Modeling the Dutch Frequency Restoration Reserve Market

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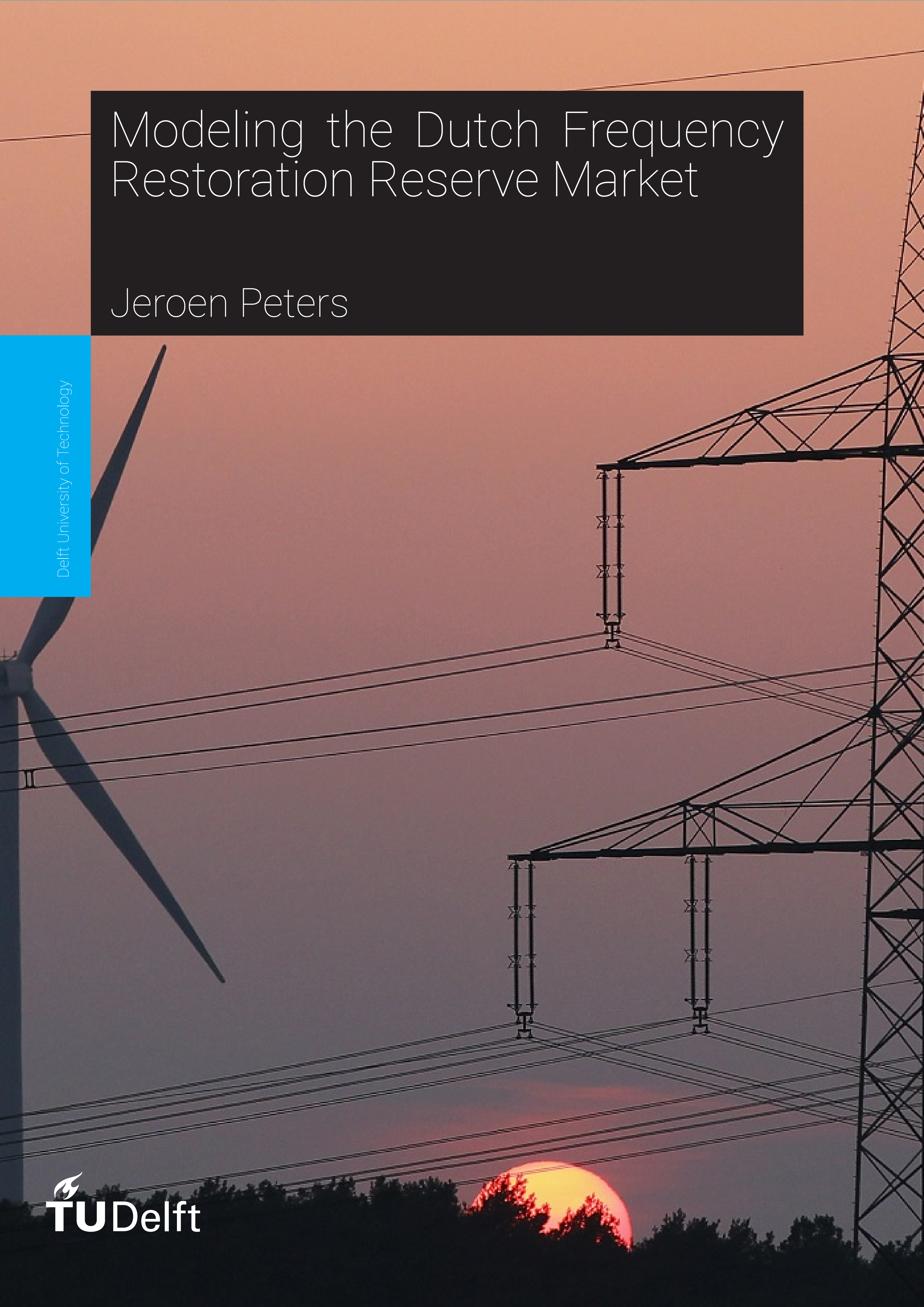

Modeling the Dutch Frequency Restoration Reserve Market

by

Jeroen Peters

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Summary

With an expected growth of renewable energy sources, the amount of variable and weather-dependent energy input to the electricity system increases. This is a growing source of deviations between day-ahead forecasts and the realisation on time of delivery. On the other hand, new sources of flexibility (demand response, storage, EV, wind curtailment) are being developed. Modeling electricity markets is becoming increasingly complex with more interconnection, stochastic inputs and smarter optimization methods.

The aim of this research project was to create a model for the Dutch Frequency Restoration Reserve (FRR) market in the Netherlands. With this model scenarios were tested extending to 2030. This was done by looking at the fundamentals of this market, expected future developments, development of a computational model and assessment of improved wind forecast accuracy, wind curtailment and large scale storage scenarios.

Combining spot market unit commitment data from Eneco scenarios with unit constraints on ramping, the available flexibility capacity was calculated for every Program Time Unit (PTU). Using this capacity and its cost price, a bidding mechanism was used to establish a merit order for the available flexibility. Bidding was modelled to reflect profit optimization and validated with historic FRR market prices and volumes. The historic FRR data was taken for PTUs with a spot market price comparable to the expected spot price market. This was done to ensure differentiation between days of the week and time of the day. Linear price elasticity was included to reflect the effect of offering a volume on market prices. Furthermore, the effects of market participation on its own imbalance costs were taken into account.

Storage and wind curtailment were shown to have an enormous impact on the availability of flexibility to the market and to market pricing. Wind curtailment will limit prices on the down regulating direction. While its availability coincides with wind production, it was shown in Chapter 4 that its availability is less than for storage. Improvements in VRES forecasting will have a much smaller impact.

Through capacity contracts the Dutch TSO ensures capacity to provide both upward and downward regulating energy. Moving towards smaller periods for contracting, could enable more participants to become active in the market.

The most important uncertainties for the future development of the FRR market are international harmonization and integration and liquidity of intraday and balancing markets as reviewed in Chapter 5. Combined with new forms of flexibility, this could lead to a different pricing regime than observed in the current scenarios.

Preface

Life is complex: it has both real and imaginary components

- Rich Rosen

Finishing my thesis marks the end of a period of studies at the Delft University of Technology. A period in which I've learned a lot about science, technology and myself.

Many colleagues at Eneco contributed with their expertise and enthusiasm to the final product here before you. My special gratitude goes towards my direct colleagues at Fundamental Analysis. The discussions we had helped me shape my view on future energy markets. I look forward to continue working with you guys!

Working with an insightful group of supervisors motivated me highly. The meetings with Paulien Herder, Martijn Warnier, Derk Straathof and Remco Verzijlbergh kept me on track during the project. Weekly meetings with the latter two, were a source for challenging discussions that helped me to get the right questions asked. Their supportive attitude made our collaboration pleasant.

This project hurled me into the world of electricity markets. I am grateful for the opportunity to continue this journey after my graduation in a joint research project with Eneco and TU Delft.

Finally, I want to thank my lovely wife Marijke, your relentless love means a lot to me!

Jeroen Peters
Berkel en Rodenrijs, October 2016

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Nomenclature

Abbreviations

$aFRR$	Automatic Frequency Restoration Reserve (also denoted as secondary reserves or R2)
BRP	Balance Responsible Party
$CAES$	Compressed Air Energy Storage
CHP	Combined Heat and Power
DSM	Demand Side Management
DSO	Distribution System Operator
EV	Electric Vehicles
FCR	Frequency Containment Reserve (also denoted as primary reserves, PCR or R1)
IDM	Intraday Market
$IGCC$	International Grid Control Cooperation
LFC	Load Frequency Control
MCP	Market Clearing Price
$mFRR$	Manual Frequency Restoration Reserve (also denoted as tertiary reserves or R3)
$P2H$	Power to Heat
PRP	Programme Responsible Party
PTU	Programme Time Unit
PV	Photovoltaics
RR	Replacement Reserve
SMP	System Marginal Price
$SRMC$	Short Run Marginal Cost
TSO	Transmission System Operator
$VRES$	Variable Renewable Energy Sources

Functions

$\delta(x, y) = \begin{cases} 0, & x \neq y \\ 1, & x = y \end{cases}$ Kronecker delta function

$u(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases}$ Heaviside step function

Parameters

ϵ^{+} Price elasticity for upward regulation

ϵ^{-} Price elasticity for downward regulation

$\lambda^{+}_{st\omega}$ System price of upward regulation in a PTU [EUR/MW]

$\lambda^{-}_{st\omega}$ System price of downward regulation in a PTU [EUR/MW]

$\lambda^{mid}_{st\omega}$ Average of lowest price in upward direction and highest price in downward direction in a PTU [EUR/MW]

$C^{+}_{gt\omega}$ Cost price of upward regulation for BRP g [EUR/MW]

$C^{-}_{gt\omega}$ Cost price of downward regulation for BRP g [EUR/MW]

$P^{ACT}_{gt\omega}$ Actual power produced in a PTU [MW]

$P^{DA}_{gt\omega}$ Day-ahead forecast of power produced in a PTU [MW]

$R_{gt\omega}$ BRP revenue from imbalance and regulation [EUR]

$S_{st\omega}$ Imbalance regulating state in the system -1, 0 or 1

$V^{+}_{st\omega}$ Upward imbalance in a PTU [MW]

$V^{-}_{st\omega}$ Downward imbalance in a PTU [MW]

Indexes and Sets

ω Scenario, from 1 to Ω

g Balancing Responsible Party and/or Balancing Service Provider, from 1 to G

s System

t Time period, from 1 to T

Variables

$\lambda^{+}_{gt\omega}$ Bid price of upward regulation in a PTU [EUR/MW]

$\lambda^{-}_{gt\omega}$ Bid price of downward regulation in a PTU [EUR/MW]

$F^{+}_{gt\omega}$ Flexibility bid volume in upward regulation [MW]

$F^{-}_{gt\omega}$ Flexibility bid volume in downward regulation [MW]

RR_{PTU} Ramprate of an asset in [%/PTU]

1

Introduction

With an expected growth of renewable energy sources, the amount of variable and weather-dependent energy input to the electricity system increases. This is a growing source of deviations between a day-ahead forecast and the realisation on time of delivery. On the other hand, new sources of flexibility are being developed. This will result in changes to the whole electricity system.

The balancing market in the Netherlands is currently divided in multiple parts based on size and timescale of interaction. This master thesis project will focus on modeling of the Dutch Frequency Restoration Reserve market up to 2030.

In the following paragraphs the research drivers, questions and objectives will be given. The last section will give a short outline of the report structure.

1.1. Social context & research drivers

This research was done as graduate intern at Eneco, a Dutch utility company. Eneco aims to differentiate itself from competitors by setting decentralized sustainable electricity for everyone as its main goal.

For Eneco, flexibility is a both a threat and opportunity. Firstly, their generation portfolio is exposed to imbalance costs. Growing volumes of VRES (wind and solar PV) increase the spread between their day-ahead forecast volumes and the actual production and demand. To better hedge this risk Eneco needs to develop a better understanding of future scenarios for balancing markets.

Secondly it has the opportunity to develop its role as provider and aggregator of flexibility. Currently, coal and gas powered thermal plants are used as the main providers of flexibility in the Dutch FRR market. In the future increased integration of renewables and decentralized assets is expected. Eneco is partnering with startups like Peeeks and Jedlix to aggregate large cooling facilities, greenhouses and electric vehicles. CHPs and wind curtailment are already used in the balancing portfolio [1].

1.2. Knowledge gap

There are various authors that have modelled balancing markets. In [2] a thorough description is given on the operational implication of the integration of renewables in electricity markets. Chapter 4 of [2] gives a theoretical framework for the working of balancing markets. In [3] an extended overview of the implications of renewable energy integration is given with a good overview on the operational side.

Looking at the price maker perspective, [4] introduces a framework for wind producers that are price takers in the day-ahead market and price makers in the balancing market. It focuses on optimizing the split of volume to be procured in the day-ahead and balancing market leaving out the intraday markets. They assume that producers whose marginal costs are below day-ahead price are dispatched and those who offer at higher costs are not dispatched. This assumption is too simplistic, considering start-stop costs of thermal power plants. Start-stop costs can result in underbidding periods to prevent a start-stop between two profitable periods.

Modeling the German balancing markets is done in [5, 6]. The German FRR market, called SRL, uses a combination of capacity and energy payments. Balance responsible parties weekly place combined capacity and energy bids for peak and off-peak hours [7]. First, the lowest capacity bids are selected in a pay as bid auction. From the accepted capacity bids, the respective energy bids are sorted by their energy price. Balancing providers that are called upon, receive the energy price of their bid for the volume of energy delivered. The opportunity costs or must-run losses are reflected in the capacity bid, the short run marginal costs of the producers in the energy bid. Multiple researchers indicate that gaming might take place due to the low amount of market participants and high repetition of pay as bid actions [8, 9].

Zooming in on the German balancing market, [10] looks at three relations between VRES and balancing. Firstly, it looks at the impact of VRES on the balancing reserve requirements. Secondly, the supply of balancing by VRES generators is looked at. Thirdly, the impact of imbalances prices on forecast improvements is discussed. They conclude that the impact of increased VRES is less dramatic than sometimes believed, with a moderate increase of prices and volumes at best. Entry barriers by market design prevent the optimal usage of VRES as source of flexibility.

In [11] the impact of the variability of VRES on the power system and thermal plants are discussed. A large scale wind integration results in a 4 % reduction in their efficiency. Increased necessity of reserves results in added costs between €1 and €6 per MWh for wind, solar PV an wave power. Furthermore they identify the need for a more comprehensive system model with a time step of less than one hour and inclusion of detailed production, flexibility and interconnection constraints and availability profiles.

A recent report, published on behalf of Agora Energiewende [12], reviews short-term electricity markets in the Pentalateral Energy Forum (PLEF) region consisting of Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland. They come to four main findings:

- Short term markets in Central Western Europe have inefficient combinations of flexibility enabling and disabling design elements.
- The markets are currently biased against DSM and vRES.
- Inefficiencies occur due to lack of market harmonisation across the region.
- Cross-border intraday trading needs reform to enhance liquidity and improve efficiency.

One of their conclusions is that efficient pricing in the balancing markets and imbalance settlement is key in facilitating efficient resource allocation in the preceding day-ahead and intraday markets.

Cross-border integration and harmonization of balancing markets has been studied by multiple authors [12–18]. A quite extensive study into this topic can be found in [14]. The author finds that security of supply and economic efficiency are the two fundamental criteria of the operation of balancing markets. Different levels of cross-border integration arrangements are given, ranging from imbalance netting to using a common merit order list. While using a common merit order list could result in cost reductions up to 30 %, technical barriers may be substantial requiring further harmonisation as a prerequisite. According to [14], especially wind power integration will drive balancing market integration.

