 MW of aFRR capacity always can be offered from Norway. The bid curves are then scaled with the three different scaling factors, presented in chapter 7.

The Norwegian bid curves are extended with the following approach, consisting of two steps.

1. The bid curves are extended so that the volume offered is minimum 400 MW. The bid curves are extended by adding the missing volume at the beginning of the curve so that the bid curve will be at least 400 MW long. The price at the beginning of the curve is set equal to the original lowest price, at a procurement volume of 5 MW.

2. The modified bid curves from step 1.) are extended even further, by adding a volume of 100 MW to each bid curve. This volume is added in the middle of

the curve from 100 to 200 MW.

This approach is chosen due to it being less cumbersome and time consuming(15600, bid curves are being extended) and also because it lowers the original Norwegian price somewhat, compared with figure 9.4. The result of the new estimated average price at the national obligation volume is shown in figure 9.7.

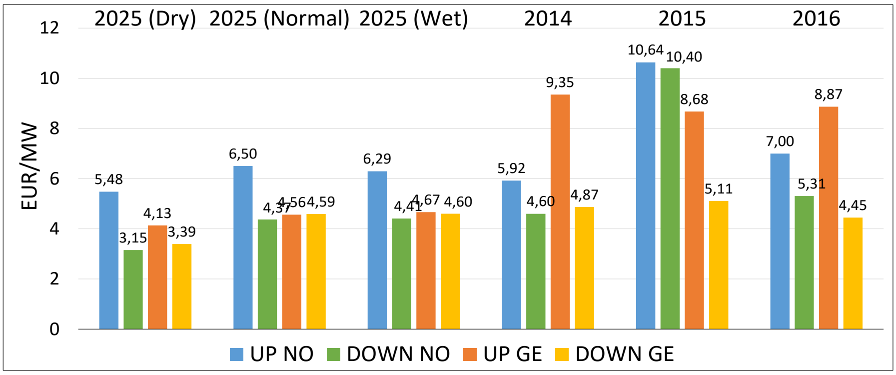

Figure 9.7: Average aFRR price at the national obligation volume for up-(UP) and down-regulation(DOWN) aFRR bid curves for Germany(GE) and extended aFRR bid curves for Norway(NO) for the different case studies.

Chapter 10

Simulation Results and Discussion

This chapter presents and discusses the simulation result from the market-based reservation model. First, the results from the simulation of the base scenario are presented. Then the results from the sensitivity analysis are provided, with the three different sensitivity scenarios presented in chapter 7.

10.1 Base scenario

This section provides the result of simulation in the market-based reservation model with the base scenario. Table 10.1 renders the simulation conditions presented in chapter 7.

Table 10.1: Simulation conditions for the base scenario.

Nation obligation volume Germany:	2000 MW
Nation obligation volume Norway:	100 MW
CZC reservation limit NO-GE:	300 MW
CZC reservation limit GE-NO:	100 MW
aFRR proving country:	Both
German provision blocks:	Night/Day
Norwegian provision blocks:	5am to 8am
Forecasting strategy	Average week before

Follows is an observation on the Day-ahead market(DAM) price in the case studies that is important to have in mind when considering the simulation result from the reservation model. The German DAM prices do not vary as much between the case studies, see figure A.2 and A.4. Hence, the difference in the simulation results are mostly due to the different Norwegian DAM prices of the case studies. The DAM price in the future case studies do not vary much between the different case studies, see figure A.3 and A.4. Consequently, the simulation results of the future case studies are more similar. In addition, there are less DAM price difference between Norway and Germany in the future case studies and therefore an overall higher socioeconomic benefit is shown for future case studies.

The results demonstrate that Germany has the highest potential of being an aFRR capacity provider. The input aFRR prices for the market-based reservation model, is indicated to be non-representative for the reasons depict in chapter 8. Therefore, discussion in this section is done in light of the input variables provided and it is important to emphasize that one should be careful of drawing any conclusions to reality.

In the base scenario the different shape of the curves could have an affect on the simulation results. This affect would be that a lower volume was decided on for Norwegian exchange of aFRR, but the effect would first be observed at higher reservation volumes. Yet, as Germany was the resulting main aFRR capacity provider in the base scenario, this effect may not have been significant.

10.1.1 Socioeconomic benefit

Here, the general accumulated result and discussion of the socioeconomic benefit achieved in the simulation results of the base scenario is provided.

Night block simulations
Figure 10.1 and 10.2 show the accumulated yearly socioeconomic benefit, value of the aFRR reservation and cost of reservation for the night block for all case studies and for up-regulation and down-regulation respectively. The results give the yearly average and is the average of the 50 bid curves for each week added up. Socioeconomic benefit is achieved for all case studies, except for down-regulation in 2014 and 2015.

Overall the result shows that the socioeconomic benefit for up-regulation decreases when the Norwegian DAM price increases. Germany is providing most aFRR capacity, see section below. Hence, reservation of cross-zonal capacity(CZC) for up-regulation capacity is mainly done in direction Germany to Norway(GE-NO). When the DAM prices are low in Norway, compared to Germany, the power flow will go more stably from Norway to Germany, and therefore the CZC reservation direction Norway to Germany (NO-GE) has a stable high MV of the CZC in the DAM. On the other hand, one will experience a low MV of the CZC in the DAM in the other direction, GE-NO. Since the reservation direction GE-NO has a low MV of the CZC in the DAM, the probability of the MV of the CZC for aFRR exchange being greater than the MV of the CZC in the DAM will be higher and thus there will be more reservations in this direction. In addition, low Norwegian DAM prices increase the Norwegian generated aFRR bid curves further, depict in figure 9.3, leading to an even greater difference between the Norwegian and the German aFRR bid curves and increasing the MV of the CZC for up-regulation aFRR exchange in GE-NO direction.

For down-regulation, the different case studies do not follow the DAM price level directly. There are observed high costs of the CZC reservation for all case studies, especially 2014 and 2015. As described above, for the lower Norwegian DAM price case studies, like 2015, the MV of the CZC in the DAM in direction NO-GE is high. Since Germany is providing most aFRR capacity down-regulation requires a reservation of CZC in direction NO-GE, which has high costs. Forecasting can be difficult, and misleading forecasts will give extra high costs.

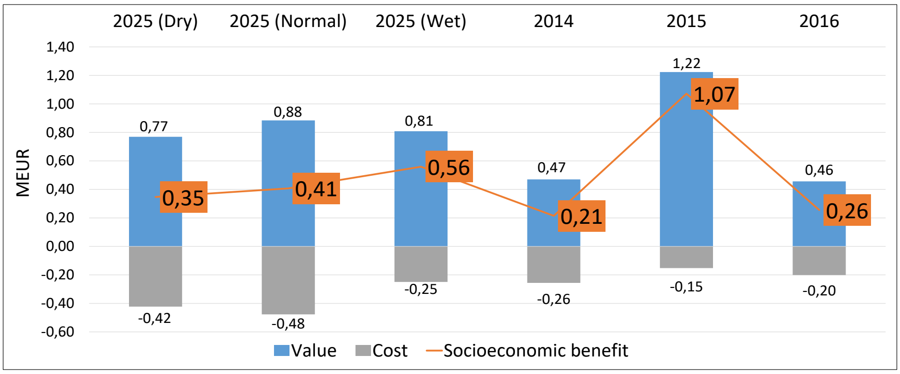

Figure 10.1: Socioeconomic benefit for up-regulation and the night block with base scenario for the different case studies.

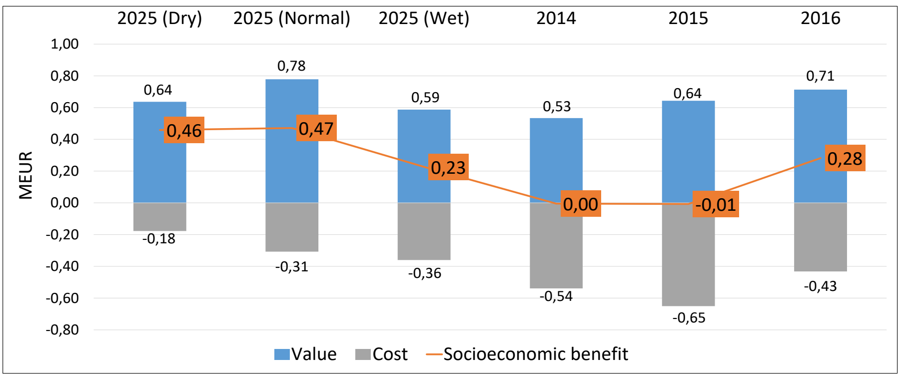

Figure 10.2: Socioeconomic benefit for down-regulation and the night block with the base scenario for the different case studies.

Day block simulations

Figure 10.3 and 10.4 show the accumulated yearly socioeconomic benefit, value of the aFRR reservation and cost of reservation for the day block for all case studies, for up-regulation and down-regulation respectively. Both countries are providing aFRR capacity. The results give the yearly average and is the average of the 50 bid curves for each week added up.

For up-regulation, the same trends as for the night block are observed. Socioeconomic benefit also increases with decreasing DAM price. Accordingly, for the same reason as highlighted above. Less cost of the CZC reservation is observed, especially for the historical case studies. This could be due to a higher DAM price difference during the day between Norway and Germany compared to the night, leading an even more low and stable MV of the CZC in DAM in direction GE-NO, see figures A.5, A.6, A.7, A.8, A.9 and A.10 in appendix 1. Consequently, there are low costs of offering up-regulation from Germany.

On the other side, providing aFRR down-regulation capacity, results in high reservation costs since a high MV of the CZC in the DAM is observed in reservation direction NO-GE. Yet, as the down-regulation price for the German day provision block is set equal to zero, for all case studies, the value of the aFRR reservation increases compared to the night block.

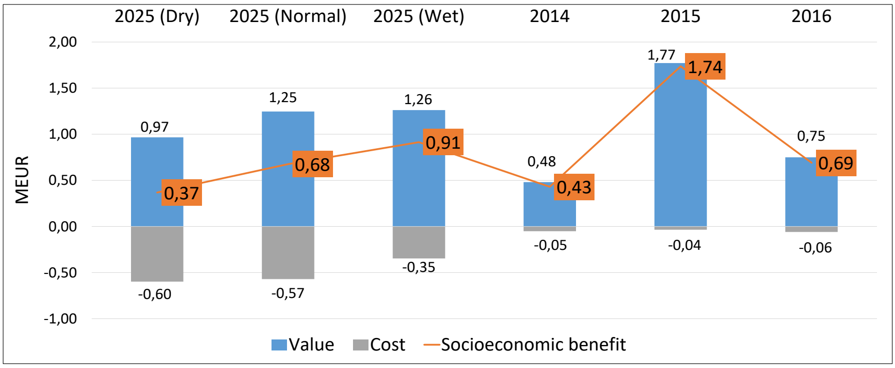

Figure 10.3: Socioeconomic benefit for up-regulation and the day block with base scenario for the different case studies.

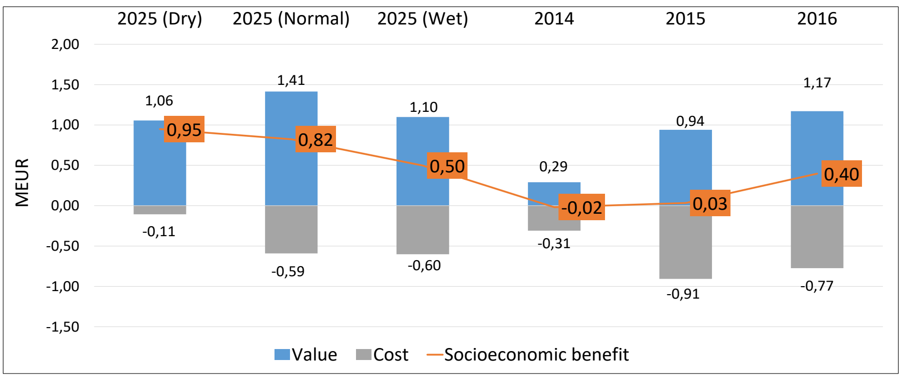

Figure 10.4: Socioeconomic benefit for down-regulation and the day block with the base scenario for the different case studies.