Looking at the interaction between participant behaviour and system behaviour in markets, agent based modeling can be used. Agent based modeling of day-ahead markets has been done with success[19]. In this study, every week agents optimize their portfolio and offering to day-ahead and balancing markets. Based on their optimized offer in an iteration, all agents get new information on the market volume and price. Between

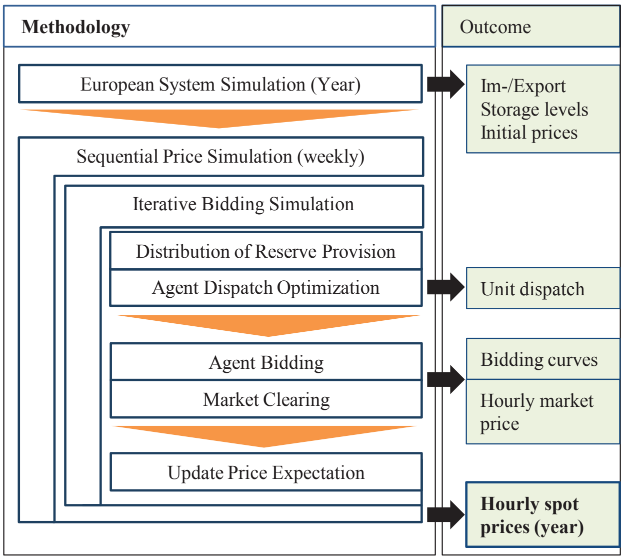


Figure 1.1: Methodology used by [19] for agent based optimization to simulate day-ahead electricity prices in Germany

cycles information about the training and results of older cycles is transferred for learning. In Figure 1.1, an overview is given of the methodological steps used in this method. A big difference between day-ahead and Frequency Restoration Reserve market is the ability to forecast the procured volume. With forecasted demand and production profiles for the week ahead, agents can make an educated guess which volumes and prices to expect on the day-ahead market. For the FRR market it is not possible to forecast volumes and prices that accurate.

To my knowledge, studies on future energy prices in the Dutch FRR market are currently missing. This study will aim to reduce this knowledge gap by modeling future energy prices in the FRR market. This will be done assuming profit optimization in the balancing market and modelled day-ahead prices as input.

1.3. Research questions

Deriving from the above mentioned background the following research question was formulated:
How will the Dutch Frequency Restoration Reserve market develop till 2030 in the Netherlands?

The answer to this question will be sought via the following structure of subsequent questions:

1. What are the fundamentals of this market?
2. How can we model the Dutch Frequency Restoration Reserve market?
3. How will imbalance develop in the future in terms of volume and price?
4. What is the impact of improved wind forecast accuracy, wind curtailment and large scale storage on this market?

1.4. Research objectives

To translate the research questions into achievable goals, research objectives were defined. The main objective was to model the Dutch Frequency Restoration Reserve market to gain both quantitative and qualitative insights about possible scenarios in its future. To accomplish this goal, a set of sub-objectives were defined. The sub-objectives are to model:

- imbalance sources

- flexibility capacity availability
- a market bidding and pricing system
- improved wind forecast accuracy, wind curtailment and large scale storage

1.5. Research method & project deliverables

For the Dutch Frequency Restoration Reserve market, the effects of integrating more renewables into the electricity system or participation by large scale storage are unknown. In this study these effects are modelled while assuming markets participants are optimizing their profit on both costs and historical prices.

The deliverables of this project consists of two parts. The first part consists of a model of the FRR market that can be used at Eneco to asses the impact of different scenarios. The model was made with the purpose of scenario assessment, showing the impacts of a number of scenarios. A stylized version of reality was modelled using the assumptions as listed in Appendix A. This also means that the model is not made to create results that are a perfect representation of reality but rather made to show the implications of certain scenarios under given assumptions.

Secondly, the report lying before you is the other deliverable of this project. In this report the market and modeling approach are described and a number of scenario are assessed.

1.6. Outline

In Chapter 2, the working of balancing markets in Europe will be explained. The modelling approach is explained in Chapter 3. Results for a base case and the scenarios are given in 4. Continuing, Chapter 5 gives limitations, improvements and recommendations. Concluding, Chapter 6 will highlight the most important results trough answering of the research questions. Chapter 7 gives a description of research process on a meta level. It includes personal remarks on the process, failures made and skills learned.

2

Balancing markets

Although the existence of market power must not necessarily cause its exercise,
it clearly offers opportunities to behave strategically.
- Sven Heim & Georg Götz in [9]

This chapter will describe the technical necessity for balancing the grid and the economical framework of balancing. A more detailed look is taken into the Dutch Frequency Restoration Reserve market.

2.1. Electricity market design

Balancing markets are part of a larger electricity trading scheme. In the Netherlands the electricity market can be roughly split up into four categories: forward markets, day-ahead market, intraday markets and balancing markets. Figure 2.1 gives an overview between the different electricity markets. In the Netherlands, the electricity market can be roughly split up into four categories: forward markets, day-ahead market, intraday markets and balancing markets. In forward markets power is traded for years and months ahead. This provides an opportunity for both the demand and supply side to hedge their positions, reducing the risks of price volatility. The remaining part of demand and supply is matched via the day-ahead market. At this stage, producers offer power based on their forecasted production of VRES and availability of thermal plants. After Gate Closure Time (GTC) the day-ahead market is cleared and Program Responsible Parties (PRPs) schedule the dispatch of their production units. Updated weather forecasts or changes in dispatch schedules can creat the necessity to trade power after GTC of the day-ahead market. PRPs can do this either bilateral or through an intraday platform. For the purpose of this thesis we zoom in the last stage of chain of markets, the balancing market.

2.2. Load-frequency control & balancing markets

Unlike other forms of energy, electricity demand and supply needs to be matched in real time. To do this, either steerable demand and supply or storage are needed. When demand and supply are not matched, the frequency will deviate from the rated frequency. In Europe the grid frequency is 50 Hz [10, 20]. The variation from system frequency is defined as, with f_n being the rated frequency:

$$\Delta f = f - f_n \tag{2.1}$$

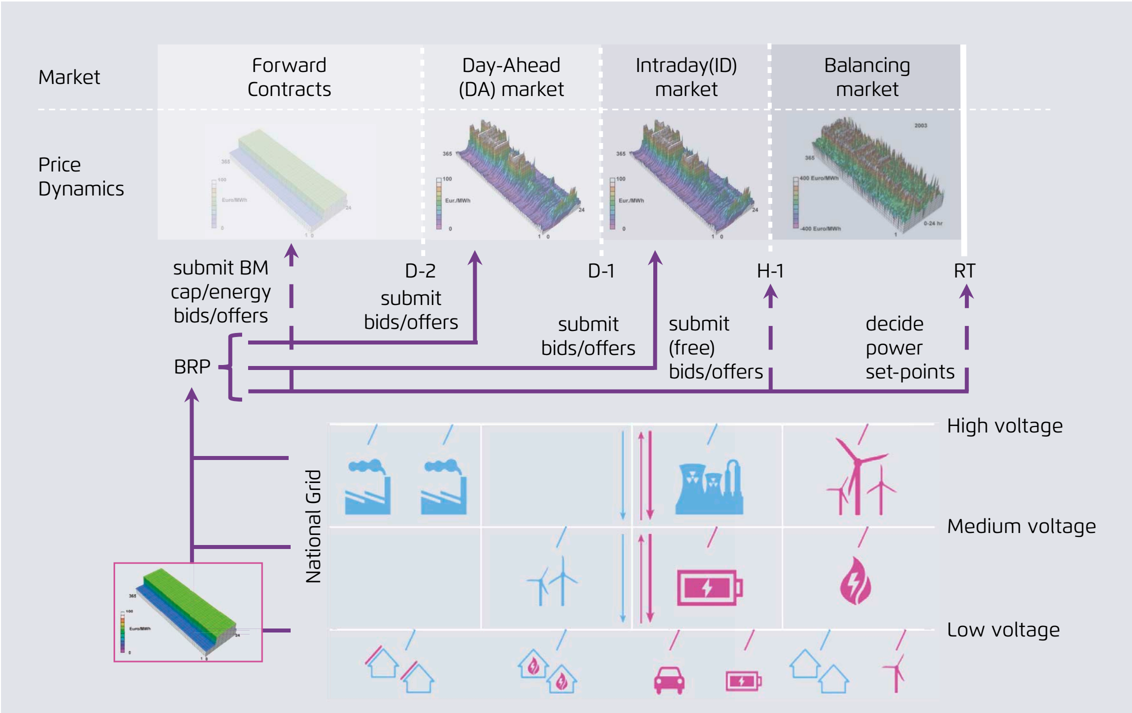


Figure 2.1: Time sequence of electricity markets showing the increased volatility from long term contracts towards the balancing market from [12].

Each synchronous area has a network power frequency characteristic:

$$\lambda_u = \frac{\Delta P_a}{\Delta f} \tag{2.2}$$

This characteristic defines the relation between power deviation ΔP_a and the frequency deviation Δf. Transmission System Operators (TSOs) are entrusted with the task to keep the frequency within predetermined bandwidths. Constant monitoring and balancing of the total input and output of power to the system is therefore required. In Europe, these bandwidths and the load-frequency control mechanisms are defined by ENTSO-E[20, 21]. Figure 2.2 shows the interactions between the different control mechanisms using the old terminology for FCR (primary control), aFRR (secondary control), mFRR (tertiary control) and RR (time control).

2.2.1. Frequency Containment Reserve

When a mismatch between demand and supply occurs the frequency deviates. Frequency Containment Reserves (FCR), also known as R1, are the first to restore balance by means of automatic frequency control. These reserves act simultaneously in the whole synchronous area, irrespective of their Load Frequency Control (LFC) area. Dimensioning of these reserves is done based on the ability to compensate for 3000 MW of generation or load losses while keeping the absolute frequency deviation within 200 mHz[22]. FCR units have a full activation time, the between deviation occurrence and full deployment, of 15 seconds for deviations up to 1500 MW. For deviations up to 3000 MW, this is 30 seconds.

Every control area must contribute with its respective contribution coefficient. This is calculated by dividing energy produced in a control area divided by total energy produced in all control areas. For the Netherlands, this results in the obligation of contracting 93 MW. This volume of FCR is auctioned on a weekly basis in a pay as bid auction. A large share of the volume, around 70 %, is auctioned in a common auction together with Germany [12].

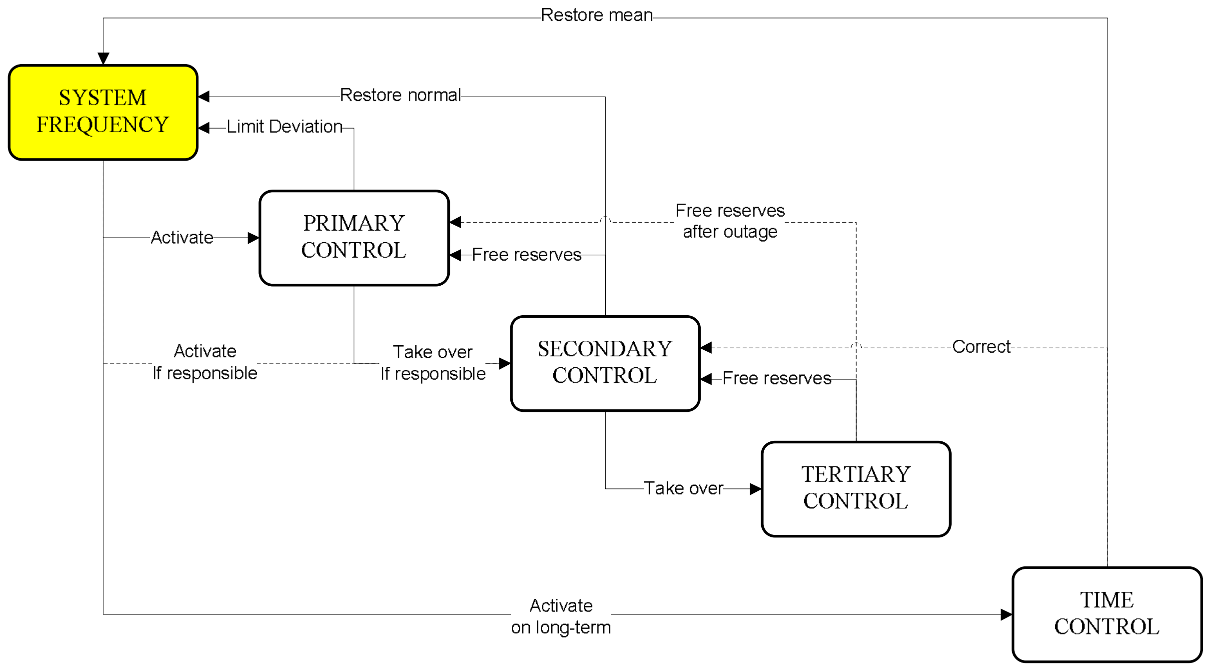


Figure 2.2: Interactions between load-frequency control mechanisms as defined by ENTSO-E[20].

2.2.2. Frequency Restoration Reserve

Within 30 seconds after the occurrence of a deviation within a control zone, the responsible TSO has to start activating Frequency Restoration Reserves (FRR) or using imbalance netting (IGCC) to solve the deviation in its zone. This product has a lead time, the time between activation by the TSO and change in output of a balancing asset, of 30 seconds. Full activation has to be reached in 15 minutes.

The volume of FRR is related to the maximum load observed in a control zone by a curve depicted in Figure 2.3. For 2015 the Dutch TSO Tennet reported a peak load of 18.2 GW, resulting in a recommended volume of FRR of a little over 300 MW. The required power is tendered by Tennet in yearly and quarterly parts. In 2015 Tennet tendered 340 MW of capacity for 2016 in 170 MW year contracts and 170 MW quarterly contracts [23]. These contracts guarantee the availability of flexibility irrespective of the energy price. Blocks sold via this procedure can only be bought symmetrical with the same volume for upward and downward regulation.

Secondly, there is the possibility to voluntarily offer volume to the market for every Program Time Unit (PTU). This is possible till one hour ahead of the start of a PTU. For every PTU, the contracted bids and voluntary bids are combined to form a merit order for both for both upward and downward regulation. The price on the merit order for the highest activated bid in a PTU defines the market clearing price (MCP) of that PTU. All bids that are called in a PTU will get the MCP times the energy they delivered during the PTU. In a PTU with both upward and downward balancing, the Balance Responsible Parties pay the mean of the lowest bid in the upward direction and the highest bid in the downward direction. This price is called the midprice. Every minute the price and volume are published on [24]. Figure 2.4 shows the price duration curve for the market in 2014 and 2015. Note that the prices here are given as delta between imbalance price and day-ahead price.