Accumulated result for the night and day block

Table 10.2 adds up the accumulated result for the different cases. That is for both the night and day block and for both up- and down-regulation. The future case studies get the highest socioeconomic benefit most likely due to small DAM price difference between Norway and Germany. Moreover, the higher DAM prices of these years, both for Norway and Germany, see figure A.3 and A.4, affects adequacy of the regression model and low aFRR price.

The total average sum of the socioeconomic benefit for up- and down-regulation, 1,97 million euro, is much lower than the socioeconomic benefit estimated previously in Statnetts' Value creation report (Verdiskapningsrapport 2016)(about 15 MEUR). The estimation also includes the activation of aFRR, which contributes mostly to the value of the estimation. The value of aFRR energy is not included in this thesis and may hence be a reason for the differentiation in the result. The estimation is also based on dynamical reservation and imbalance netting is included, both contributing to a higher estimated socioeconomic benefit. The whole amount of the available CZC can only be used for the aFRR market in this thesis's simulations. There could be greater potentials in other balancing markets, which was captured by the estimation in the Value creation report. Most importantly, analysis provided in the value creation report shows most potential of Norway as the aFRR providing country.

One reason for the low socioeconomic benefit, as a result of the inputs, may be that there are too small spreads between the Norwegian and the German aFRR prices. Even though Germany has the lowest aFRR prices, and this is not seen as representative for the reasons described in chapter 8, the German marginal price of exchange is not that much lower compared with the Norwegian marginal price of exchange. This can be observed in figure 9.4.

Table 10.2: Accumulated socioeconomic benefit for the case studies.

Case studies	**2014**	**2015**	**2016**	**2025 (Dry)**	**2025 (Normal)**	**2025 (Wet)**
Total yearly result[MEUR]	0,62	2,84	1,63	2,12	2,38	2,20

10.1.2 Weekly Socio-economic benefit

Figure 10.5 and 10.6 provides the average socioeconomic benefit achieved for every week in the case studies for the night block. In figure 10.7 and 10.8 the average socioeconomic benefit achieved for every week in the case studies for the day block is shown.

One first observation is that the result appears to vary more week by week for the future case studies, most likely a result of a more varying future DAM prices from week to week. In addition, correlation with the MV of the CZC in the DAM provided in appendix A can be observed. The resulting weekly socioeconomic benefit for up-regulation appears to be more volatile in the higher Norwegian price periods, fall and winter. This may be due to more shifting MV of the CZC in the DAM in direction GE-NO.

Some of the results for the case studies provided show extreme results. Some of these case studies will be briefly discussed below, to explain and give understanding of why the simulation results ended up this way. Discussion is presented for up-regulation in case study 2015, up- and down regulation in case study 2014. The result of case study 2025(Dry) is also included to study the effect of the high DAM prices, some above the satisfactory level in the regression model.

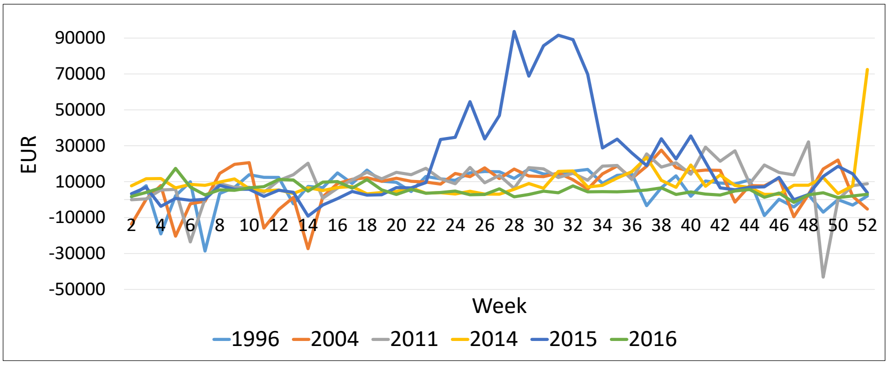

Figure 10.5: Average weekly socioeconomic benefit for up-regulation and the night block with the base scenario for the different case studies.

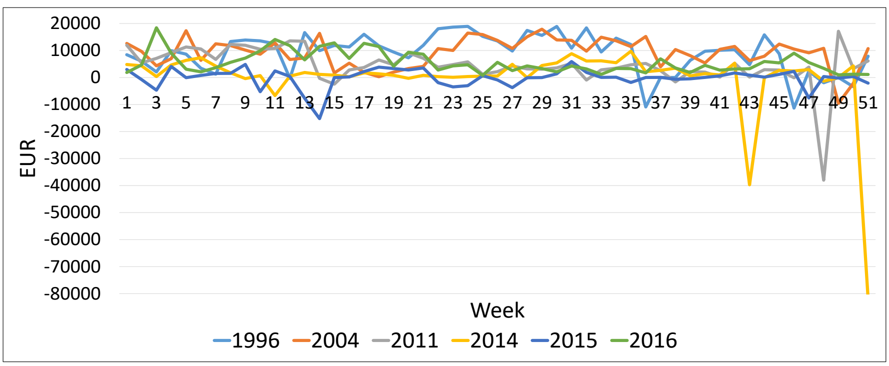

Figure 10.6: Average weekly socioeconomic benefit for down-regulation and the night block with the base scenario for the different case studies.

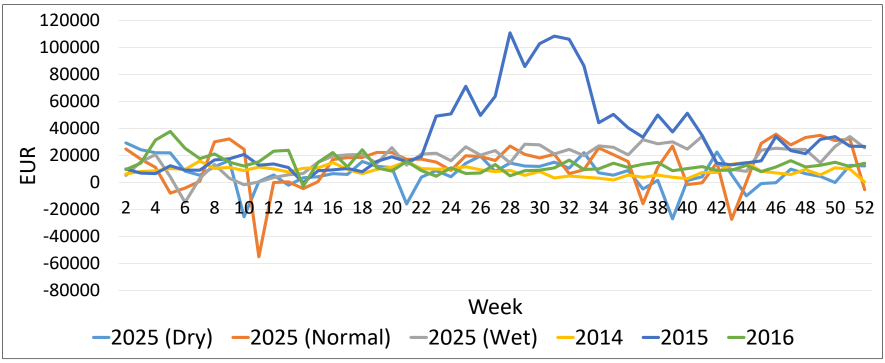

Figure 10.7: Average weekly socioeconomic benefit for up-regulation and the day block with the base scenario for the different case studies.

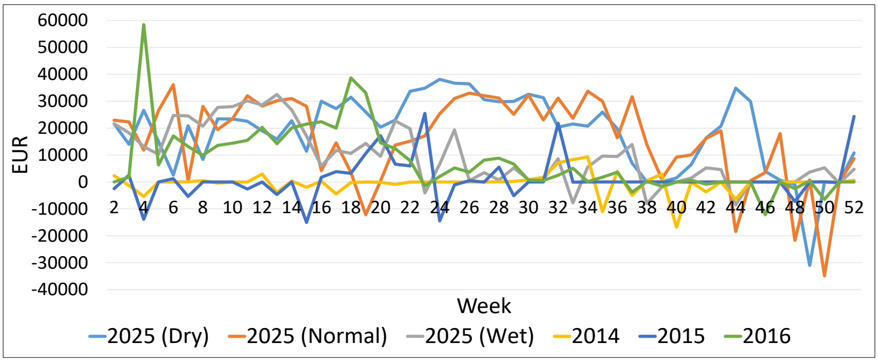

Figure 10.8: Average weekly socioeconomic benefit for down-regulation and the day block with the base scenario for the different case studies.

The case study 2015 is studied by only considering Germany as the aFRR provider. The reason for this is that Germany has a much higher share of reservations than Norway, seen in figure 10.9 and explained in the next subsection. Only the night time simulation are studied.

The case study 2014 and 2025 dry year have highest share of reservations with Norway as the aFRR capacity provider for up-regulation and the night block. Therefore, the presentation of these case studies will be provided by studying the result when Norway is the only aFRR provider. This study also contributes to an understanding of Norway as an aFRR provider in the market-based reservation model.

Case study 2015, Germany as the aFRR provider

For up-regulation the case study 2015 has the highest socioeconomic benefit. While for down-regulation 2015 has very high costs for reservation and consequently ends up with a negative socioeconomic benefit. See figure C.1 and C.1 in appendix C.

Abnormally low Norwegian DAM prices in the summer of 2015 resulted in a large DAM price difference between Norwegian and German DAM prices and thus a high MV of the CZC in the DAM in direction NO-GE. The MV of the CZC in the DAM in the opposite direction(GE-NO) ended up being equal to zero for this period, due to a stable flow from Norway to Germany (stable high DAM price difference). This can be studies in figure A.6 in appendix A.

Low Norwegian DAM prices resulted in a greater difference between the aFRR bid curves, see figure 9.4, yielding a higher value of the reservation and together with a big reservation volume, high socioeconomic benefit was achieved, see figure C.1. There were little costs for up-regulation as the MV of the CZC in the DAM from GE-NO was low.

The high MV of the CZC in the DAM in direction NO-GE gave high reservation costs for down-regulation provided by Germany, see figure C.2. These costs were so high that the socioeconomic benefit ended up being negative.

Case study 2014, Norway as the aFRR provider

Case study 2014 has periods around week 30 to 40 and week 50 to 52 where the forecasted MV of the CZC in the DAM in direction NO-GE is especially low. These periods have higher Norwegian DAM prices than normal which, together with a normal German DAM price level, yields a low MV of the CZC in the DAM in direction NO-GE, facilitating for exchange of Norwegian aFRR. In addition, the high Norwegian DAM price impacts the generation of the bid curves by generating lower prices aFRR bid curves. The result is demonstrated in figure C.3 in appendix C.

A reason for the high overall costs for aFRR capacity for up-regulation may be that the MV of the CZC in the DAM in direction NO-GE curve varies more than the other historical case studies throughout the years. Consequently, using the week before as forecast is not a satisfactory strategy.

For down-regulation, an abnormally high MV of the CZC in the DAM in direction GE-NO is observed in the end of 2014, due to an increase in the Norwegian DAM prices. This market change yields a high share of reservations for down-regulation from Norway in week 51, but as the MV of the CZC in the DAM in direction GE-NO increases even more in week 52, the forecasted MV of the CZC in the DAM is too low and an extreme reservation cost is observed, see figure C.4 in appendix C.

Case study 2025(Dry), Norway as the aFRR provider

The case study 2025(dry year) has high DAM prices. The prices are so high that the result should be treated carefully, as some of the prices are above the accepted level for the regression model. In the high DAM price weeks of this case study, like for example week 39 with average Norwegian DAM price equal to 58,6 EUR/MW, one can observe both a high cost, high value and a high socioeconomic benefit, see figure C.5 in appendix C.

10.1.3 Share of reservations between Germany and Norway

Night block simulations

Figures 10.9 and 10.10 show the share of the simulations that a country is providing aFRR capacity for the night block for up- and down-regulation, respectively. CZC is only reserved for Norway as a provider of aFRR capacity up-regulation an average of 15% of the time, and only 12% of the time for down-regulation. Up-regulation aFRR capacity was provided by Germany in average 47% of the time, while down-regulation was provided in average 41% of the time.

Germany having the highest share as an aFRR capacity provider in both regulation directions is not surprising based on the input in the model, as chapter 8 showed that the German aFRR capacity price were overall lower than the Norwegian aFRR capacity price. Yet, this result contradicts the expected results, based on theory on electric power mixes in the two countries and market expectations.

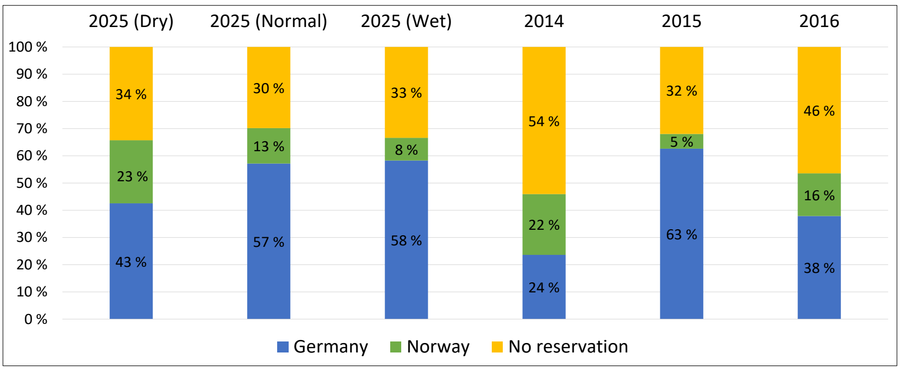

Figure 10.9: Distribution of the reservations between Norway and Germany with the base scenario for up-regulation and the night block.

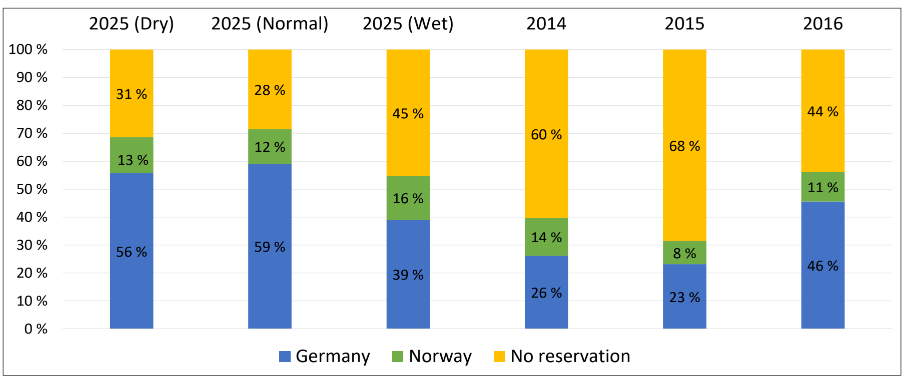

Figure 10.10: Distribution of the reservations between Norway and Germany with the base scenario for down-regulation and the night block.

Day block simulations

In figure 10.11 and 10.12 the share of reservation between Norway and Germany is depicted for the day simulations, for up- and down-regulation respectively. As the figures show there are even less reservations done where Norway is the providing aFRR capacity country. For down-regulation no reservations are done where Norway is providing aFRR capacity. The reason for this is that the German generated aFRR curves are lower than the night curves.

Another observation is that there are less reservations executed for down-regulation with the day block compared to the night block for the historical cases and more reservations executed for the future cases. This appears to be the result of the difference in the MV of the CZC in the DAM for the direction NO-GE for the different cases, as discussed above.

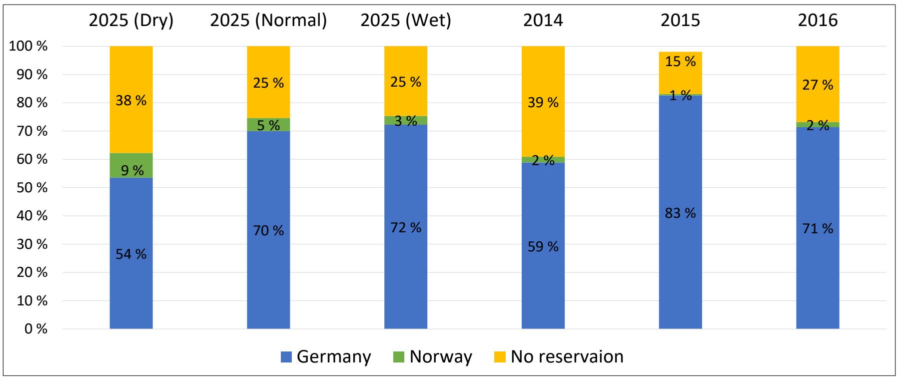

Figure 10.11: Distribution of the reservations between Norway and Germany with the base scenario for up-regulation and the day block.

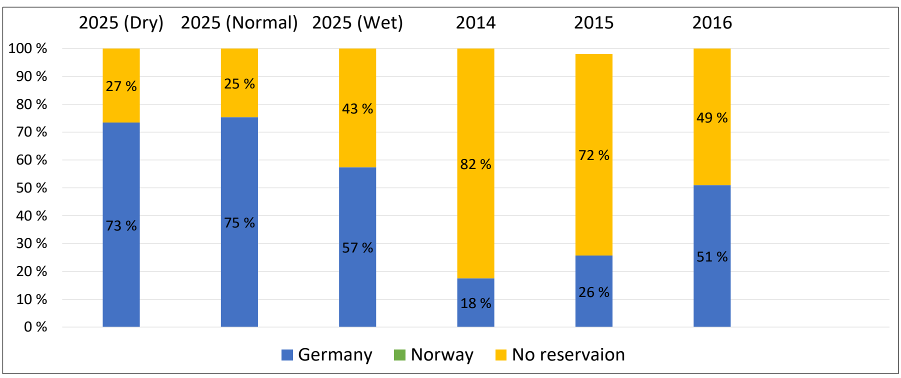

Figure 10.12: Distribution of the reservations between Norway and Germany with the base scenario for down-regulation and the day block.

10.1.4 Beneficial and non-beneficial reservation

It is interesting to study the accuracy of the reservation model. The results should indicate of how well the DAM forecasting strategy works.

Night block simulations

For the night block up-regulation has overall the most beneficial reservations. In figure 10.13 and 10.14 the resulting distribution between beneficial reservations, non-beneficial reservations and no reservations are displayed for up- and down-regulation respectively.

Of the reserved capacity the Norwegian reservations are beneficial 74% of the time for up-regulation and 70% of the time for down-regulation, according to the model. 83% of the reservations in which Germany served as the provider of up-regulation were beneficial and, for down-regulation, 77% of the reservations were beneficial.

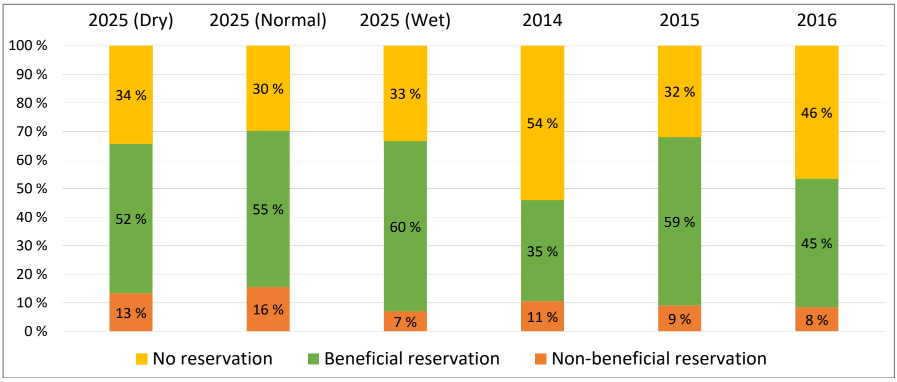

Figure 10.13: Distribution between beneficial and non-beneficial reservations for up-regulation and the night block.

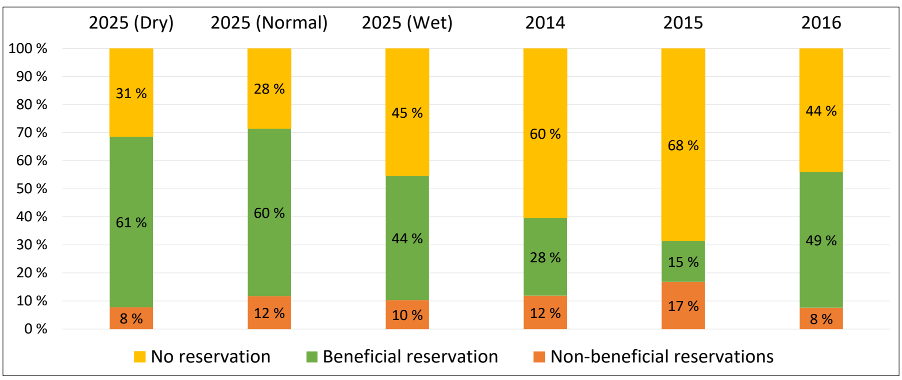

Figure 10.14: Distribution between beneficial and non-beneficial reservations for down-regulation and the night block.

Day block simulations

The day time results show higher accuracy then the night time simulations, see figure 10.15 and 10.16. This is most likely due to a more stable DAM day price difference from week to week. The MV of the CZC in the DAM is low and stable in direction GE-NO(equal to zero most of the time, see figure A.5, A.6 and A.7) for the historical case studies, and thus easier to forecast. While for the future case studies, the German and Norwegian price is much more equal, making it more difficult to forecast this reservation direction(GE-NO). Another explanation could be that the DAM price in the future case studies varies more from week to week.

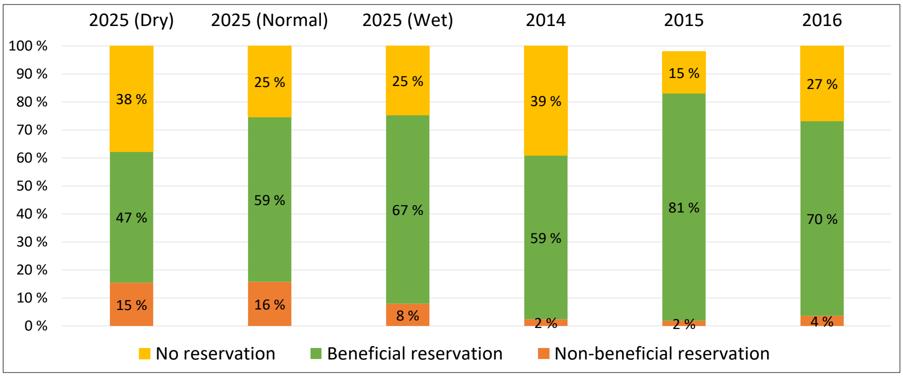

Figure 10.15: Distribution between beneficial and non-beneficial reservations for up-regulation and the day block.