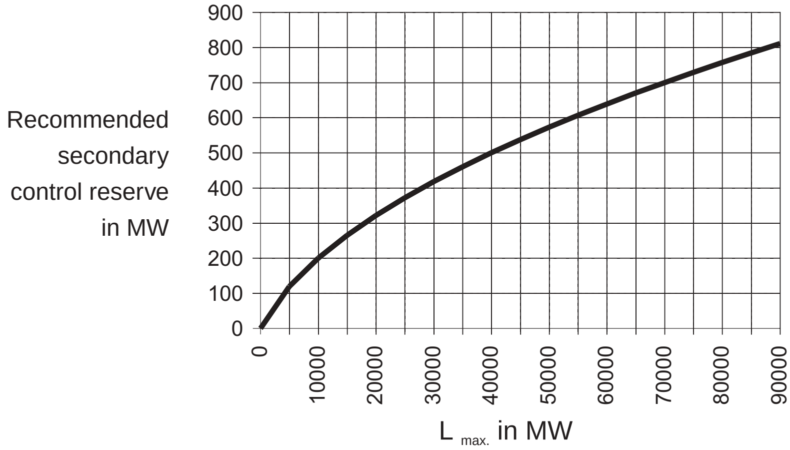


Figure 2.3: Volume of recommended aFRR based on the maximum load of a control zone as defined by ENTSO-E[20].

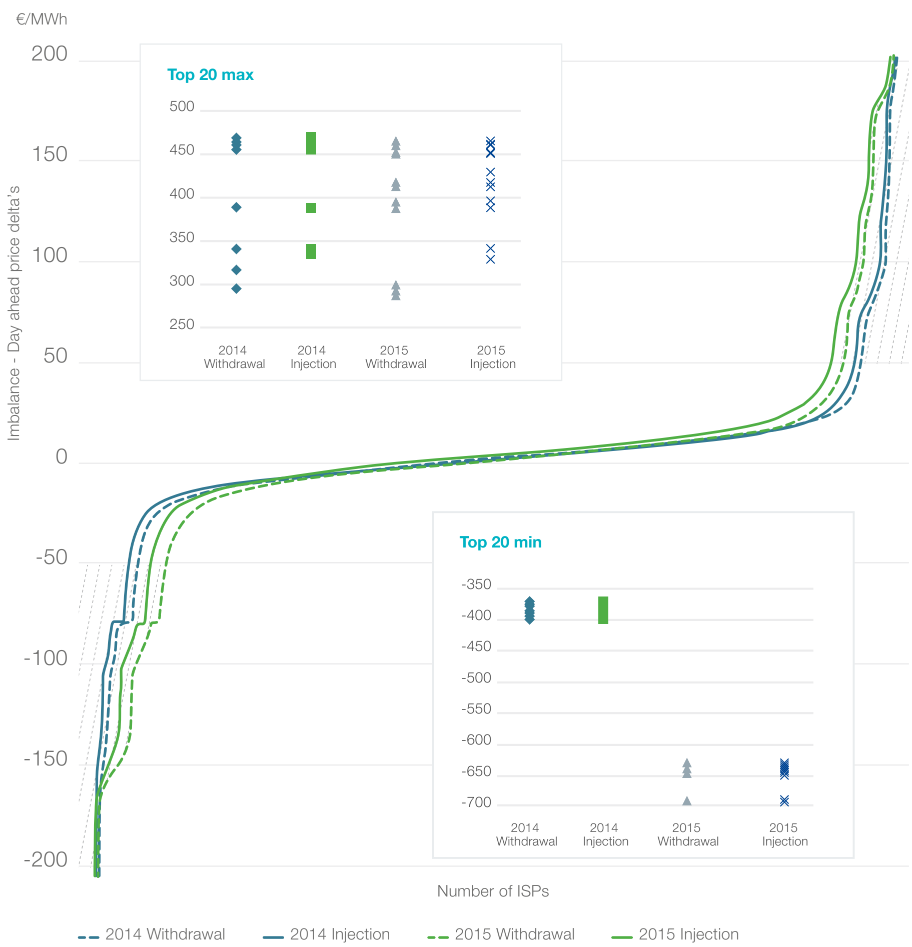


Figure 2.4: Price duration curves for the Dutch FRR market in 2014 and 2015 from [25].

Table 2.1: Imbalance source categories.

	Systematic	Supply side	Transport	Demand side
Hour to PTU shaping	x			
VRES forecast errors		x		
Outages		x	x	x
Load forecast errors				x
Strategic position taking	x			x

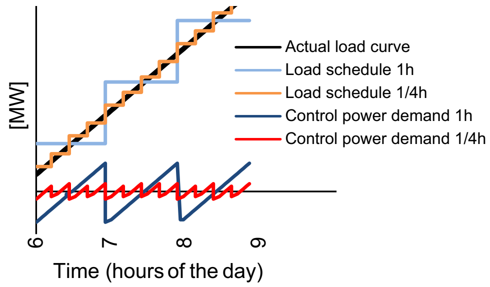


Figure 2.5: Effects of different schedules during the morning ramp from [10].

2.2.3. Restoration Reserve

When large or prolonged deviations occur, the TSO can use RR (Restoration Reserves). These reserves are manually operated by the TSO to restore balance. By activating these slower reserves, FRR becomes available again for balancing.

2.3. Sources of imbalance

In [10] the imbalance sources are divided in thermal and hydro generation outages, VRES generation forecast errors, unplanned interconnection line outages, load forecast errors and schedule leaps. Strategic position taking on the balancing market could be added as a last source. These sources could be categorized to supply side, transport, demand side or systematic sources. Systematic sources are imbalance sources as a result of how the market is arranged. Table 2.1 gives a sorting of the imbalance sources by these categories. In the next paragraphs the different forms of imbalance will be discussed in more detail.

2.3.1. Hour to PTU shaping

Blocks on the day-ahead market have a length of one hour. On the FRR blocks have a length of fifteen minutes. During ramping hours this results in shaping effects. Figure 2.5 shows the effect of imbalance caused by different granularities of day-ahead markets. The hourly time steps of the day-ahead market create an inherent need for balancing power to follow the shape of the actual load.

In [26] the impact of time discrete trade of electricity on the German FRR market is analyzed. They find that the cascaded demand-load-curve leads to significant shaping effects. Using FRR demand and grid frequency data with a 4 second granularity from the German TSO 50 Hertz, they calculate the demand for FRR. This demand is different from the activated FRR bids due to IGCC (Paragraph 2.4.1), passive balancing (Paragraph 2.4.2) and availability.

Using a carpet plot of FRR demand they show distinct deviations at the change of hour, as can be seen in Figure 2.6 along the time axis. Seasonal fluctuations along the date axis can also be observed. The decrease in deviations starting around mid 2012 corresponds with the introduction of 15-minute products on the German intra-day market in the end of 2011.

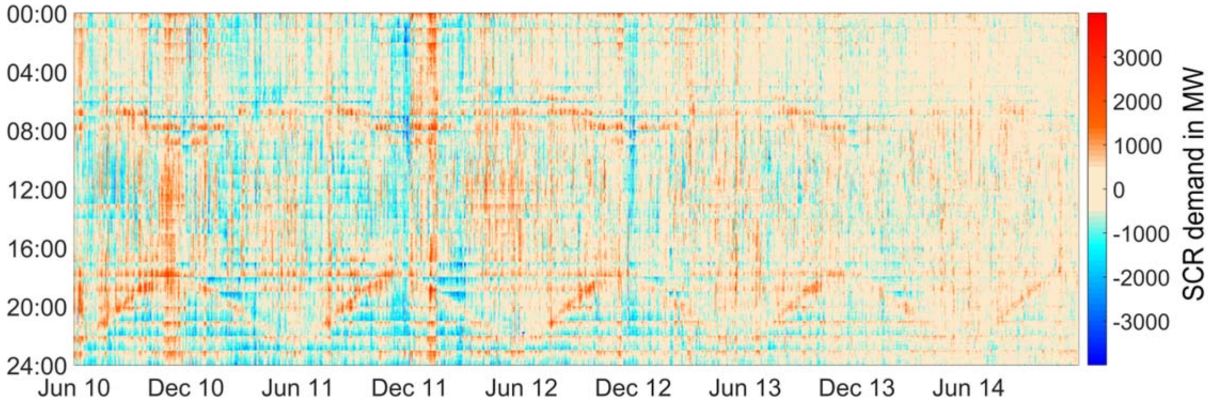


Figure 2.6: Carpet plot showing the FRR demand from [26].

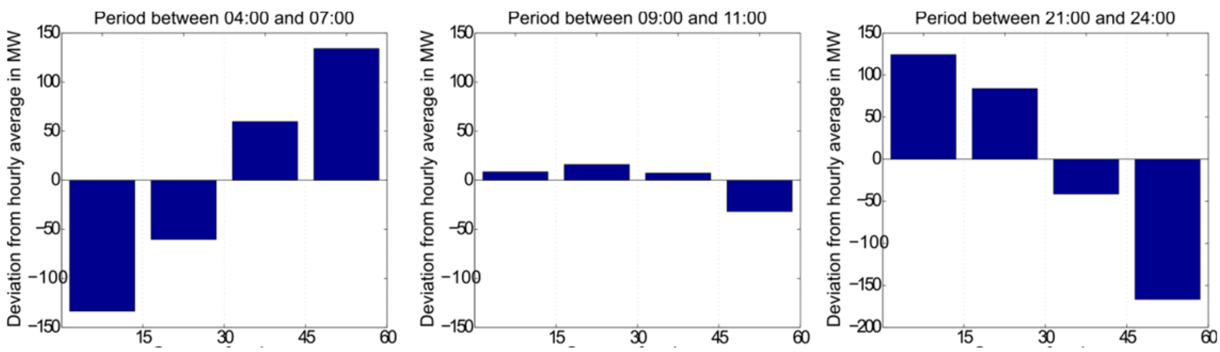


Figure 2.7: Mean deviation from hourly average for different time periods (using data for 01-01-2012 till 31-05-2012) from [26].

Looking at the deviations per 15 minute period from the hourly mean, in Figure 2.7, the pattern is even clearer. Costs of the described effect are estimated at 20 % of the total costs of activated bids.

2.3.2. Wind, solar and load forecast error

In the Netherlands, the main unpredictable VRES sources are solar PV and wind with an installed capacity of 1.485 GW and 3.388 GW [27]. This unpredictability results in deviations between the forecast at spot market gate closure and the real production.

Forecasts are done 12 to 36 hours prior to realization due to the GTC of the day-ahead market. Inaccuracy in weather models cause significant differences between day-ahead forecasts and realization. In [28, 29], the aggregated wind forecast error is estimated with by double exponential with $\mu = 18.8$ MW and $\sigma = 116.19$ MW for 7830 MW installed wind power.

In a similar way, as the wind forecast error was modelled in [28], the impact of solar forecast errors was modelled by [30]. For the load forecast error, the error is rather low at 2 %, but correlated with the solar forecast errors.

2.3.3. Outages

Outages have a very different character than wind and solar forecast errors. They can be best characterized as an asymmetric imbalance cause with a low probability but high impact. When a large power plant or interconnector has an unplanned outage, a sudden gap ranging from hundreds of megawatts to a little over thousand megawatt occurs.

Figure 2.8: Development of the IGCC zone from [18].

2.3.4. Strategic position taking

Some producers will take a strategic position, knowingly offering a different volume for the spot market than the forecasted production volume. This results in a chosen volume of imbalance. A price difference between exposure in the upward balancing direction and downward balancing direction can result in this behaviour.

2.4. Balancing outside the market

A number of external mechanisms take a significant portion of the total imbalance volume that is procured through the FRR market. It is necessary to understand the importance and character of these mechanisms to estimate their future development.

2.4.1. International Grid Control Cooperation

With imbalance being a problem for all TSOs, a part of the problem can be solved by power flows between different control zones. This mechanism is applied in the International Grid Control Cooperation[18][31]. Figure 2.8 gives a timeline of its development. It currently includes 11 TSOs from 8 countries. Imbalance is netted when interconnection capacity is available between control zones. More than 350 GWh of imbalance is netted monthly.

Figure 2.9 shows an example of how four control zones in Germany, can reduce the amount of needed flexibility by netting. By interchanging power between control zones, the total imbalance can be reduced to −300 MW. Improving interconnection capacities available for exchanging balancing power between control zones can reduce the imbalance volumes. This can either be done by adding interconnection capacity or reserving interconnection capacity for balancing purposes.

2.4.2. Passive balancing

In the Dutch FRR market BRPs with imbalance opposed to the market imbalance, get paid the market price. Combined with near real time publication of volumes and prices, this gives an incentive to BRPs to balance the system[32]. It also enables the use of assets that are (not yet) qualified to enter the market to provide balancing power. Furthermore, extra capacity available on assets that fall outside of the FRR product specifications can be used for passive balancing. BRPs that provide passive balancing power take a small risk due to the time delay between real time and time of publishing of the market data. In the Netherlands, this delay is in the order of a couple of minutes[33]. When imbalance volumes are low this can result in BRPs unintentionally creating imbalance.

Figure 2.9: Example of IGCC netting between TSOs in Germany [31].

2.4.3. Imbalance source correlation

The correlation between the forecast errors of solar PV and wind were studied within the Western Interconnection in the United States by [34]. They conclude that the correlation between solar PV and wind forecast errors have low negative correlation for small regions. Averaging the Pearson's coefficient of 26 pairs of wind and solar forecast errors they come to -0.03. Aggregating the solar and wind forecast errors first, results in a slightly larger correlation of -0.09. Scaling to all 76 wind and 455 solar power forecast errors within the Western Interconnection results in a doubling of the correlation to -0.18. While no studies are available for the Dutch case, we assume the correlation to be comparable with the aforementioned case with 26 pairs. Another study showed that load and wind forecast errors are uncorrelated [35].

2.5. Flexibility

To keep the system balanced, flexibility is needed from assets that can reduce or increase demand or production. In the following paragraphs we will discuss different types of flexibility that are currently used or have a potential for future use in the FRR market.

2.5.1. Asset based flexibility

While demand side management is seen as a necessity to reach the EU 2030 and 2050 carbon goals, less than 4% of demand was utilized as such in 2014 [36]. In [37], an overview is given of the flexibility sources in 2011. It can be observed that thermal generation, must run plants and interconnection were the biggest sources of flexibility in the Netherlands according to their study.

Flexibility of thermal plants is delivered by increasing or decreasing production from the scheduled pro-

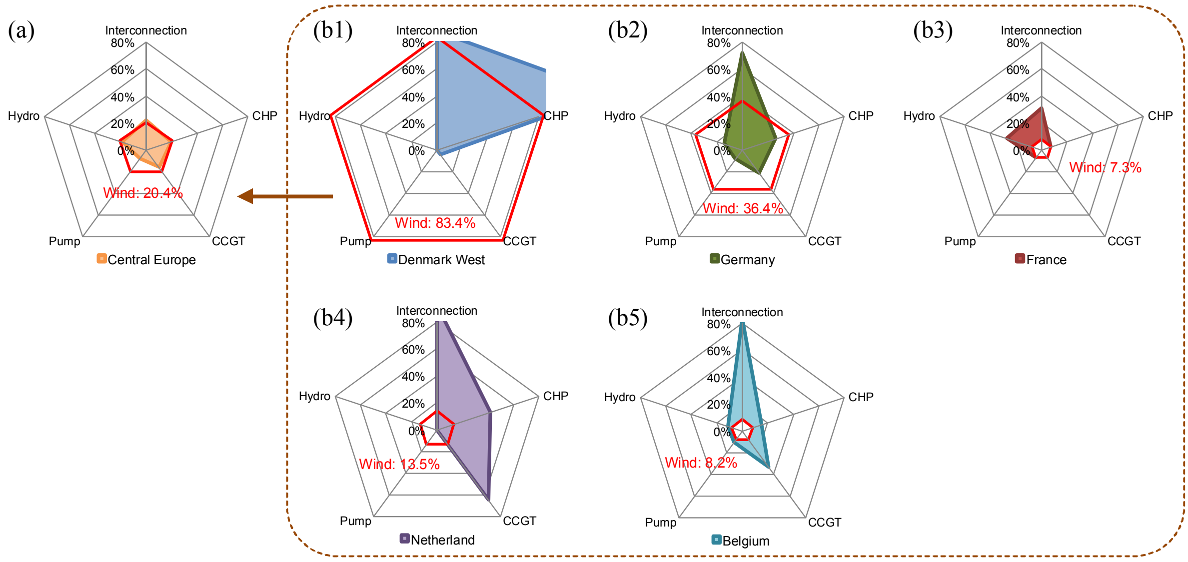


Figure 2.10: Flexibility charts of Central Europe region in end of 2011 from [37].

duction. For thermal plants the amount of flexibility that can be delivered is limited by the ramprate and their minimum and maximum output. Plants scheduled to run at full load can only deliver downward flexibility, decrease their production. Those running at minimum level can deliver flexibility in the upward direction. Currently installed thermal plants in the Netherlands are not capable to do a cold start within the requirements of the FRR market. The FRR market requires plants to start reacting on the steering signal within 30 seconds[38].

2.5.2. Storage

Storage was already used for balancing since the start of large scale development of electrical systems. In the early 20th century, the first hydro-electric pumped storage systems were brought into use for this purpose [39]. For the Dutch system the following options are possible:

- Large scale pumped hydro: either importing and exporting the flexibility of pumped hydro storage via interconnectors or by building a dedicated offshore lagoon. The possibility of building a large offshore lagoon for flexibility purposes was already explored in 1981 by Lievense. Plan Lievense was to create a offshore island providing 1500 MW of power and up to 20 GWh of storage[40].
- Large scale storage: multiple technologies are possible to deliver balancing power for the FRR market. For example compressed air energy storage (CAES), flywheels or utility scale lithium-ion batteries [41]. Currently, a CAES project is under development in Northern Ireland. The development of CAES in other regions is mainly limited by its low round-trip efficiency compared to other storage solutions[42]. Rapidly falling prices of lithium-ion batteries combined with high round-trip efficiencies make them very interesting for balancing purposes[43].
- Power to products: producing hydrogen, ammonia or other chemical products from electricity. This production, could be used as a variable load for balancing. In the case of fuel production, the produced fuels could be used for the flexible production of electricity [44].
- Decentralized storage: integration of electric vehicles (EV) and home battery storage as flexibility source. EV storage utilization can be achieved by altering charging behaviour or by using a part of the EV battery in both directions (vehicle-to-grid) [43, 45–47].

2.5.3. Demand side response or management

Demand side response or management is the ability to alter the demand of electricity users. This can be achieved in multiple ways:

- Large scale DSR or DSM: integration of demand side management flexibility of large industrial customers and agricultural growers is already being used for balancing purposes. It challenges electricity producing companies to be involved with customers to be able to alter their demand pattern while keeping the interference with their processes limited.
- Consumer flexibility: electrification of heating (breakthrough of (hybrid) heat-pumps[45]) and other appliances create more possibilities for shifting consumer demand.

2.5.4. VRES curtailment

Curtailment of sustainable energy can be used to control its production. More and more wind turbines are installed with wind curtailment optionality [48]. Wind curtailment can be achieved by pitching blades out of the wind or by combining wind turbines with storage facilities. Currently, wind curtailment in the Netherlands is limited by the SDE subsidy scheme. For the amount of full load equivalent hours specified in this subsidy scheme, producers get subsidized. This makes curtailment only profitable for production hours on top of this scheme.

2.6. Summary

The physical problem of balancing demand and supply is caused by a spectrum of different sources. We can categorize them by source into the categories production (wind forecast errors, solar forecast errors, outages), demand (load forecast errors), transport (outages) and systematic (hour to PTU shaping, structural position taking, IGCC, passive steering). Flexibility can be divided into curtailment, storage, asset based and demand side management or response. Tennet, the Dutch TSO, uses the FRR market to activate flexibility bids. Some of these bids are contracted in a separate tender to secure a minimum available volume.

3

Model conceptualisation & implementation

On two occasions I have been asked,
"Pray, Mr. Babbage, if you put into the machine wrong figures,
will the right answers come out?" ...
I am not able rightly to apprehend the kind of confusion
of ideas that could provoke such a question.
- Charles Babbage in Passages from the Life of a Philosopher [49]

In this chapter, the concept behind the model used to answer the research questions is explained. Section 3.7 will explain how this conceptual model was validated. As introduction, a textual model description is given.

3.1. Textual model description

Modeling electricity markets is becoming increasingly complex with more interconnection, stochastic inputs and smarter optimization methods. Thus, in order to not create a monstrous model, the scope of the model was limited. The focus was to generate scenarios that create insights in the effects of chosen parameters on the energy price in the FRR market.

Multiple methods can applied for the valuation of flexible assets. One way of doing this is by valuation of the profitability of an asset for historic years. More advanced models take into account price elasticity effects of the evaluated asset. These models are a very safe bet when making predictions for this year or the next. However, fundamental processes that could cause landslide changes are not captured. This makes these models bad long term predictors.

The second option is the route taken in this research project, taking historic information and adding fundamental trends to create scenarios for the future. A very big, if not the biggest, weakness of this approach lies in the validity of the input and modelled market mechanisms.

For all aforementioned approaches, the long term validity of the market structure needs to be considered. In multiple decades, we can expect that markets may be shaped very differently. Therefore, different market structures should be incorporated in long term scenarios.

Combining day-ahead model data from Eneco scenarios with unit constraints on ramping, the available flexibility capacity was calculated for every PTU. Using this capacity and its cost price, a bidding mechanism

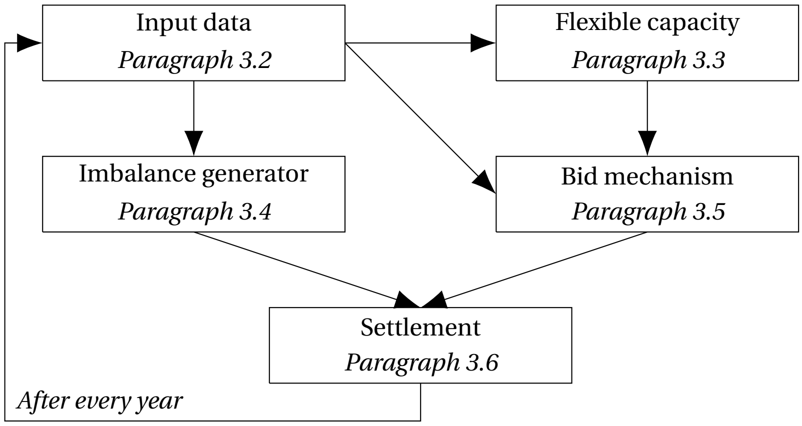


Figure 3.1: Overview of the main components of the model and interaction between them

was used to establish a merit order for the available flexibility. Bidding was based on profit optimization using historic FRR market prices and volumes. The historic FRR data was taken for PTUs with a spot market price comparable to the expected spot price market. This was done to ensure differentiation between days of the week and time of day. In the profit optimization, the imbalance position of the asset owner and price elasticity were taken into account. Linearized price elasticity was used to reflect the effect of the offered volume on market prices.

In Figure 3.1, an overview is given of the interactions between the main parts of the model. The respective paragraphs are given for the different parts of the model.

3.2. Input data

Inputs for the model can be put into three categories: future scenarios, historical data and asset type specifications. These inputs were brought together from different sources.

3.2.1. Scenario input

The choice for input was steered by the necessity to calculate flexibility capacities for future years. Therefore, a unit commitment model for long term scenarios used within Eneco was chosen as input. The following time series were available for every asset for the year of scope:

- Short run marginal costs: the marginal cost price of an asset based on fuel and emission prices, efficiency and variable costs
- Capacity available: amount of MW of the installed capacity that is available for generation
- Generation: production level in MW

For the Netherlands, the following series were also available:

- System marginal price: day-ahead price for each hour
- Demand: total demand in MW for each hour

3.2.2. Plant type data

Next to these time series, a table with technical capabilities per plant type was used with:

- Flexibility participation: a factor defining the share of plants, within a certain plant type category, that is active in delivering flexibility in the FRR market. This factor was used as a fitting parameter.
- Minimum stable level: the minimum level at which an asset can run stable, defined as a percentage of

its maximum output. Data from [44] was used for this parameter.

- Ramprate: a limit at the rate at which a type of plant can ramp up or down its production def,ined as a percentage of its maximum output. For this parameter data was also taken from [44].

In Appendix B, the values of these parameters are listed.

3.2.3. Historical data

Datasets from 2014 and 2015 from Tennet and APX NL were used for calibration and validation. These historical series were used:

- System marginal price: per hour spot price from APX NL
- Imbalance volume: per PTU volume of the FRR market from Tennet
- Imbalance price: per PTU price of the FRR market from Tennet

3.3. Flexibility capacity

As a starting point, delivering flexibility was assumed to be an optionality only becoming available after the spot market is cleared. Starting from this assumption, flexible capacity is the capacity that can be altered on the supply or demand side after spot market closure. For this study, only production side flexibility was taken into account. Flexibility delivered by thermal plants are constrained by either their minimum or maximum power output or their ramprate.

We define upward flexibility capacity $F^+_{gt,max}$ to be:

$$F^+_{gt,max} = \max(\min[P_{max} - P, RR_{PTU} * P_{max}], 0) \tag{3.1}$$

And downward flexibility capacity $F^-_{gt,max}$ as:

$$F^-_{gt,max} = \max(\min[P - P_{min}, RR_{PTU} * P_{max}], 0) \tag{3.2}$$

With $F_{gt,max}$ the flexible capacity in a PTU, P_{max} and P_{min} its minimum and maximum output levels and RR_{PTU} the ramprate. In Example 3.3.1, a calculation example is given for a CCGT plant.

Example 3.3.1 *CCGT flexibility capacity*
A CCGT plant has the following specifications:

- $P_{max} = 800MW$, *maximum power output*
- $P_{min} = 350MW$, *minimum power output*
- $RR_{PTU} = 25\%$ *of its maximum capacity per PTU*

For a certain PTU it is scheduled to run at full capacity, $P = 800MW$. *In this case, the CCGT is constrained by its maximum output for upward regulation to* $F^+_{gt\omega} = 0MW$ *and constrained by its ramprate in the downward direction to* $F^-_{gt\omega} = 200MW$.

All assets were categorized by type of technology. In the model the following types of plants were defined:

- Combined Cycle Gas Turbine (CCGT)
- Gas Turbine
- Coal power plant
- Nuclear power plant
- Solar

- Wind
- Storage

For these asset categories plant type data, as described in Section 3.2.2, was used for calculating the flexible capacity available for every PTU.

3.3.1. Contracted capacity

The major part of the bids in the merit order are filled by the producers that have capacity contracts with the Dutch TSO Tennet. Unfortunately, Tennet does not disclose which producers have been contracted for the delivery of flexibility. We assumed that the contracted volume was delivered by plants that are must-run and are capable of ramping up and down. In the current Dutch power market, this comes down to coal fired plants. Thus, these plants were chosen as producers of the contracted volume. A volume of 300 MW divided over three major coal fired power plants was set as permannently available flexibility.

3.4. Imbalance sourcing

As described in Section 2.3, there are a number of different imbalance sources that have to be taken into account. This was done by:

- Hour to PTU shaping: different time units in day-ahead and balancing market are an inherent source of imbalance. By multiplication of a stepwise function with demand, the sawtooth of imbalance from shaping was replicated.
- Wind forecast error: following the approach of [28, 29], the wind forecast error was estimated with a double exponential function. While in the former the error was calculated based on the installed capacity, we chose to base the error on the day-ahead forecast of generated power. This was necessary to create valid time series for the forecast error in respect to the time of day. Using installed capacities could result in hours with more curtailment than power production because of the independence of the two series. Using a double exponential, values for the imbalance error were generated. To create a valid time series however, the forecast error should never result in negative production. Therefore the error was cut off when larger than the production volume. An absolute mean forecast error of 20 % was taken for the base scenario.
- Solar forecast error: for the solar forecast error, the same error of 20 % was applied [30]. A chop off at zero production was used, prohibiting forecast errors larger than the produced energy. Assuming a weak correlation between solar and wind forecast errors, both were modelled using independent error distributions[34].
- Outages: these were implemented as events with a random chance of happening. A small event of 300 MW occurring in 960 PTUs per year and large event of 600 MW occurring in 192 PTUs per year were implemented happening in randomly selected PTUs.
- Load forecast errors: implemented the same as the solar forecast error but with a lower forecast error of 2 %.
- Strategic position taking: as a static offset of 29 MW based on historic observations.
- International Grid Control Cooperation and passive balancing: due to the limits of the scope International Grid Control Cooperation (IGCC) contribution cannot be achieved by real netting between modelled control zones. Also, the effects of passive balancing cannot be modelled. Therefore, after system imbalance time series calculation, the imbalance was multiplied with a factor of 0.285 to compensate for these.

3.5. Market bid mechanism

The fundamental goal of the market bid mechanism is to couple prices to volumes from a perspective of the producer. In this section optimization of the producers is explained.