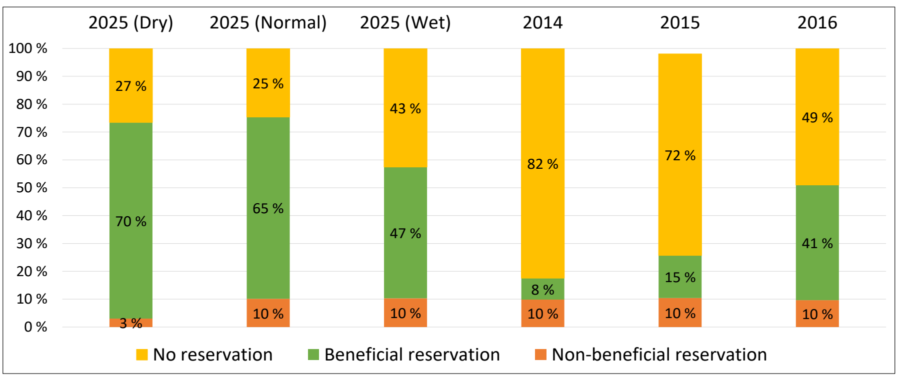

Figure 10.16: Distribution between beneficial and non-beneficial reservations for down-regulation and the day block.

10.1.5 Base scenario: Perfect foresight

The same conditions as presented in table 10.1 are simulated. The actual average MV of the CZC in the DAM for the respective week is applied to uncover the true potential of reservation of CZC for aFRR, and also the potential of having a better forecast strategy than the week before. A forecast will, of course, never be better than perfect foresight. Since the reservation volume is constant for all weekdays of the respective week, the average price for the respective week reveals the true cost of reservation(with the assumptions established in chapter 5).

Figure 10.17, 10.18, 10.19 and 10.20 illustrates the socioeconomic benefit when applying a perfect forecasting. The socioeconomic benefit with perfect foresight is naturally higher than with a forecast from the week before and the costs are minimized with regards to achieving the highest socioeconomic benefit.

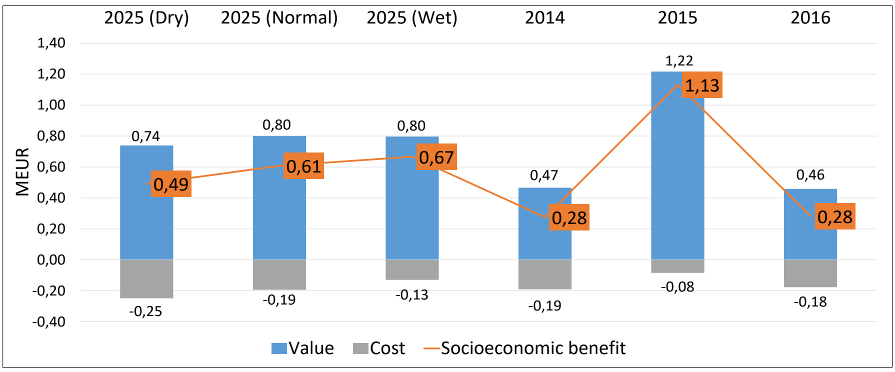

Figure 10.17: Socioeconomic benefit for up-regulation and the night block with perfect foresight.

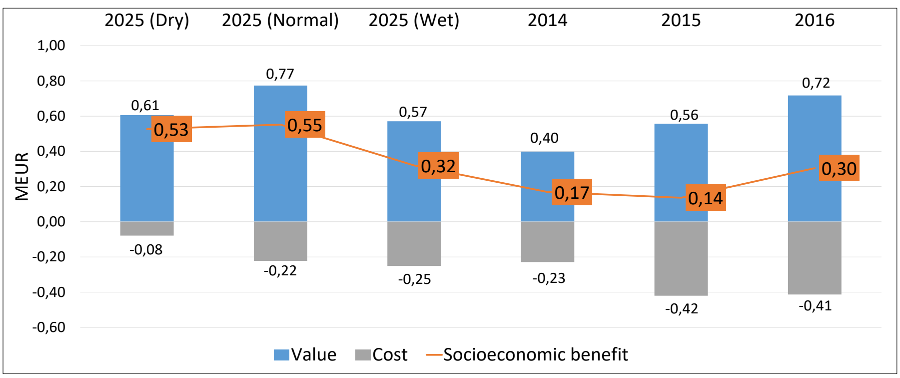

Figure 10.18: Socioeconomic benefit for down-regulation and the night block with perfect foresight.

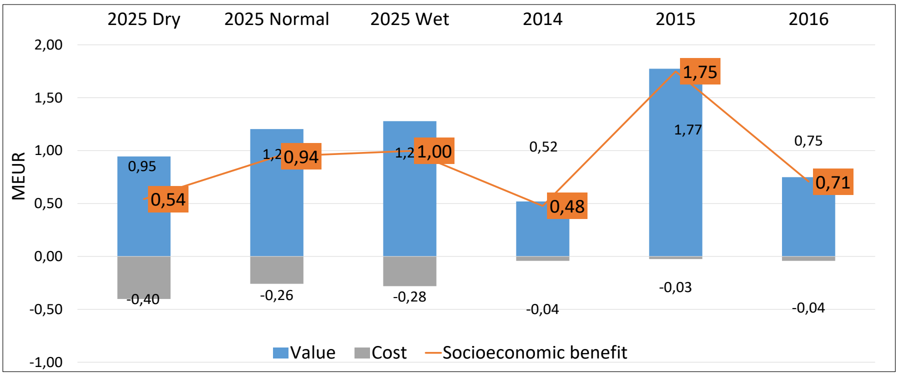

Figure 10.19: Socioeconomic benefit for up-regulation and the day block with perfect foresight.

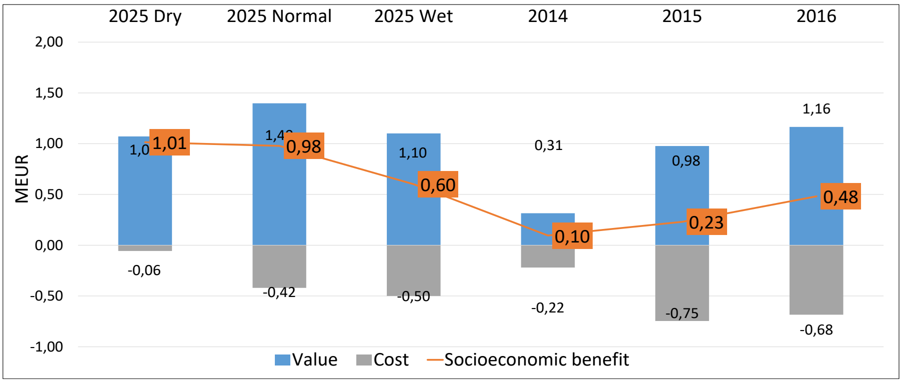

Figure 10.20: Socioeconomic benefit for down-regulation and the day block with perfect foresight.

Even though a perfect forecast strategy is applied, the socioeconomic benefit is not increased significantly. The yearly socioeconomic benefit is given in table 10.3 and yields an average yearly socioeconomic benefit equal to 2,38 million euro, an increase of approximately 21%.

Table 10.3: Accumulated socioeconomic benefit with perfect foresight.

Case studies	2014	2015	2016	2025 (Dry)	2025 (Normal)	2025 (Wet)
Total yearly result[MEUR]	1,02	3,25	1,78	2,57	3,08	2,58

There are obviously no non-beneficial reservations, as the forecasting method is perfect. The frequency of CZC reservation being executed is given in table 10.4. The reservation frequency has increased for the night block, and stayed the same for the day block. This indicates that the the forecast strategy of applying the average price from the week before is better in the day than during the night hours.

Table 10.4: Reservation frequency with perfect foresight.

	Up-regulation	Down-regulation
Night	61%	52%
Day	72%	50%

10.2 Sensitivity study on aFRR bid prices

The sensitivity study was conducted with the aFRR bid curves scaled as shown in table 10.5 and described in chapter 7, section 3. Only aFRR bid curves from the German night provision blocks have been used, both for day and night time simulation. The reason for this are the low values(zero for down-regulation) of the German day provision block. Therefore, the scaling gave little effect. As the aim of the sensitivity analysis is to study the trend in the results when increasing the German bid prices and decreasing the Norwegian bid prices, this was considered to be satisfactory. The simulation was performed with the conditions in table 10.6.

Table 10.5: Sensitivity scenarios.

Scenario	NO scaled	GE scaled
Sensitivity scenario 1	-10%	+10%
Sensitivity scenario 2	-20%	+20%
Sensitivity scenario 3	-30%	+30%

Table 10.6: Simulation conditions for the sensitivity studies.

Nation obligation volume Germany:	2000 MW
Nation obligation volume Norway:	100 MW
CZC reservation limit NO-GE:	300 MW
CZC reservation limit GE-NO:	100 MW
aFRR proving country:	Both
German provision blocks:	Only night
Norwegian provision blocks:	5am to 8am
Forecasting strategy	Average week before

The extended Norwegian aFRR bid curves, see chapter 9 section 3, have been used to scale the Norwegian bid curves. Only the German night provision block is scaled, as it is only this curve that should be applied in the analysis.

Since the scaling result depends on the size of the original price curves, the alternation gave different result for the different case studies. An illustration of the average price at the national obligation volume of the scale curves are provided in figures, C.7, C.8 and C.9, in appendix C.

10.2.1 Socioeconomic benefit

The socioeconomic benefit increases as the aFRR price difference between the countries increase, see figure 10.21, 10.22, 10.23 and 10.24, except for up-regulation, both night and day, in the case study of 2015. The socioeconomic benefit is highest for the historical years simulated, and also appears to increase more rapidly with the increasing scaling factor. These years also have the highest cost. This can be both due to a greater reservation volume, see figure 10.25 and 10.26, and that the MV of the CZC in DAM is greater and varies more than the future case studies, discussed in the previous section.

Down-regulation shows the highest potential in increasing socioeconomic benefit, especially for the day block. Reasons for the rapid increase in socioeconomic benefit when scaling the curves may be that the share of Norway as a down-regulation country is increasing rapidly. In addition, there are, especially during the day and for the historical cases, high price differences between Norway and Germany. Hence, reservations for down-regulation from Norway, in CZC direction GE-NO, have low costs.

The base scenario simulation indicated potential of Norwegian provision of aFRR for the future case study 2025(Dry), yet this case does not show as much potential as the historical case studies. The case study 2025(Dry) has high Norwegian DAM prices, leading to a lower price DAM difference with Germany, and implying that more reservations can be executed. Yet, the low price generated aFRR prices makes the effect of the scaling factor little, and contributing to less change being observed.

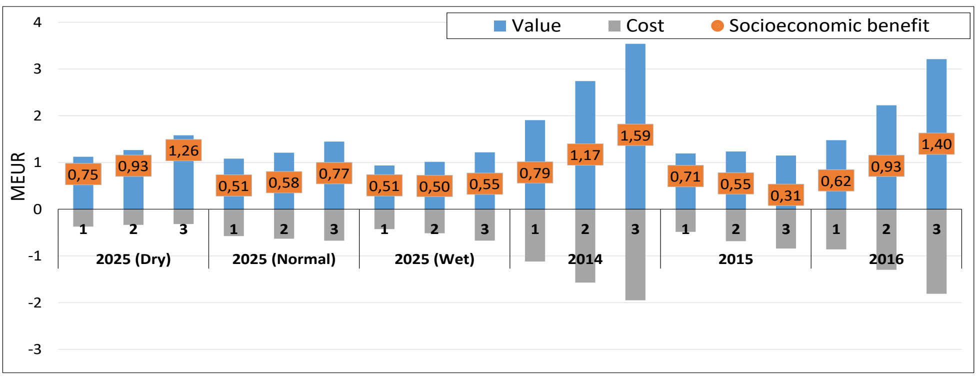

Figure 10.21: Socioeconomic benefit for up-regulation and the night block of the sensitivity scenario 1, 2 and 3 in each case study.

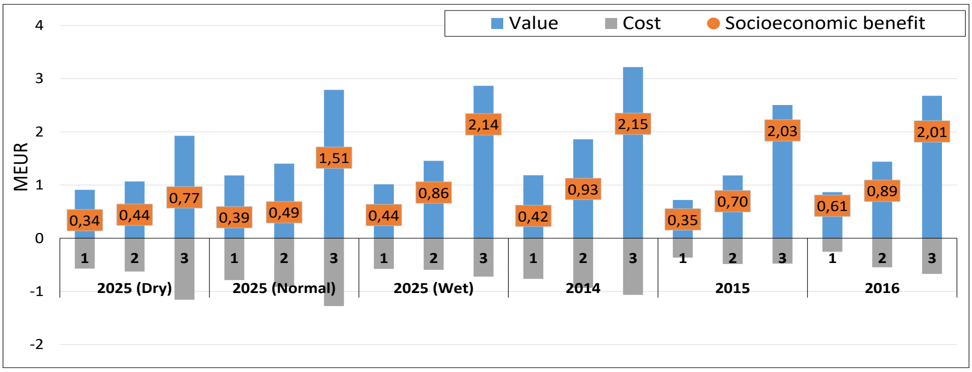

Figure 10.22: Socioeconomic benefit for down-regulation and the night block of the sensitivity scenario 1, 2 and 3 in each case study.

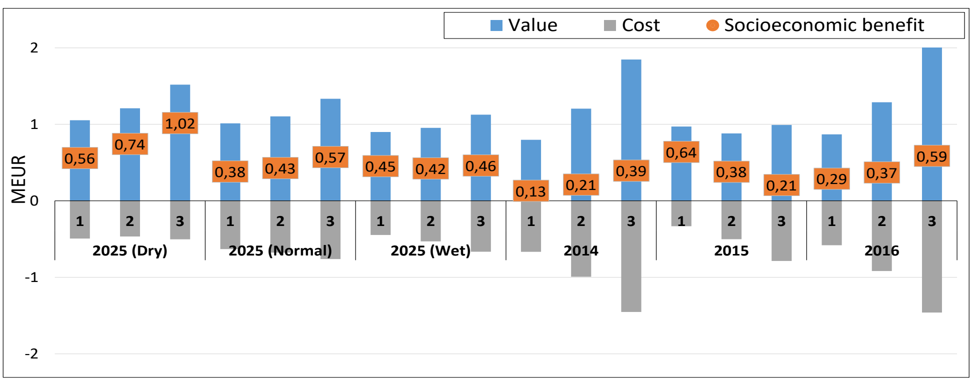

Figure 10.23: Socioeconomic benefit for up-regulation and the day block of the sensitivity scenario 1, 2 and 3 in each case study.

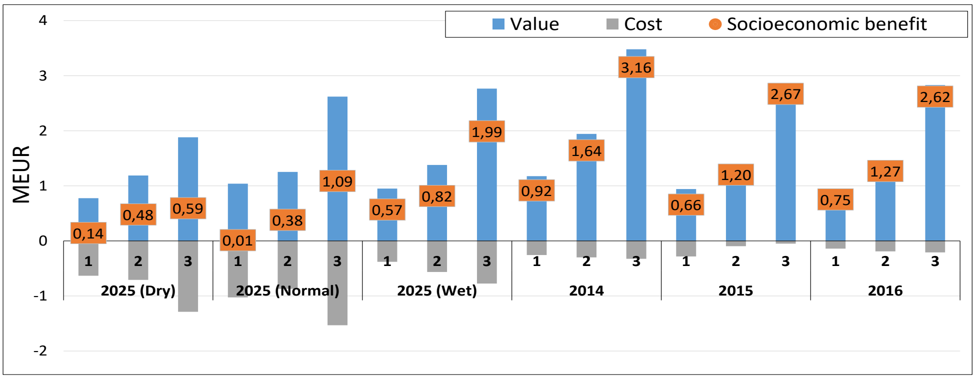

Figure 10.24: Socioeconomic benefit for down-regulation and the day block of the sensitivity scenario 1, 2 and 3 in each case study.

Table 10.7 shows that the total socioeconomic benefit increases as the Norwegian aFRR prices become cheaper and the German aFRR prices become more expensive. Scenario 3 ends up with an average yearly aFRR price equal to 5,31 million euro.

Table 10.7: Accumulated socioeconomic benefit for the different sensitivity scenarios [MEUR].

Case studies	2014	2015	2016	2025 (Dry)	2025 (Normal)	2025 (Wet)
Sensitivity scenario 1	2,86	2,36	2,27	1,79	1,30	1,97
Sensitivity scenario 2	3,95	2,83	3,46	2,60	1,88	2,60
Sensitivity scenario 3	7,29	5,21	6,62	3,64	3,95	5,14

10.2.2 Share of German and Norwegian reservations

When the Norwegian aFRR prices decreases and the German aFRR price increases, subsequently the share of Norway providing aFRR capacity increases, see figures 10.25, 10.26, 10.27 and 10.28. A lower share of Norwegian reservations is observed for the day-block, particularly with up-regulation. This can be due to higher MV of the CZC in DAM in direction NO-GE compared to the night block, and therefore fewer reservations for Norwegian up-regulation are executed.

The case studies 2014, 2025(Normal) and 2025(Wet) achieves the highest increase of Norwegian reservations with down-regulation simulation for both the night and the day block. These are high Norwegian price year, hence there will be a low MV of the CZC in the DAM in direction GE-NO and providing Norwegian down-regulation will be profitable. For down-regulation, the price difference achieved by scaling the bid curves was much less than for up-regulation, see figures in section 10.2.1.

In the previous section the case study of 2015 showed a reduce in socioeconomic benefit while increasing the scaling factor for the sensitivity studies. The case study of 2015 has, as discussed in the previous section, especially low Norwegian

DAM prices during the summer, and above it was shown that providing German up-regulation was extra profitable. Germany is no longer providing the highest share of up-regulation for this case study, and hence, it actually becomes less profitable. The Norwegian DAM prices are assumed to increase, hence the historical case study of 2015 may not be representative for the future market changes.

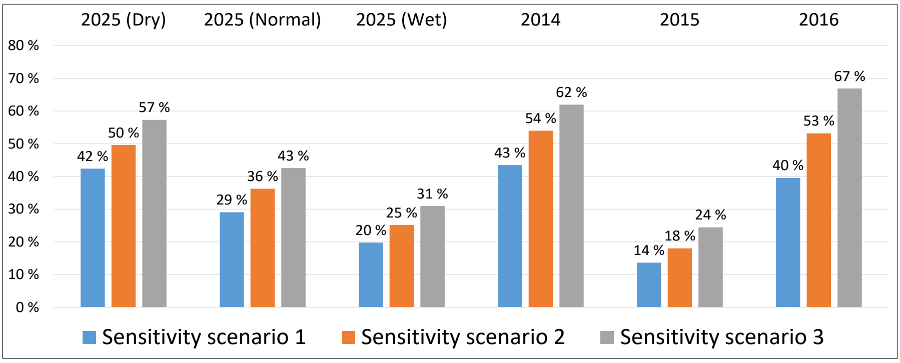

Figure 10.25: Share of Norwegian reservations for up-regulation and the night block of the sensitivity scenarios in each case study. The share is of all the simulations, i.e. of Norwegian, German and non-reservations.

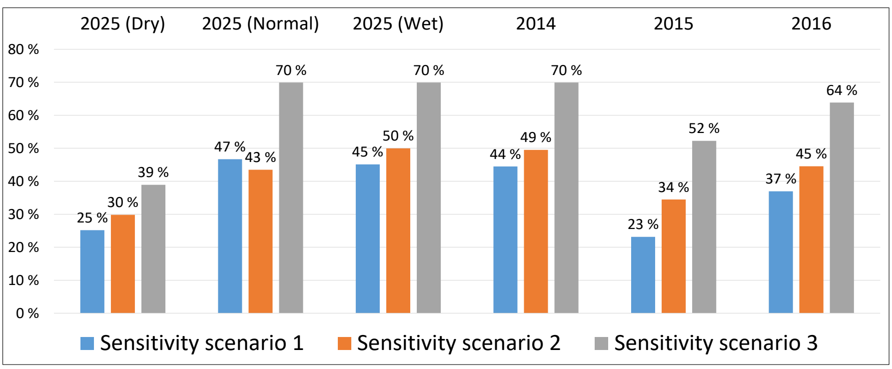

Figure 10.26: Share of Norwegian reservations for down-regulation and the night block of the sensitivity scenarios in each case study. The share is of all the simulations, i.e. of Norwegian, German and non-reservations.

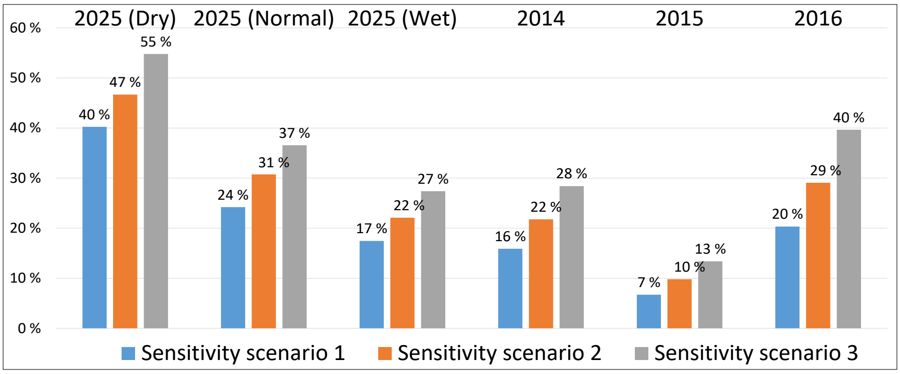

Figure 10.27: Share of Norwegian reservations for up-regulation and the day block of the sensitivity scenarios in each case study. The share is of all the simulations, i.e. of Norwegian, German and non-reservations.

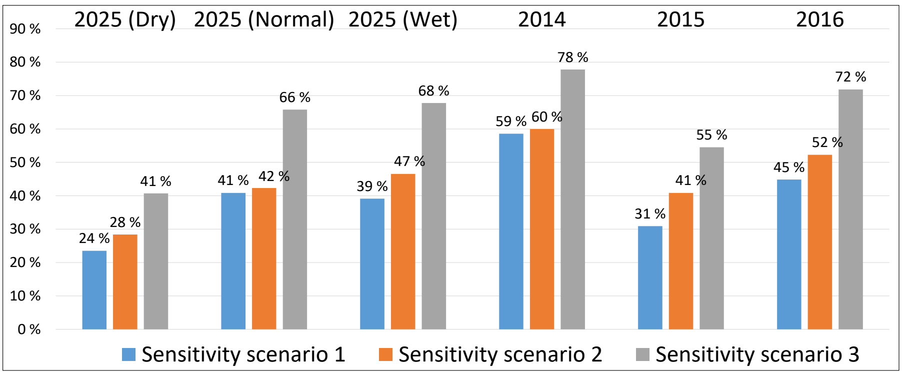

Figure 10.28: Share of Norwegian reservations for down-regulation and the day block of the sensitivity scenarios in each case study. The share is of all the simulations, i.e. of Norwegian, German and non-reservations.

10.2.3 Reservation volume

The reservation volume increases as the scaling factor increases, depict in figure 10.29, 10.30, 10.31 and 10.32. The highest increase with increasing scaling factor is observed for the simulations with down-regulation. The reason for this, is as described above that there are low costs of reservation in direction GE-NO and therefore Norwegian provision of down-regulation is most beneficial. It is important to emphasize that the average will be limited of the 300 MW restriction on CZC reservation. The situations in which it had been beneficial to reserve CZC above 300 MW will decrease the overall average reservation volume.