3.5.1. Objective function

For the bidding mechanism, all asset owners follow the same objective function for revenue maximisation. The revenue consists of three parts: the revenue it makes from delivering upward flexibility, downward flexibility and the costs it makes on imbalance. The costs of imbalance of the asset owner are included to account for the effect his bid has on the imbalance price. Subsequently we come to the following formulation with $R^+_{gt\omega,flex}$ the profit from upward flexibility, $R^-_{gt\omega,flex}$ the profit from downward flexibility and $-R_{gt\omega,imbalance}$ the costs from imbalance:

$$\max_{F^+_{gt\omega},F^-_{gt\omega},\lambda^+_{gt\omega},\lambda^-_{gt\omega}} R_{gt\omega}(F^+_{gt\omega},F^-_{gt\omega},\lambda^+_{gt\omega},\lambda^-_{gt\omega}) = R^+_{gt\omega,flex} + R^-_{gt\omega,flex} - R_{gt\omega,imbalance} \tag{3.3}$$

Profit on flexibility can only be made when the offered bid is accepted. In the upward direction, this takes place when the price of a bid is lower than or the same as the price of the amount of imbalance in that PTU. The case of bid acceptance could be stated as:

$$u(\lambda^+_{st\omega} - \lambda^+_{gt\omega}) = \begin{cases} 0, & \text{bid price is higher than market price} \\ 1, & \text{bid price is lower or the same as market price} \end{cases} \tag{3.4}$$

And for downward regulation as:

$$u(\lambda^-_{gt\omega} - \lambda^-_{st\omega}) = \begin{cases} 0, & \text{bid price is lower than the market price} \\ 1, & \text{bid price is higher or the same as market price} \end{cases} \tag{3.5}$$

The profit on flexibility could be defined as the difference between bid price and cost price times, multiplied by the volume of the accepted bid. This can be formulated as:

$$R^+_{gt\omega,flex} = u(\lambda^+_{st\omega} - \lambda^+_{gt\omega}) * F^+_{gt\omega} * (\lambda^{+*}_{st\omega} - C^+_{gt\omega}) \tag{3.6}$$

$$R^-_{gt\omega,flex} = u(\lambda^-_{gt\omega} - \lambda^-_{st\omega}) * F^-_{gt\omega} * (C^-_{gt\omega} - \lambda^{-*}_{st\omega}) \tag{3.7}$$

For the costs of imbalance there are three cases. Balancing volume is priced at upward price, downward price or at midprice. Tennet defines the midprice as the midpoint between the lowest bid price at the upward and the highest bid price at the downward regulating side [50]. In case of upward or downward pricing, the price paid is determined by the direction of imbalance of the producer. When its imbalance is opposite to the imbalance of the control zone it receives money, otherwise it pays. In the case of a PTU with midprice, the absolute volume counts and a producer always pays. Variable $S_{st\omega}$ is introduced to differentiate between the three payment regimes. We come to the following formulation:

$$\begin{aligned} R_{gt\omega,imbalance} = {} & \delta(-1,S_{st\omega}) * (\lambda^{day-ahead}_{st\omega} - \lambda^{-*}_{st\omega}) * (P^{ACT}_{gt\omega} - P^{DA}_{gt\omega}) \\ & +\delta(0,S_{st\omega}) * \left|\lambda^{mid}_{st\omega} - \lambda^{day-ahead}_{st\omega}\right| * \left|P^{ACT}_{gt\omega} - P^{DA}_{gt\omega}\right| \\ & +\delta(1,S_{st\omega}) * (\lambda^{+*}_{st\omega} - \lambda^{day-ahead}_{st\omega}) * (P^{DA}_{gt\omega} - P^{ACT}_{gt\omega}) \end{aligned} \tag{3.8}$$

3.5.2. Price elasticity

In a market with enough volume and market participants, it would be safe to assume that a producer receives the market price irrespective of its offer made to the market. Due to the small size and low number of participants in the Dutch FRR market, we concluded this assumption would not hold. Figure 3.2 illustrates the effect a flexibility offer can have on market prices.

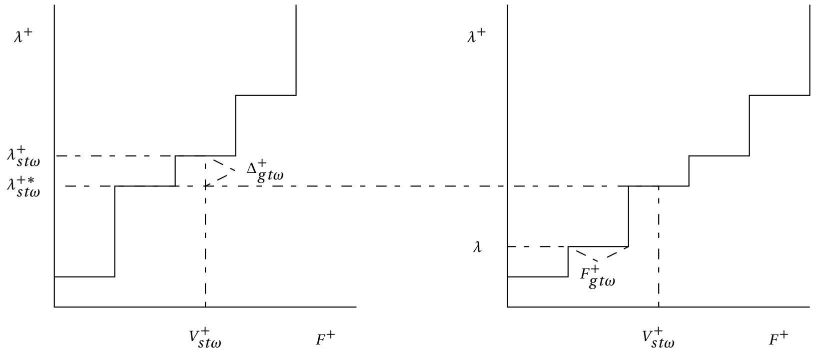


Figure 3.2: Model price elasticity, offering volume $F^+_{gt\omega}$ reduces the market price at imbalance volume $V^+_{st\omega}$ from $\lambda^+_{st\omega}$ to $\lambda^{+*}_{st\omega}$.

In the case of upward regulation, we assume that the volume offered by the flexibility provider lowers the market price linearly. The new price becomes:

$$\lambda^{+*}_{st\omega} = \lambda^+_{st\omega} - \Delta^+_{gt\omega} \tag{3.9}$$

For the price effect we take a linear approximation between the mid price and the positive price:

$$\Delta^+_{gt\omega} = u(\lambda^+_{st\omega} - \lambda^+_{gt\omega}) * \epsilon^+_{st\omega} * \frac{F^+_{gt\omega}}{V^+_{st\omega}} \tag{3.10}$$

$$\epsilon^+_{st\omega} = \lambda^+_{st\omega} - \lambda^{mid}_{st\omega} \tag{3.11}$$

For the downward direction the formulation becomes:

$$\lambda^{-*}_{st\omega} = \lambda^-_{st\omega} + \Delta^-_{gt\omega} \tag{3.12}$$

$$\Delta^-_{gt\omega} = u(\lambda^-_{gt\omega} - \lambda^-_{st\omega}) * \epsilon^-_{st\omega} * \frac{F^-_{gt\omega}}{V^-_{st\omega}} \tag{3.13}$$

$$\epsilon^-_{st\omega} = \lambda^{mid}_{st\omega} - \lambda^-_{st\omega} \tag{3.14}$$

3.5.3. Constraints

The optimization process is constrained by a number of inequalities. Part of these constraints are given by how the market is organized, part of them are due to computational limitations.

The volume offered in the bid has to be within the capacity limits of what the flexibility provider can do:

$$F^{+*}_{gt\omega} \leq F^+_{gt,max} \tag{3.15}$$

$$F^{-*}_{gt\omega} \leq F^-_{gt,max} \tag{3.16}$$

Prices of the bid have to be higher than cost price for upward regulation and lower than cost price for downward regulation:

$$\lambda^+_{gt\omega} \geq C^+_{gt\omega} \tag{3.17}$$

$$\lambda^-_{gt\omega} \leq C^-_{gt\omega} \tag{3.18}$$

For producers that are contracted to deliver flexibility, the following volume constraints are in place:

$$F^+_{gt\omega} = F^+_{Contract} \tag{3.19}$$

$$F^-_{gt\omega} = F^-_{Contract} \tag{3.20}$$

This simply means that contracted assets always have to bid in their total contracted volume.

3.5.4. Producer imbalance

While having good data on the total imbalance volume per PTU, no such data is publicly available per BRP. Therefore, we estimated the BRP imbalance using the following formulation:

$$V_{gt\omega} = f_{imb} * (V^{+}_{st\omega} - V^{-}_{st\omega}) \tag{3.21}$$

With f_{imb} giving the share of imbalance a BRP has, compared to the total imbalance of the market. For f_{imb} the best fit was obtained using:

$$f_{imb} = 0.1. * (randn + 0.5) \tag{3.22}$$

3.5.5. Bid selection

For ω scenarios the revenue is calculated. Not every scenario has the same probability. If all scenarios are sorted by price, we assume that the highest priced scenario has a chance of $1/\omega$ to occur. Every lower priced scenario has a chance of occurrence, that is the sum of those of higher priced scenarios. This results in the following chance vector:

$$p(\omega) = [\frac{\omega}{\omega}, \frac{\omega-1}{\omega}, ..., \frac{1}{\omega}] \tag{3.23}$$

After multiplication with this chance vector, we come to a weighted revenue. The bid volume and price from the scenario with the highest weighted revenue, is than selected as bid. This is done separately for the upward and downward flexibility.

Example 3.5.1 gives a calculation of the bid in the upward direction.

Example 3.5.1 *Bid calculation & selection*
For a given PTU the following holds:

- *Flex gen positive capacity input:* $F^{+}_{gt,max}$ = 12 MW
- *Cost gen positive:* $C^{+}_{gt\omega}$ *= 40 €*
- *Scenarios = 4*
- *Granularity = 3*

The following scenarios are put in:

- *Lambda system positive:* $\lambda^{+}_{st\omega}$*= [50 45 30 100]*
- *Imbalance system positive:* $V^{+}_{st\omega}$*= [100 40 10 300]*
- *Lambda system mid:* $\lambda^{mid}_{st\omega}$*= [30 25 25 35]*

Assuming the producer has no imbalance, this results in a bid volume shown in Table 3.1.
Using the given upward and mid prices for balancing from the scenarios, we calculate the elasticities:

Table 3.1: Flexibility bid calculation example: producer flexibility bid volume. With a to c being the bid volume and 1 to 4 the scenarios.

	a	*b*	*c*
1	0	6	12
2	0	6	12
3	0	5	10
4	0	6	12

$\epsilon^{+}_{st\omega}$ *= [20 25 25 35]*
Then we calculate the system delta caused by price elasticity shown in Table 3.2, resulting in the final bid given in Table 3.3.

Table 3.2: Flexibility bid calculation example: price delta of bid.

Scenario	*a*	*b*	*c*
1	0	1.2	2.4
2	0	3.75	7.5
3	0	12.5	25
4	0	0.7	1.4

Table 3.3: Flexibility bid calculation example: bid price. Prices between brackets are not bid into the market as they are lower than the cost price of the producer.

Scenario	*a*	*b*	*c*
1	50	48.8	47.6
2	45	(39)	(33)
3	(30)	(17.5)	(5)
4	100	99.3	98.6

3.5.6. Bidding mechanism flowchart

For every asset, the bid is calculated based on a number of input scenarios. In Figure 3.3, a flow chart is given of how the different parameters are interlinked with each other. The inputs fall into three classes:

- Scenario data: $\lambda^+_{st\omega}$, $\lambda^-_{st\omega}$, $\lambda^{mid}_{st\omega}$, $V^+_{st\omega}$, $V^-_{st\omega}$
- Asset limitations: $F^+_{gt,max}$, $F^-_{gt,max}$
- Fitting parameters: f_{imb}, $p(\omega)$

3.6. Settlement

For every time step, all bids from the different assets are put in one big list and sorted by their price. Doing this we create a merit order of the flexibility. Combining the flexibility merit order with the generated time series for imbalance, we derive the imbalance prices. Subsequently prices at 100 MW and 300 MW are taken from the merit order. In the current implementation, the producers don't get direct feedback on their performance via settlement. The settlement is purely done to generate the market prices.

3.7. Model verification, calibration and validation

To test the correctness of the model and establish the fitting factors, it was trained and validated. Furthermore, verification steps were taken to ensure correct depiction of the real market in the model. This paragraph outlines these processes.

3.7.1. Verification

During this research, which was done at Eneco, the model and results have been verified. This was mainly done by discussions with various experts on modeling and market design within the company. Secondly, at various stages of the project presentations were given. These presentations were given to stakeholders and experts within Eneco and to a group of interested scientists from the TU Delft Energy & Industry department. Assumptions and parameters used can be found in Appendix A and B. Modelled forecast errors for VRES were compared with forecast errors for Eneco wind and solar assets. The results showed little difference between the modelled error distribution and the real error distribution.

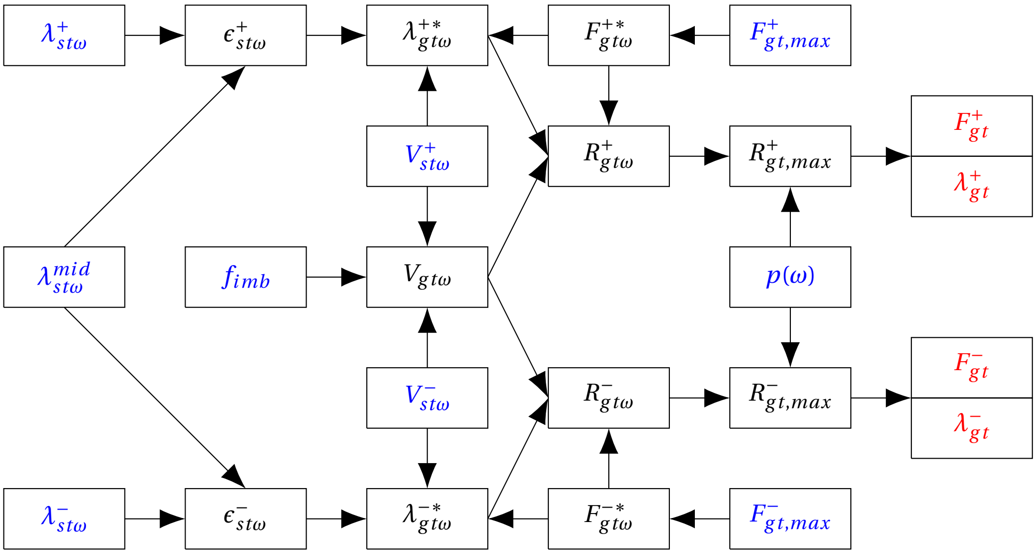


Figure 3.3: Flowchart of bidding mechanism, input in blue and output in red. Shown is how the different input parameters are interlinked with each other. A full list of symbols can be found in the Nomenclature.

3.7.2. Calibration & validation

Both historical data and scenario data were used in the model. The historic data from 2014 & 2015, as provided by Tennet [24], was randomly split into two parts. One part was used as training set, the other as validation set. The training set was put into the model and calibration was done to ensure the modelled output of the training set was comparable to the real training set. For validation the other half of the set was used. Results from validation can be found in Chapter 4.

3.8. Summary

As input a combination from long term scenarios on the asset base, capabilities, spot price and short run marginal costs were taken. Flexibility cost price and availability time series are generated using these inputs. Using error distributions, time series are generated for different sources of imbalance. A market bidding system is used to combine volumetric flexibility series with prices, while including effects of market power. Via settlement we derive the imbalance prices by combining the imbalance time series with the flexibility merit order. The conceptual model was translated into a modular system written in Matlab. Scenario data already available within Eneco was applied as input.

4 Results

You don't get results by focusing on results.
You get results by focusing on the actions that produce results.
- Mike Hawkins

This chapter highlights the most important modeling results by showing time series and snapshots from key years. For 'key years' a detailed overview is given. As key years 2015, 2020, 2025 and 2030 were chosen. Four different scenarios were tested to determine the impact of wind curtailment, large scale storage and improved VRES forecast accuracy.

4.1. Scenarios

We will look at four different scenarios depicting four different developments:

- Base case: this case reflects the system with flexibility developments in a 'frozen' state. It shows the implication of what could happen with growing balancing needs due to increased VRES input while no sources of flexibility are brought to the market. This scenario has no storage and no wind curtailment.
- Wind curtailment: this case is the base case with the addition of wind curtailment. In this case 50 % of generated wind power can be curtailed at a cost price of zero. This reflects the effects of what could happen when curtailment becomes a standard option for newly build wind turbines.
- Large scale storage: in this scenario we add large amounts of storage to the base case. Starting in 2019, 80 MW is added per year. The cost price is based on the day-ahead price with a 25 % markup due to cycle losses. It was assumed, that all capacity is fully available every PTU.
- Improved day-ahead VRES forecast accuracy: this scenario is a run of the base case with lower imbalance volumes. Due to increased day-ahead forecast accuracy the forecast error is reduced from 20 % to 15 % for both wind and solar.

Using these cases, the mechanisms and relations of the FRR market are further explored in this chapter.

4.2. Calibration & validation

In this section results of calibration and validation, as described in Chapter 3, are given.

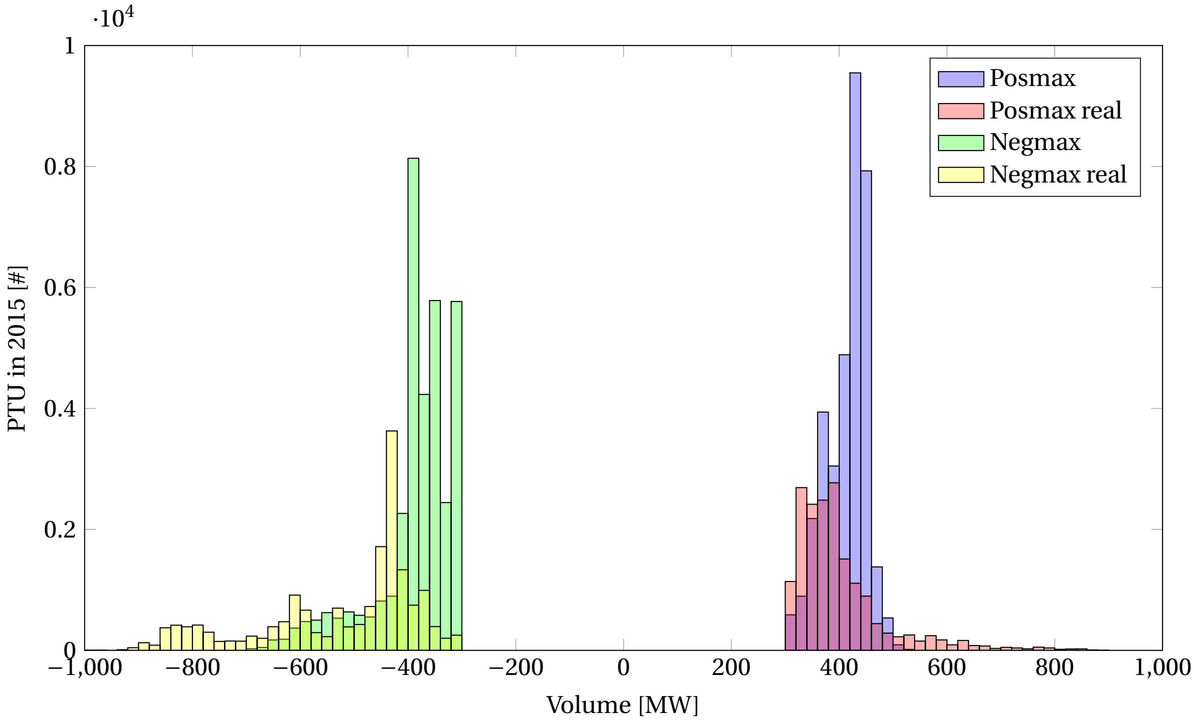


Figure 4.1: Comparison of realized and modelled market total merit order volume in both directions.

4.2.1. Imbalance

The imbalance was modelled based on a number of different sources. Addition of all sources resulted in an imbalance volume much higher than observed in the FRR market. We assume this is caused by:

- IGCC: a share of the imbalance is netted with other countries. This volume never shows up in the volume procured through the market.
- Passive balancing: a part of the imbalance is solved outside of the market. This is done by producers that use a delayed market signal to steer passively. This results in a reduction of volume in the FRR market.
- Intraday rescheduling: updated forecasts between day-ahead forecast and realization can result in BRPs deciding to change dispatch of production units. These changes will often result in reduced imbalance.

To compensate for the aforementioned causes, the modelled imbalance volume for all time steps was multiplied with a fitting factor of 0.285. The resulting imbalance can be seen in Figure 4.4a and is further described in the base case section.

4.2.2. Flexibility

On the flexibility side, the total volume of bids in the market was chosen as a characteristic to fit on. Figure 4.1 shows a comparison of the volume of flexibility offered to the market for the modelled and validation data for both up- and downward regulation. To get a proper fit for this characteristic, we lowered the availability of plants in the stack to values found in Appendix B.

This metric shows how small the FRR market size is. Secondly, we observe a limit at 300 MW. This is caused by three contracted plants forced to offer 100 MW each.

Clearly visible is the more pronounced long tail in the downward direction. This can be explained by the availability of running thermal plants, that offer their down ramping capacity to the market. For the up-

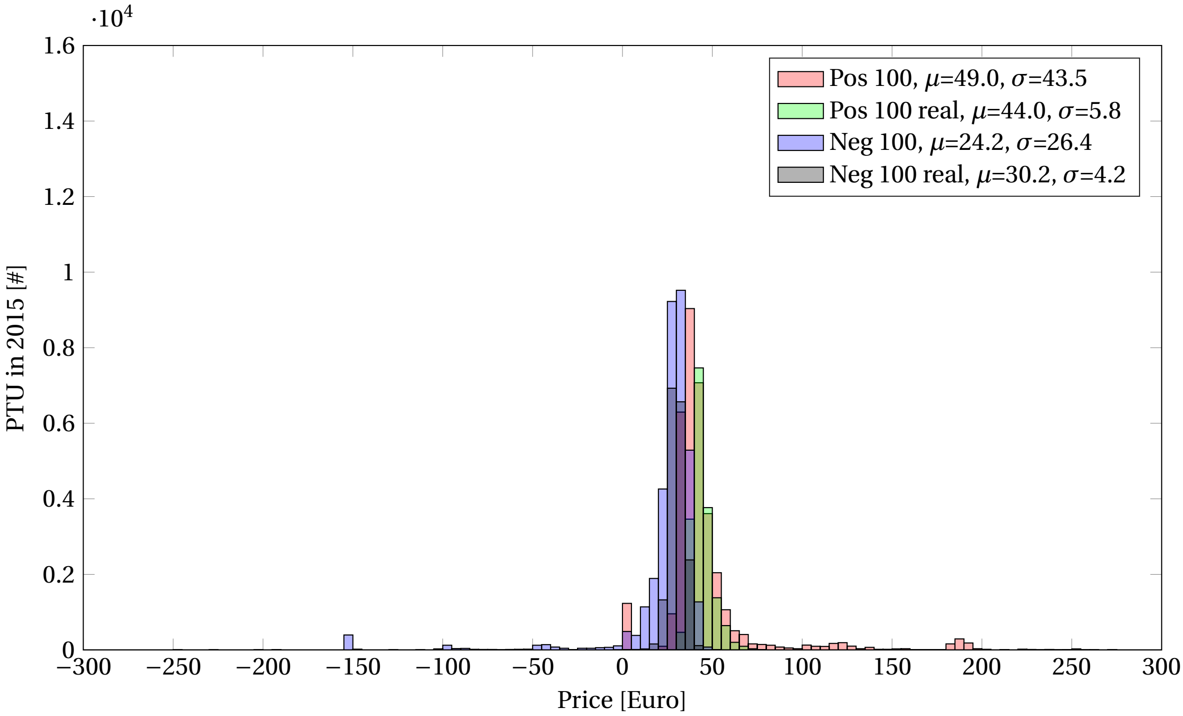


Figure 4.2: Comparison of realized and modelled imbalance prices at 100MW up and down.

ward direction, producers have to reserve capacity on their production units, resulting in less volume offered. These characteristics can also be observed in the modelled version.

4.2.3. Prices

Tennet provides limited data on the merit order of the market. Only for fixed volumes of 100MW, 300MW and 600MW on the merit order, prices are made available. These volumes are shown in Figure 4.2 and 4.3 together with the modelled prices. Fitting on prices was done after the volumetric fit, explained in the previous paragraph. The main parameter for fitting was the imbalance market share f_{imb}. Also, the day-ahead price bandwidth for scenario selection, the number of scenarios used for optimization and bid granularity were used for fitting. The values used and their description, can be found in Appendix C.

The modelled prices at 100 MW are slightly higher, while those at 300 MW are much lower. It can be concluded that, even after fitting, our flexibility merit order in the upward direction is less steep. For the downward direction, the modelled and observed prices are closer in correspondence with the real values.

4.3. Scenario: base case

For the base scenario, new flexibility options like wind curtailment and storage were excluded. This leaves the role of delivering flexibility to thermal capacity.

4.3.1. Imbalance

In Figure 4.4, the growth of imbalance is shown. From 2015 to 2030, the standard deviation of imbalance grows with a factor 2.5. The strongest change can be observed in the first years and can be related to a strong growth in installed capacity of wind and solar PV.

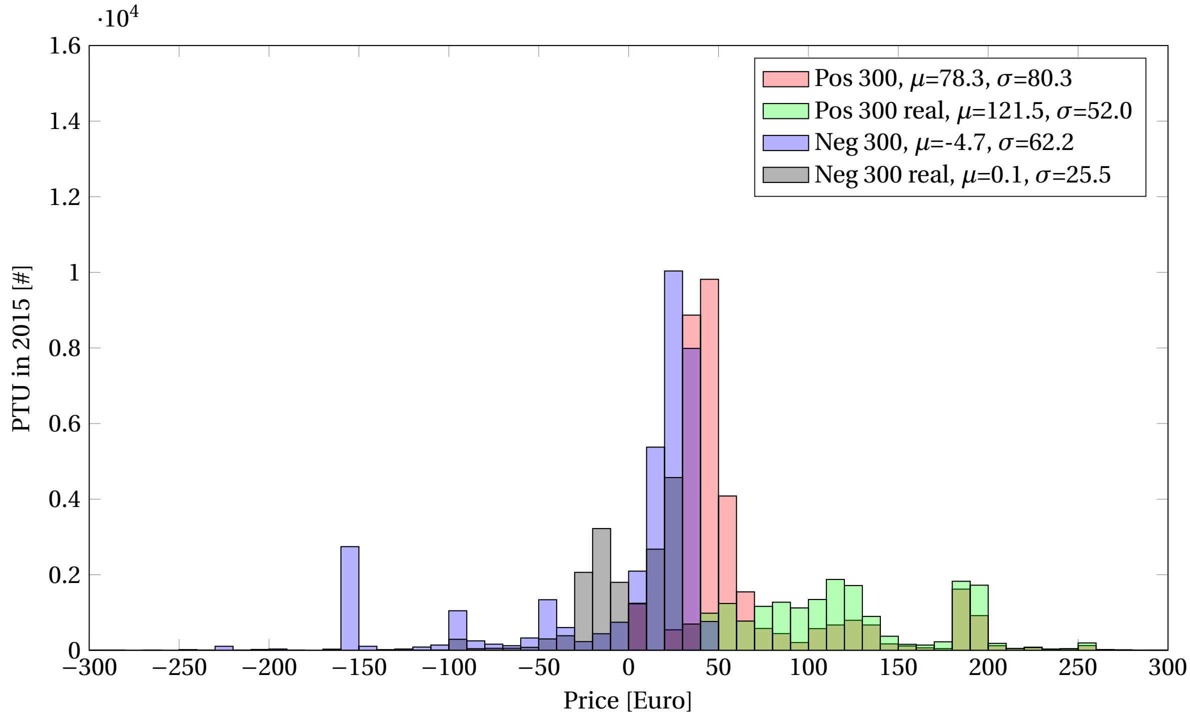


Figure 4.3: Comparison of realized and modelled imbalance prices at 300MW up and down.

4.3.2. Flexibility

A measure for the market size of flexibility is the volume at the end of the ladder. In other words, the total volume available in the merit order. Figure 4.5 shows this volume in both upward and downward direction for the base case. Also, in this visualisation the long tail for downward flexibility is visible.

4.3.3. Prices at fixed volume

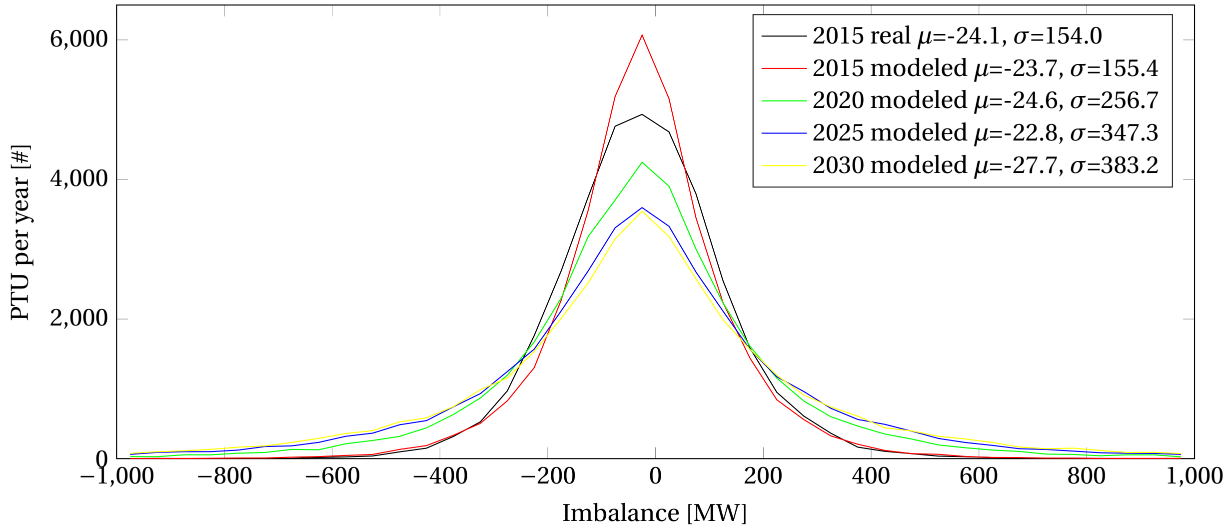
Figure 4.6 shows the development of fixed volume price points through time. In later years, a seasonal pricing component is clearly visible. This is a result of higher expected day-ahead prices. Price spikes in the day-ahead price from 2023 onwards, are amplified in the FRR market for upward regulating power. Due to the higher availability of flexibility in the negative direction, the impact on those prices is much lower.