An important issue is that the German exchange was restricted by the Norwegian demand. Since Germany has a much higher national demand for aFRR the exchange of aFRR from Norway is not restricted, and will have a greater up-side than when Germany is the aFRR providing country.

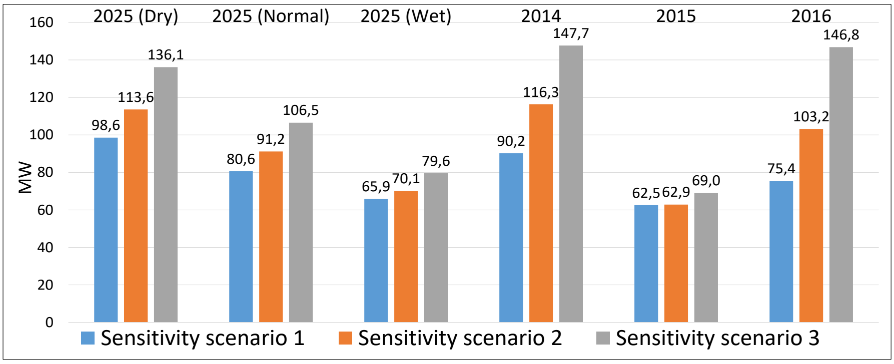

Figure 10.29: Average weekly reservation volume for sensitivity scenario 1, 2 and 3 in each case study. Results are shown for up-regulation and the night block.

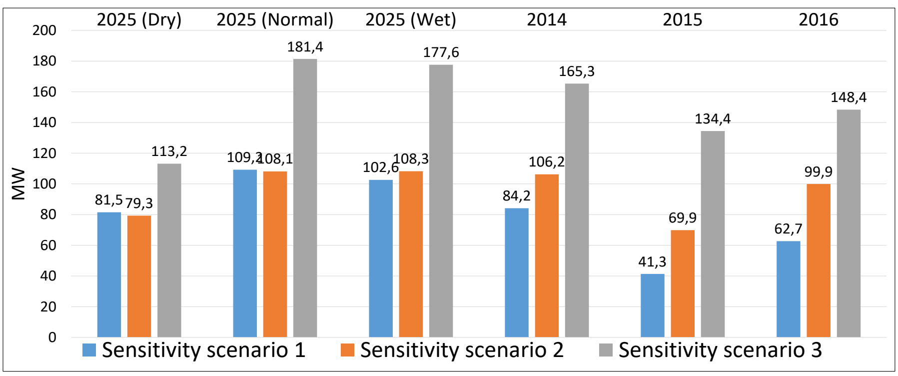

Figure 10.30: Average weekly reservation volume for sensitivity scenario 1, 2 and 3 in each case study. Results are shown for down-regulation and the night block.

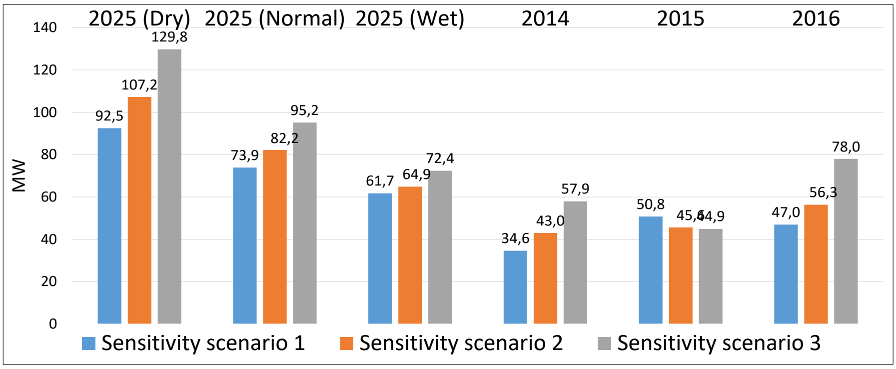

Figure 10.31: Average weekly reservation volume for sensitivity scenario 1, 2 and 3 in each case study. Results are shown for up-regulation and the day block.

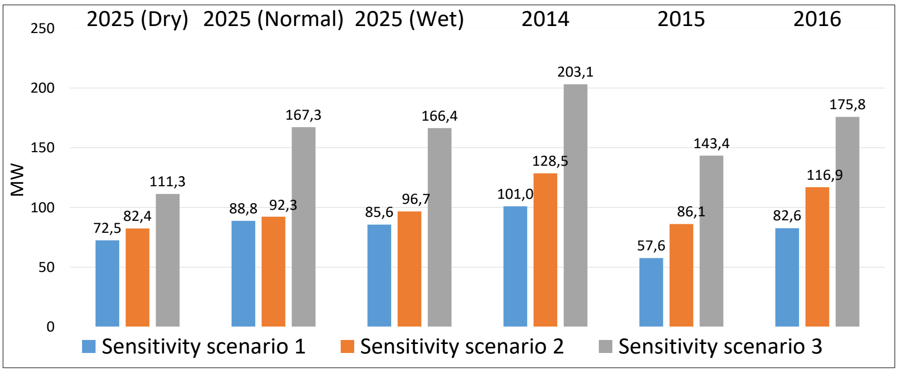

Figure 10.32: Average weekly reservation volume for sensitivity scenario 1, 2 and 3 in each case study. Results are shown for down-regulation and the day block.

Chapter 11

Conclusion and Further Work

This chapter provides a conclusion of the master thesis in addition to recommendation for further work.

11.1 Conclusion

Exchange of balancing services can be an instrument to meet the challenges in the European power system, with a growing share of intermittent renewable resources and increasing demand. In this thesis the possibility of aFRR capacity exchange on NorLink was quantified by simulating case studies of cross-zonal capacity reservation in a market-based model.

The case studies simulated using the base scenario proved that socioeconomic benefit could be achieved with the input data developed and provided in this thesis. A higher potential of achieving socioeconomic benefit was observed for the case studies with lower Norwegian Day-ahead market price.

The historical German aFRR prices were overall lower than the historical Norwegian aFRR prices, resulting in Norway having little potential as aFRR capacity provider. In addition, the socioeconomic benefit was small compared to a previous analysis. The main reason for the low socioeconomic benefit achieved herein was that the German and Norwegian marginal bid prices of exchange were similar.

The Norwegian power mix, with a high share of hydro power, is expected to have a competitive advantage in offering balancing services, due to the regulating capability and flexibility of hydro power. The underlying assumptions of the thesis do not appear to hold, and it is expected that there is a higher potential for Norwegian socialeconomic benefit than identified in this thesis. Quantification of the true value of aFRR capacity proved to be difficult.

A qualitative analysis conducted in this thesis suggests that the main reason for the non-representative results is that the aFRR bid prices provided, and used to generated aFRR bid curves for the case studies, do not appear reflect the true cost of offering balancing capacity. The Norwegian and German aFRR markets are not harmonized and thus the difference in auctioning, pricing methodology and time frames result in different bidding strategies for the producers in the two countries.

The difference in the dependencies between the balancing energy and balancing capacity bidding in the Germany and Norway appears to have the highest impact on the formation of the aFRR prices, and shifts the Norwegian and German aFRR capacity prices in opposite direction.

There are also uncertainties related to the method behind the generation of aFRR bid curves, and this may have contributed to the non-representative simulation results.

A sensitivity analysis was conducted to attempt to capture the trend when the Norwegian aFRR prices became cheaper than the German aFRR prices. Increasing the aFRR price difference between Norway and Germany, resulted in an increasing socioeconomic benefit. Most potential in achieving socioeconomic benefit was demonstrated for aFRR down-regulation capacity provided by Norway. The results of the sensitivity analysis suggests that if the two aFRR markets are harmonized and the Norwegian prices ends up being cheaper than the German prices, as expected, there is a potential of achieving higher socioeconomic benefit than first estimated in this thesis.

11.2 Recommendation for further work

There are two key-improvements that can be recommended for further work on the topic.

The first key-improvement involves improved quantification of the possibility of aFRR capacity exchange on NordLink, which was the aim of this thesis. The input into the reservation model has to be representative, and a way to compared the two capacity markets should be identified. To uncover the true potential of reserving CZC for aFRR capacity, bid curves could be developed with a bottom up approach, revealing the true cost of offering aFRR capacity for the producer.

The second key-improvement, is developing a model that includes additional values of the reservation, such as the value of activated aFRR and imbalance netting, in order to quantify the whole value of the aFRR exchange. When including activation of aFRR in the model the dependencies between the aFRR capacity and aFRR energy bids will be less significant.

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Appendix A

More Detailed Information About the Basis Data Set

Table A.1: Weeks included in the Norwegian basis aFRR data set.

Year	Weeks
2014	35-51
2015	3-26, 32-51
2016	36-52
2017	2-8

A.1 Day-ahead market(DAM)

A.1.1 DAM prices

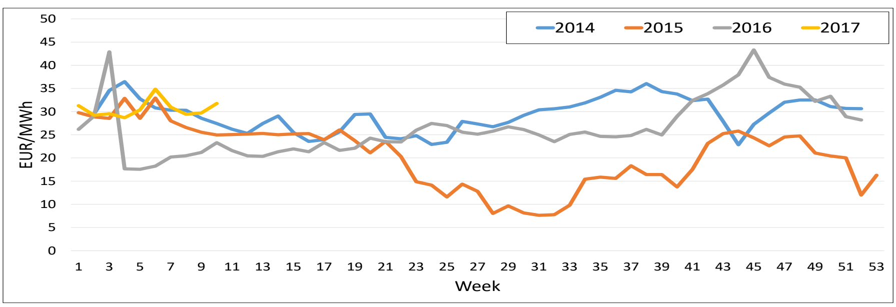

Figure A.1: Norwegian average weekly DAM price for historical years. The DAM price is the average price for all the Bid Zones in Norway.

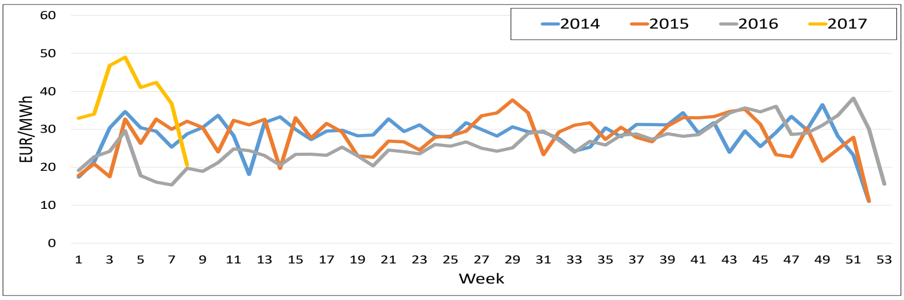

Figure A.2: German average weekly DAM price for historical years.

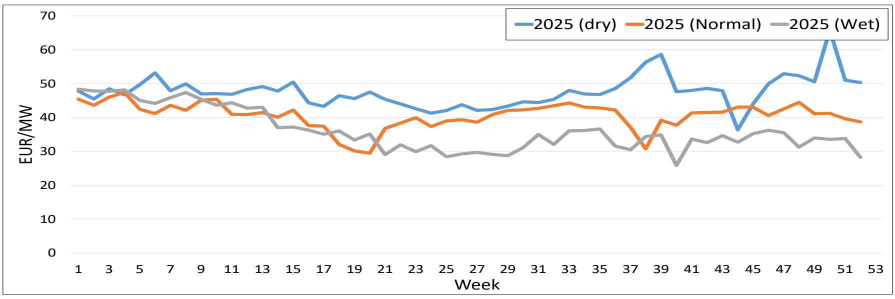

Figure A.3: Norwegian average weekly DAM price for future years. The DAM price is the average price for all the Price areas in the Samlast model.