4.3.4. Prices at imbalance volume

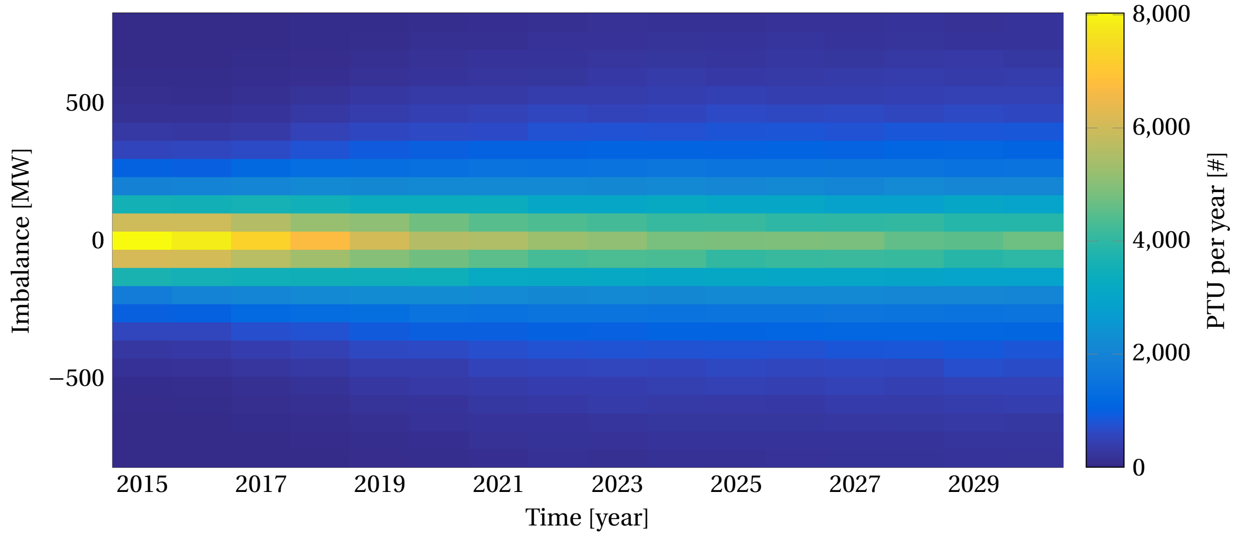
Looking at the imbalance prices in Figure 4.7, the change in the upward direction discussed in the last paragraphs is also visible here. We see that, on the positive side, prices go to very high levels in more and more PTUs throughout the years. Scenario selection through spot prices, creates a new regime with extreme upward prices in hours with a high day-ahead price.

4.4. Scenario: wind curtailment

For this scenario, wind curtailment was included and storage was excluded. This leaves the role of delivering upward flexibility over to thermal capacity installed. On the other hand, downward flexibility was delivered by both thermal capacity and wind turbines. We assume similar imbalance as in the base scenario. For this scenario, 10 % of the generating wind power was allowed to ramp down to zero at any time. Note that in this case the Short Run Marginal Cost (SRMC) of wind power was set to zero.

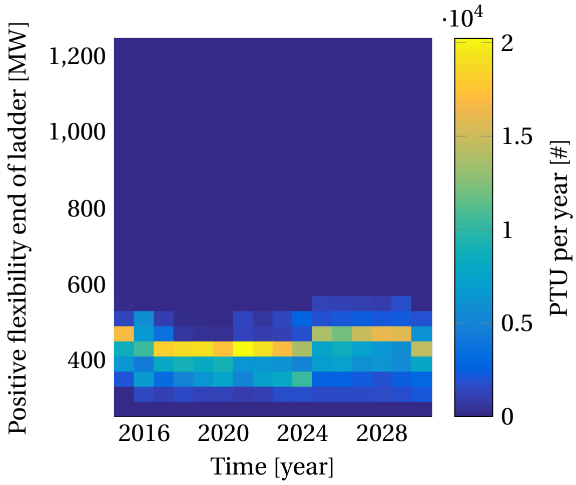


(a) 2015 real versus 2030 modelled

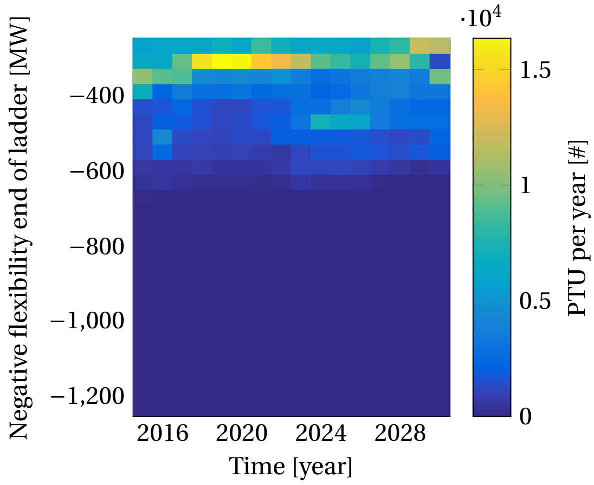


(b) 2015 till 2030 modelled

Figure 4.4: Time series of modelled imbalance and histograms comparing modelled imbalance in key years with real imbalance in 2015.



(a) Upward flexibility



(b) Downward flexibility

Figure 4.5: End of ladder volume from 2015 till 2030 for the base scenario.

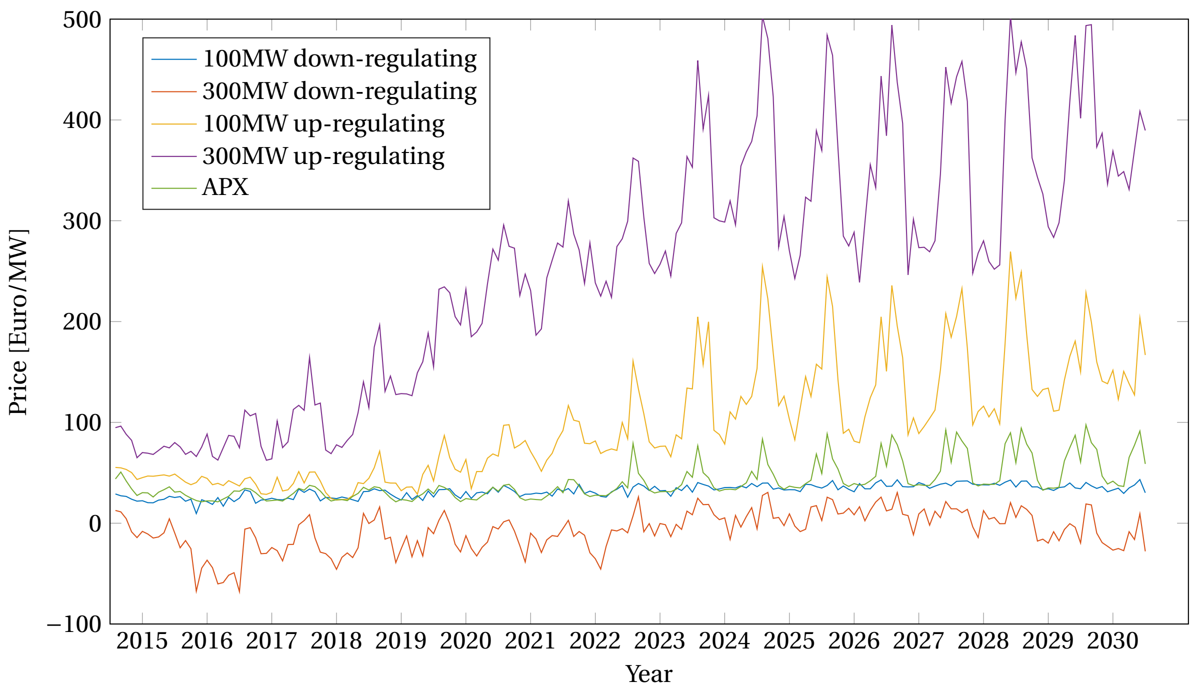


Figure 4.6: Modelled month averaged prices at 100MW and 300MW up and down combined with the base scenario curve for day-ahead prices

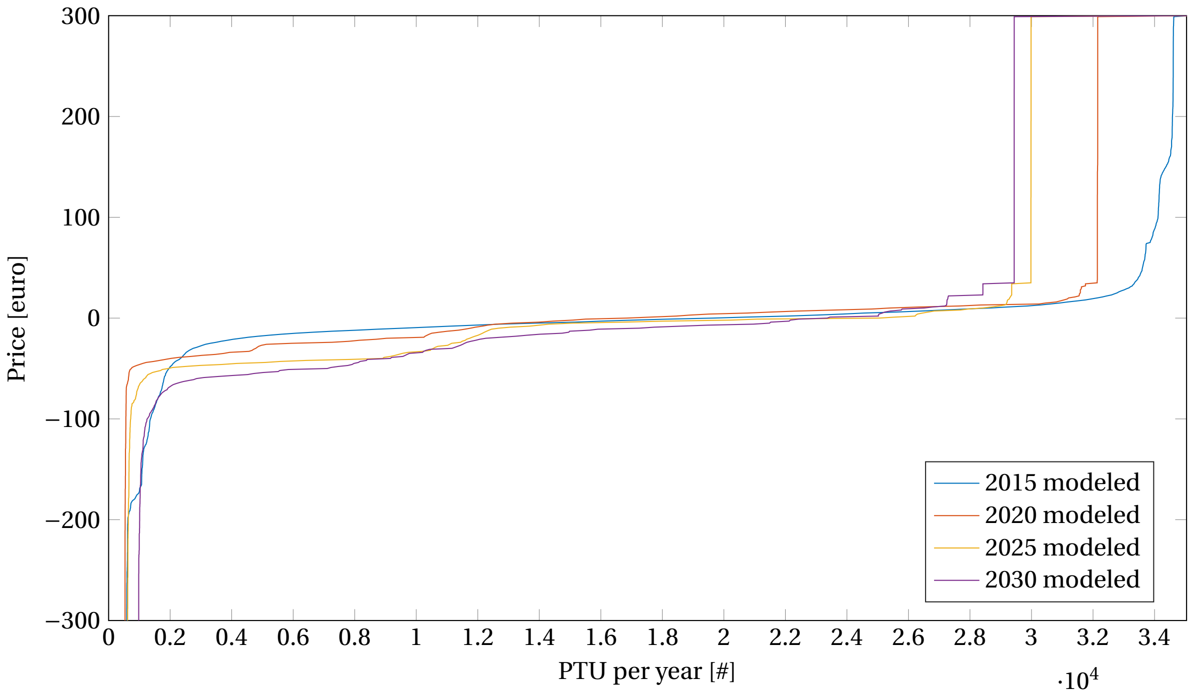


Figure 4.7: Price-duration curve with modelled imbalance prices for the base scenario.

4.4.1. Flexibility

Figure 4.8 shows the volume of flexibility in the merit order, when wind curtailment is applied. It can be seen that, while upward volumes are the same as in the base scenario, the downward volumes grow rapidly with increasing wind power. Due to the varying availability of wind power, we see that downward flexibility in 2030 ranges between 300 MW and 1500 MW.

4.4.2. Prices at imbalance volume

Shown in Figure 4.9 is the impact of wind curtailment on the price-duration curve. With similar imbalance volumes to the base scenario, the curve shows a strong decrease of PTUs with very low prices. Even in 2015, with curtailment possible for 10 % of the wind turbines, a major change in prices is observed. This underlines the potential for wind curtailment in reducing high imbalance prices in the downward direction.

4.5. Scenario: VRES forecast improvement

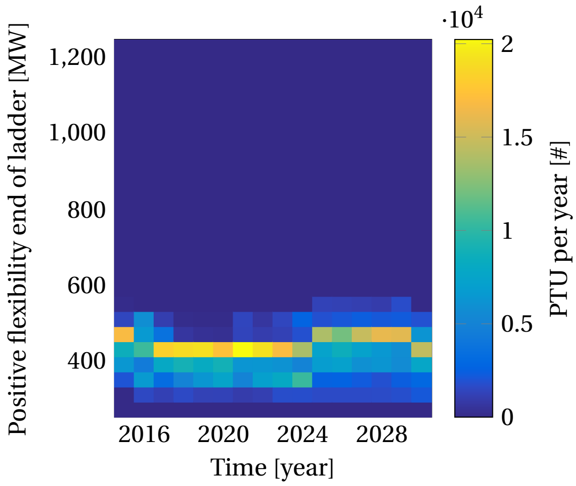
In this case, we look at a reduction of the forecast error for solar and wind from 20 % to 15 %. This scenario is different because, instead of adding more flexibility, only the main sources of imbalance are reduced.

4.5.1. Imbalance

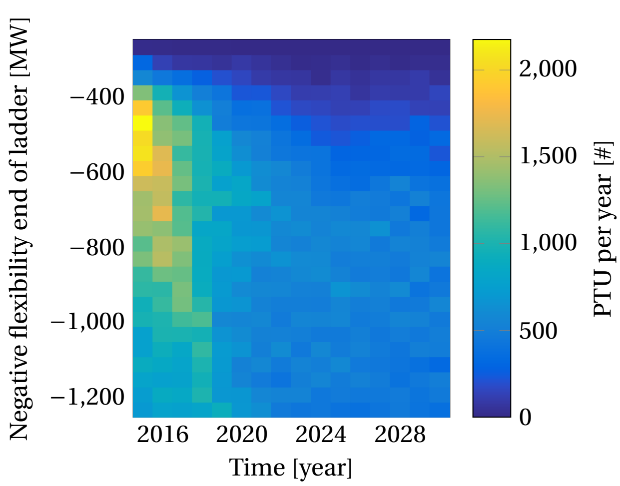
Figure 4.10 shows the imbalance volume for the improved forecast scenario. A small decrease of imbalance is seen for all years. The 25 % lower forecast error for wind and solar results in about 22 % less imbalance.