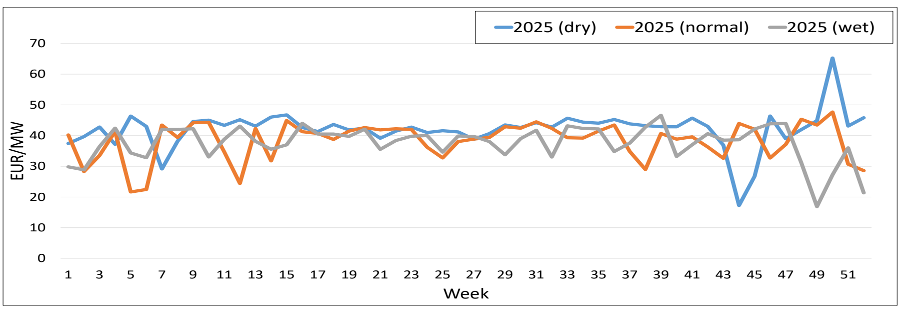

Figure A.4: German average weekly DAM price for future years.

A.1.2 MV of the CZC in the DAM

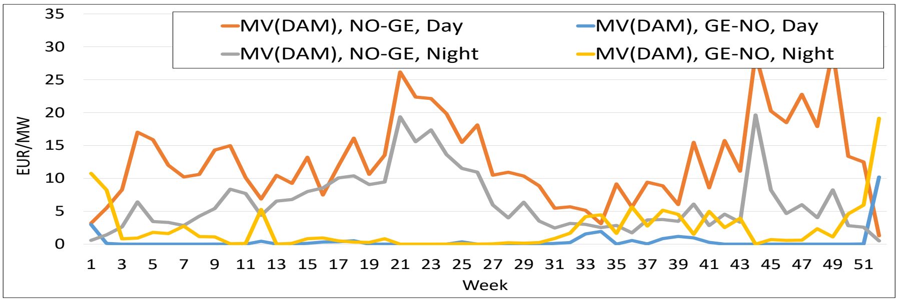

Figure A.5: Estimated MV of the CZC in DAM for case study 2014.

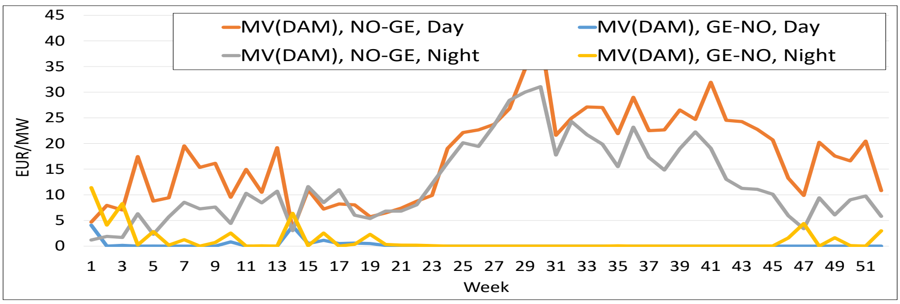

Figure A.6: Estimated MV of the CZC in DAM for case study 2015.

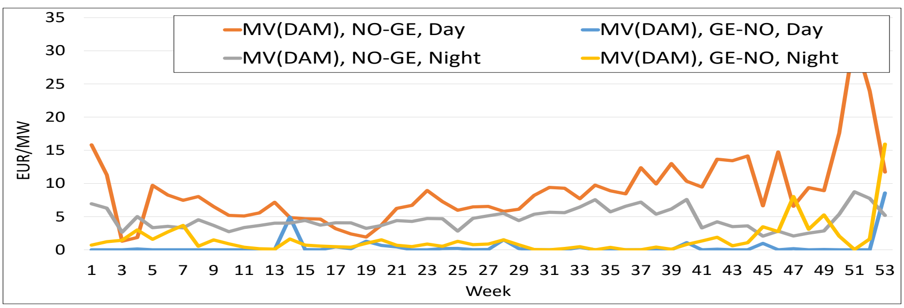

Figure A.7: Estimated MV of the CZC in DAM for case study 2016.

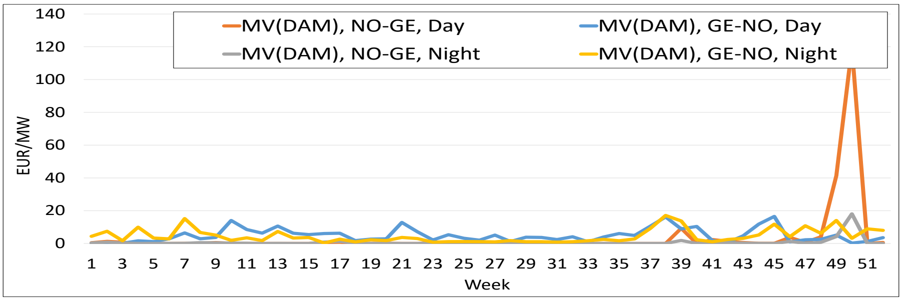

Figure A.8: Estimated MV of the CZC in DAM for case study 2025(Dry).

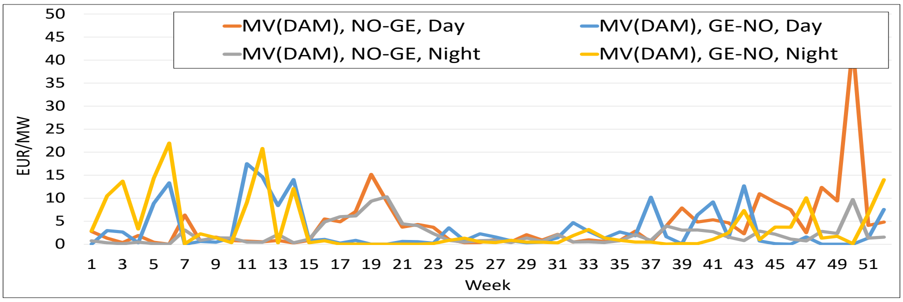

Figure A.9: Estimated MV of the CZC in DAM for case study 2025(Normal).

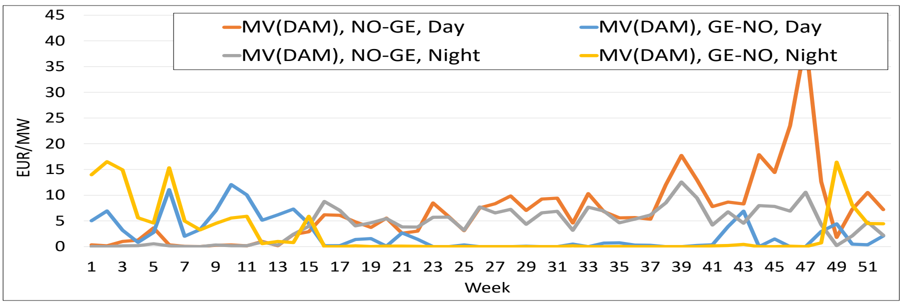

Figure A.10: Estimated MV of the CZC in DAM for case study 2025(Wet).

Appendix B

More Results from Generation of aFRR bid Curves

B.1 Regression results

Not all results are included in the tables, due to space limitations.

Table B.1: Regression result for up-regulation in Norway.

Regression Statistics					
Multiple R	0.82984526361578659				
R square	0.68864316154555438				
Adjusted R square	0				
Standard Error	2.4538023180738899				
Observations	78				
ANOVA					
	df	SS	MS	F	Significance-F
Regression	3	985.47745877670786	328.4924862589026	54.556474180697833	1.0304760482949602E-18
Residual	74	445.56479039767487	6.0211458161847959		
Total	77	1431.0422491743827			
	Coefficients	Standard Error	t-Stat	P-value	
Intercept	46.544246823382537	5.9144178277500918	7.8696243956589838	2.2843737288563373E-11	
DAM	-2.6734083809446827	0.77510008821336152	-3.4491137616910894	9.3184583232410422E-4	
DAM square	6.3769052837481535E-2	3.2011671649955838E-2	1.9920563204192903	5.0054603368955231E-2	
DAM cube	-4.7591189939214591E-4	4.1922009794905201E-4	-1.1352315924748047	0.25994193476399674	

Table B.2: Regression result for down-regulation in Norway.

Regression Statistics					
Multiple R	0.88923759968953819				
R-kvadrat	0.79074350870161136				
Justert R-kvadrat	0.7822601374327578				
Standard error	2.1802818243521895				
Observasjoner	78				
ANOVA					
	df	SS	MS	F	Significance-F
Regression	3	1329.271473740785	443.09049124692837	93.210998745840456	4.534833929891024E-25
Residual	74	351.76853368643788	4.7536288336005121		
Total	77	1681.0400074272229			
	Coefficients	Standard Error	t-Stat	P-value	
Intercept	56.179241469261157	5.2551493641060834	10.690322496441054	1.159332809818322E-16	
DAM	-3.8070988979135647	0.68870121359730618	-5.5279398710913723	4.6281481229765372E-7	
DAM square	0.10314388973935835	2.8443393891776126E-2	3.6262863050664453	5.253594370073527E-4	
DAM cube	-9.2110945146407102E-4	3.7249046234454628E-4	-2.4728403666133687	1.570062785577955E-2	

Table B.3: Regression result for up-regulation and the night block in Germany.

Regression Statistics					
Multiple R	0.42368655407988781				
R-square	0.17951029610808972				
Adjusted R-square	0.15860609983058882				
Standard error	3.1352869102078209				
Observation	162				
ANOVA					
	fg	SK	GK	F	Signifance-F
Regression	4	337.65288026155326	84.413220065388316	8.587285238098147	2.7131588836338379E-6
Residual	157	1543.313769463319	9.8300240093205034		
Total	161	1880.9666497248722			
	Coefficients	Standard Error	t-Stat	P-value	
Intercept	48.665070942156433	8.7426193773685679	5.5664176651830957	1.0998768183271356E-7	
DAM night	-3.7686216353238082	0.90481038831911631	-4.1650954542253311	5.120594449074469E-5	
DAM night square	0.11981186086346529	3.1197544308522625E-2	3.8404260181060077	1.7780945171243419E-4	
DAM night cube	-1.2726458818299027E-3	3.4721626455316466E-4	-3.6652830289147911	3.3754514413787982E-4	
Wind Night	-2.5934302940969672E-4	6.8775348455898364E-5	-3.7708719073375301	2.2995232372102265E-4	

Table B.4: Regression result for down-regulation and the night block in Germany.

Regression Statistics					
Multiple R	0.52996394278531844				
R-square	0.28086178065256023				
Adjusted R-square	0.26253978780294396				
Standard error	3.713447715450279				
Observation	162				
ANOVA					
	fg	SK	GK	F	Signifance-F
Regression	4	845.54077171284553	211.38519292821138	15.329215711294314	1.3255549086046535E-10
Residual	157	2164.9819478551144	13.789693935382894		
Total	161	3010.5227195679599			
	Coefficients	Standard Error	t-Stat	P-value	
Intercept	71.565226941569279	10.488643877558784	6.8231153404577194	1.8260107475078056E-10	
DAM Night	-6.8693681513824094	1.0654401406605409	-6.4474463550093084	1.3337437268052122E-9	
DAM Night square	0.21935506949631112	3.7055811181324484E-2	5.9195862269198534	1.9625803159004777E-8	
DAM Night Cube	-2.2598110232405631E-3	4.1263942114003194E-4	-5.4764787547374958	1.688367299849975E-7	
Consumption Night	1.7152924829932335E-2	4.9024449047258542E-2	0.34988511167962894	0.72689383599183555	

Appendix C

Results of Simulation in the Market-based Reservation Model

C.1 Base scenario

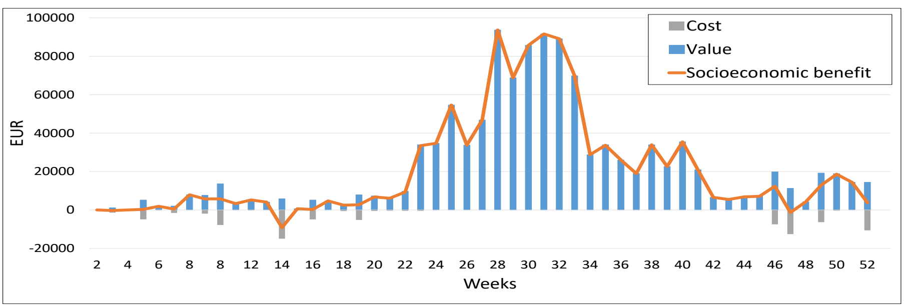

Figure C.1: Socioeconomic benefit for up-regulation with the basis scenario for the case study 2015 and Germany as the aFRR providing country.

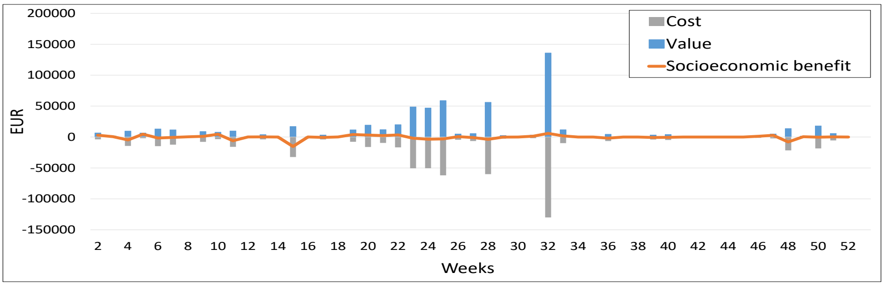

Figure C.2: Socioeconomic benefit for down-regulation with the basis scenario for the case study 2015 and Germany as the aFRR providing country.

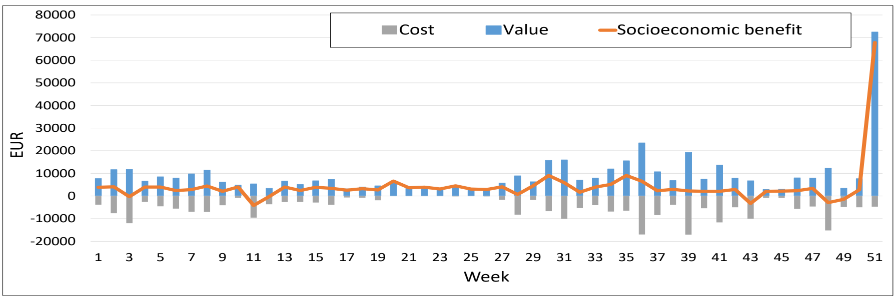

Figure C.3: Socioeconomic benefit for up-regulation with the basis scenario for the case study 2014 and Norway as the aFRR providing country.

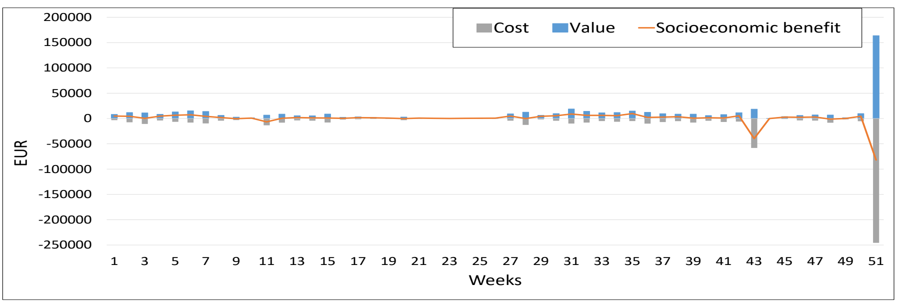

Figure C.4: Socioeconomic benefit for down-regulation with the basis scenario for the case study 2014 and Norway as the aFRR providing country.

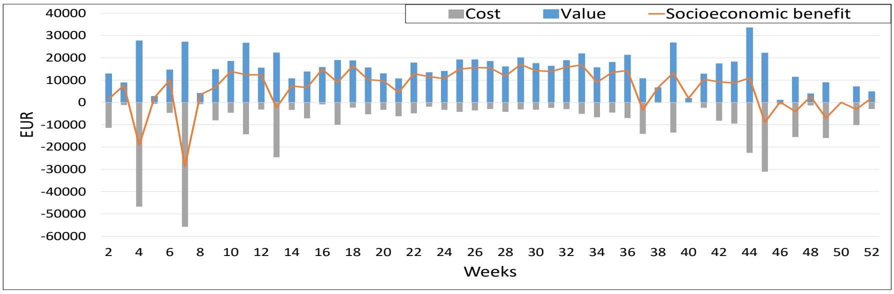

Figure C.5: Socioeconomic benefit for up-regulation with the basis scenario for the case study 2025(Dry) and Norway as the aFRR providing country.

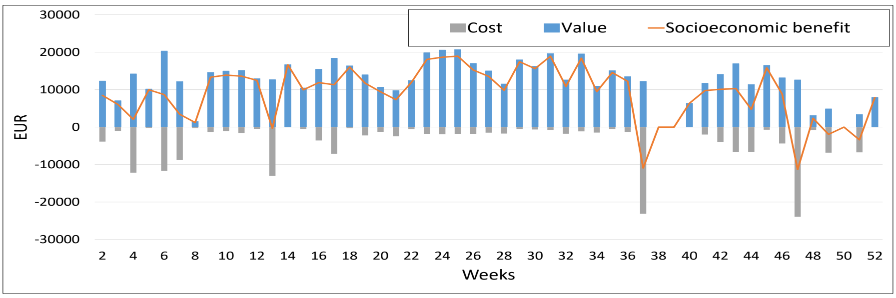

Figure C.6: Socioeconomic benefit for down-regulation with the basis scenario for the case study 2025(Dry) and Norway as the aFRR providing country.

C.2 Sensitivity analysis

C.2.1 Scaled bid curves

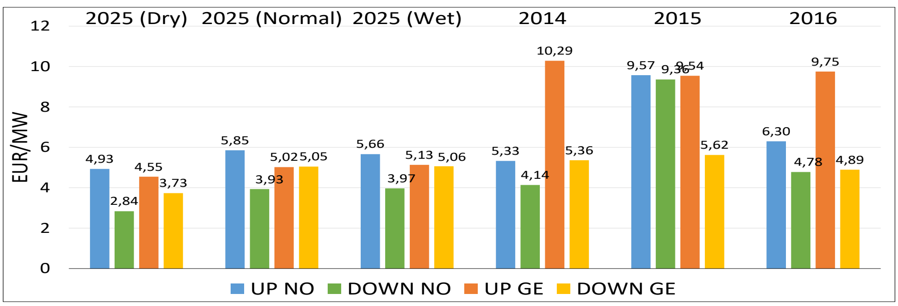

Figure C.7: Average aFRR bid price at the national obligation volume for sensitivity scenario 1.

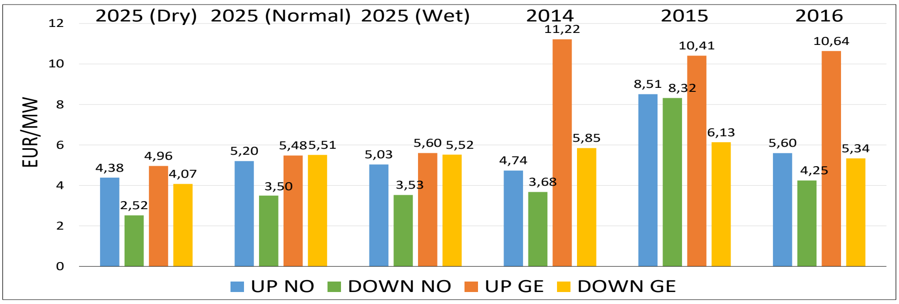

Figure C.8: Average aFRR bid price at the national obligation volume for sensitivity scenario 2.

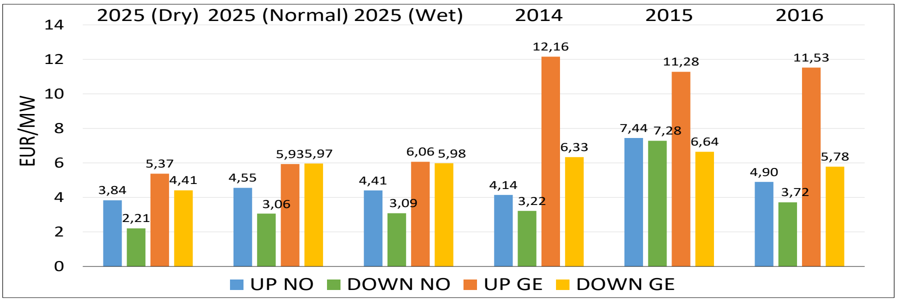

Figure C.9: Average aFRR bid price at the national obligation volume for sensitivity scenario 3.

Appendix D

E-mail Correspondence

Email correspondance with Ceceilie Seem at Statnett copy pasted 10:23 14.06.2016:
Hei Ellen,

Under følger en kort beskrivelse av analysen bak estimatet for verdi av handel med balansetjenester med Tyskland over NordLink oppgitt i Verdiskapningsrapporten for 2016.

Analysen ser på merverdien av handel med aFRR på NordLink. Merverdien på 150 MNOK er estimert med utgangspunkt i historiske markedsdata fra 2012 og 2013. Estimatet er basert på dynamisk allokering i steg på 50 MW opptil 300 MW. Det var en forutsetning i analysen å være reservert for å kunne bli aktivert, i tråd med gjeldende markedsdesign i begge land. Analysen tar dermed høyde for mulige prisingsinsentiver som følge av det. Det er sett på verdien av netting, aktivering og reservasjon. Estimatet er et resultatet av den kvantitative analysen og kvalitative vurderinger. Det at verdien av reservasjon og aktiveringen ble sett under ett, innebærer at det er mulig at det blir eksport fra Norge selv om kapasitetsprisen er lavere i Tyskland, hvis aktiveringen er tilstrekkelig mye gunstigere priset i Norge.

Kort om funnene i analysen. Inntektene fra aktiveringer bidrar med den største delen av verdiskapningen. Det er tråd med funnene i analysen til konsesjonssøknaden for NordLink (og NSL), slik vist i figur 1 i kapittel 6.1.1 i denne. Videre lå den største verdien i salg av balansetjenester fra Norge til Tyskland (norske aFRR leverandører leverer opp- eller nedregulering). Det siste henger nært sammen med at det er aktiveringsinntekten som bidrar med den største delen av verdiskapningen. Slik vist i figur 6 i Verdiskapningsrapporten (selv om figuren viser priser for en dag i 2016) er det en stor prisdifferanse mellom Norge og Tyskland på aktiveringsprisene, hvor prisene i Norge er klart gunstigere.
Håper overstående er til nytte for oppgaven!
Hilsen Cecilie
Rådgiver
System- og balansetjenester
Divisjon Drift og marked, System- og markedsutvikling