4.5.2. Prices at fixed volume

Shown in Figure 4.11, is the impact of improved VRES forecast accuracy on the fixed volume prices. Due to the lower imbalance volumes, the high prices of upward flexibility stabilize at a lower level. For the downward direction, this even results in a total flattening of prices for imbalances of 100 MW.



(a) Upward flexibility



(b) Downward flexibility

Figure 4.8: End of ladder volume from 2015 till 2030 for the wind scenario.

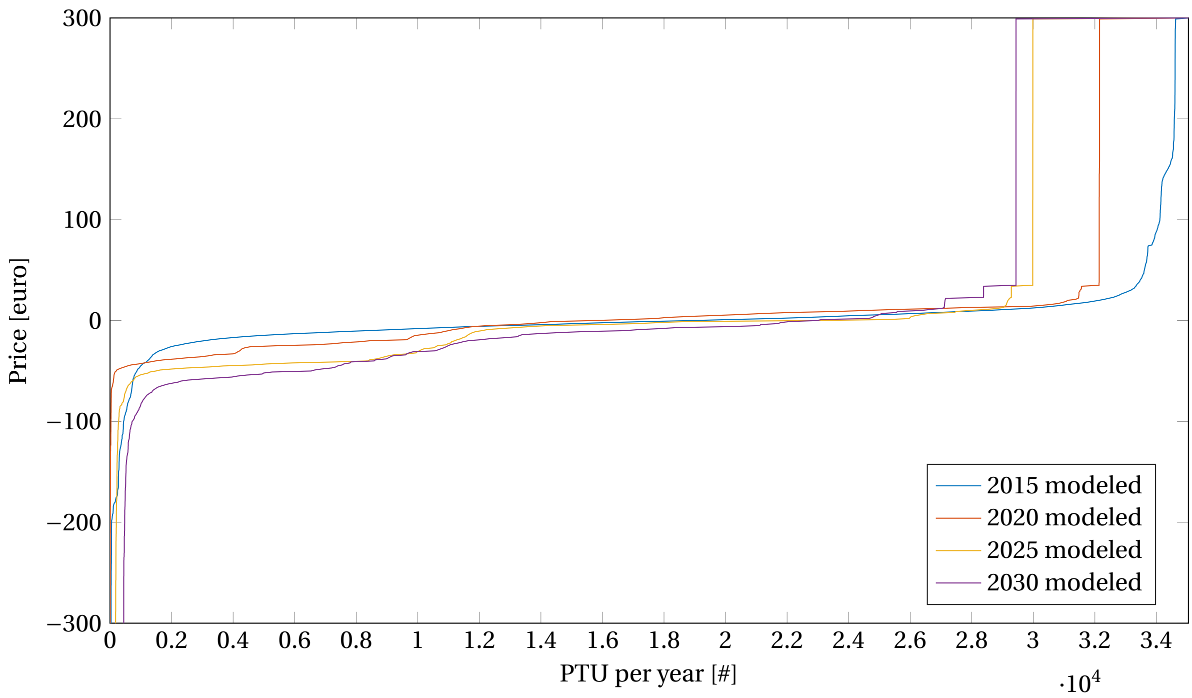


Figure 4.9: Price-duration curve with modelled imbalance prices for the wind curtailment scenario.

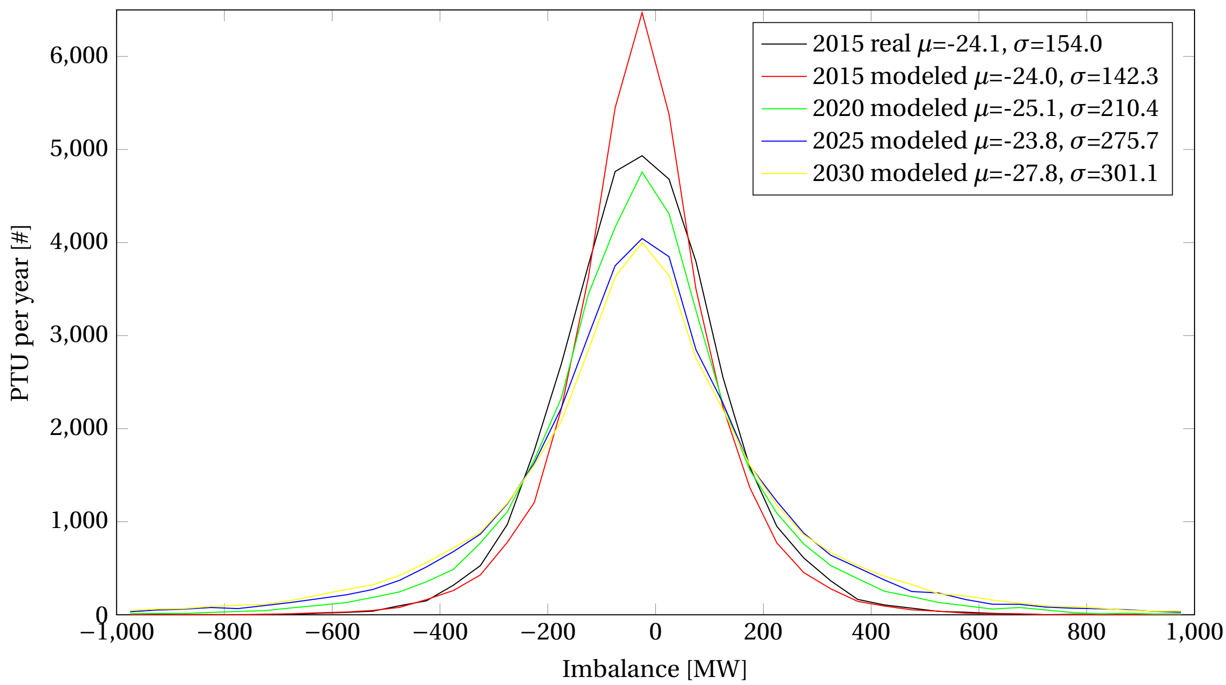


Figure 4.10: Histograms comparing modelled imbalance with improved VRES forecast accuracy in key years with real imbalance in 2015.

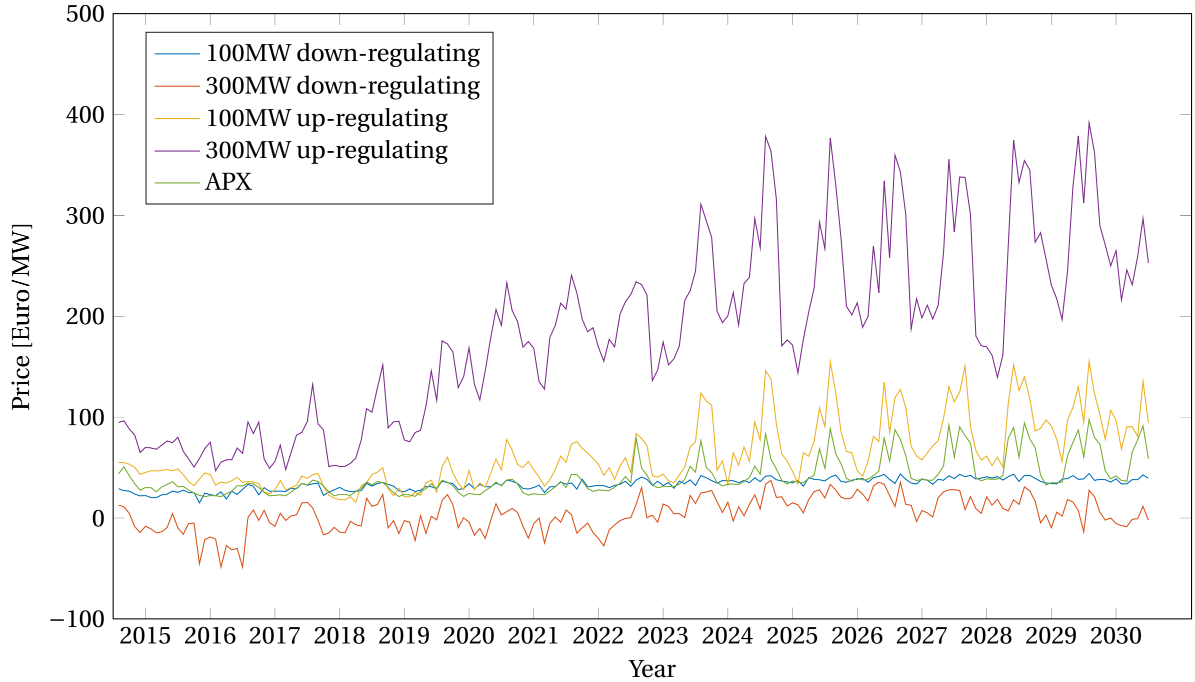


Figure 4.11: Modelled imbalance prices for the improved VRES forecast scenario at 100MW and 300MW up and down combined with the base scenario curve for day-ahead prices.

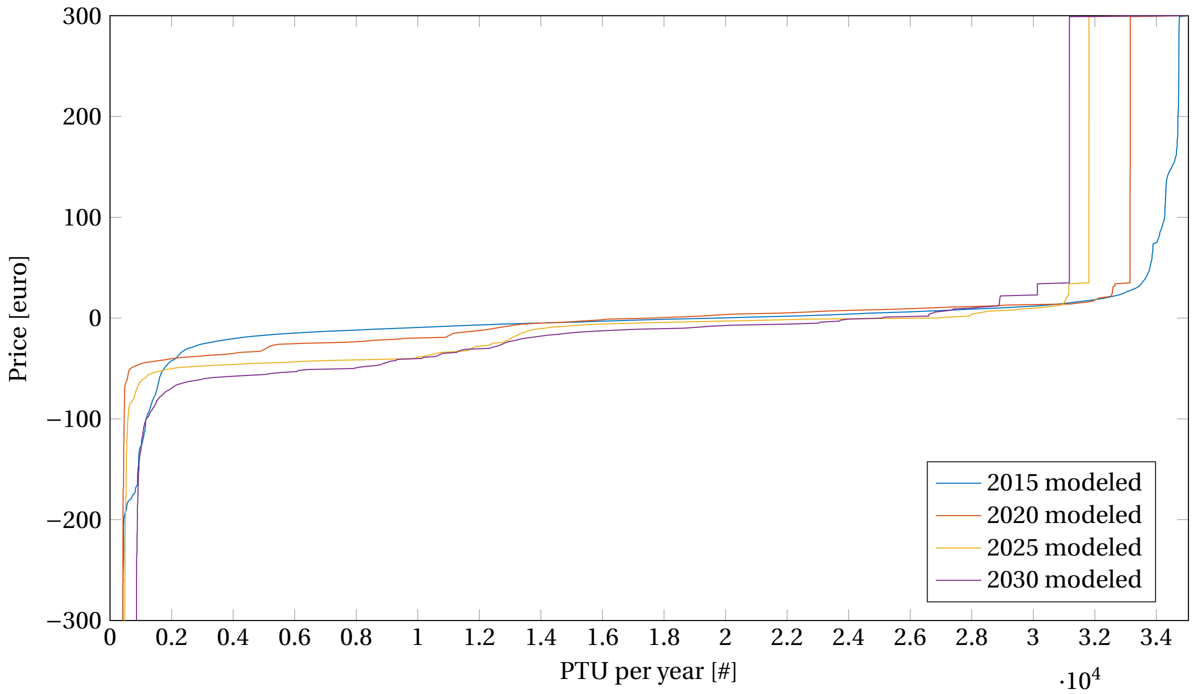


Figure 4.12: Price-duration curve with modelled imbalance prices for the improved VRES forecast scenario.

4.5.3. Price-duration curve

Looking at Figure 4.12, we can see that the amount of high priced hours are lower than in the base case. On the negative side, no significant changes are visible.

4.6. Scenario: large scale storage

In this scenario, we will be looking at the effects of large scale storage. Starting in 2019, the amount of storage available to the market is increased with 80 MW per year.

4.6.1. Flexibility

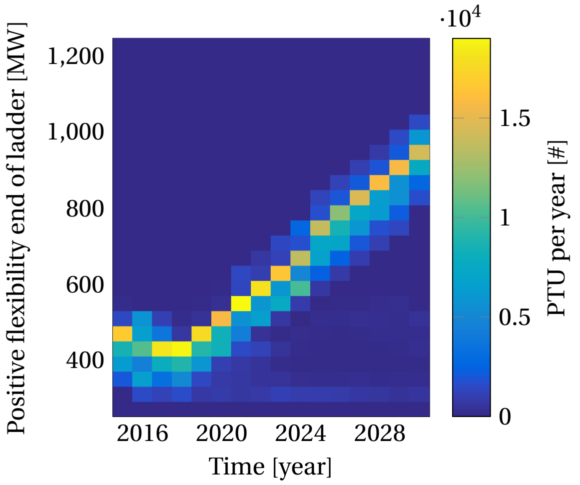
Figure 4.13 shows the total market size. The fast growth from 2019 onwards in the upward direction is clearly visible. Remarkable is the absence of the same strong growth in the downward direction, though the activity of storage is observed in some hours. This could be attributed to the much lower opportunity in the downward direction.

4.6.2. Prices at fixed volume

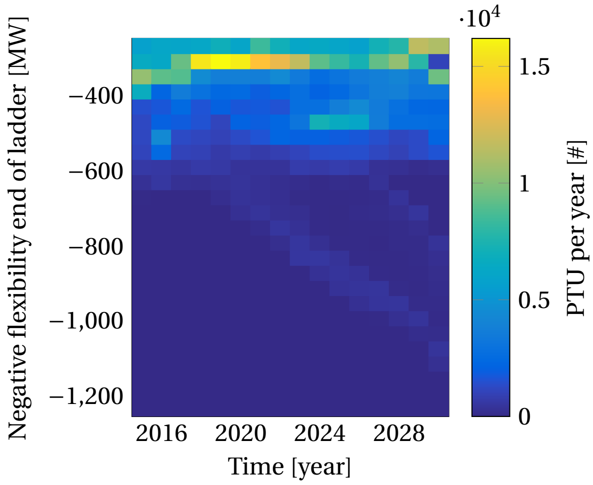
In Figure 4.14, the impact of large scale storage on the fixed volume prices is shown. The impact of storage is quite large and results in lower price levels than currently observed in the market.

4.6.3. Price-duration curve

Using the imbalance volumes from the base scenario results in a price-duration curve for the storage scenario as shown in Figure 4.15. A reduction in the number of high priced hours from 2020 onwards is visible, which can also be seen in Figure 4.14.



(a) Upward flexibility



(b) Downward flexibility

Figure 4.13: End of ladder volume from 2015 till 2030 for the storage scenario.

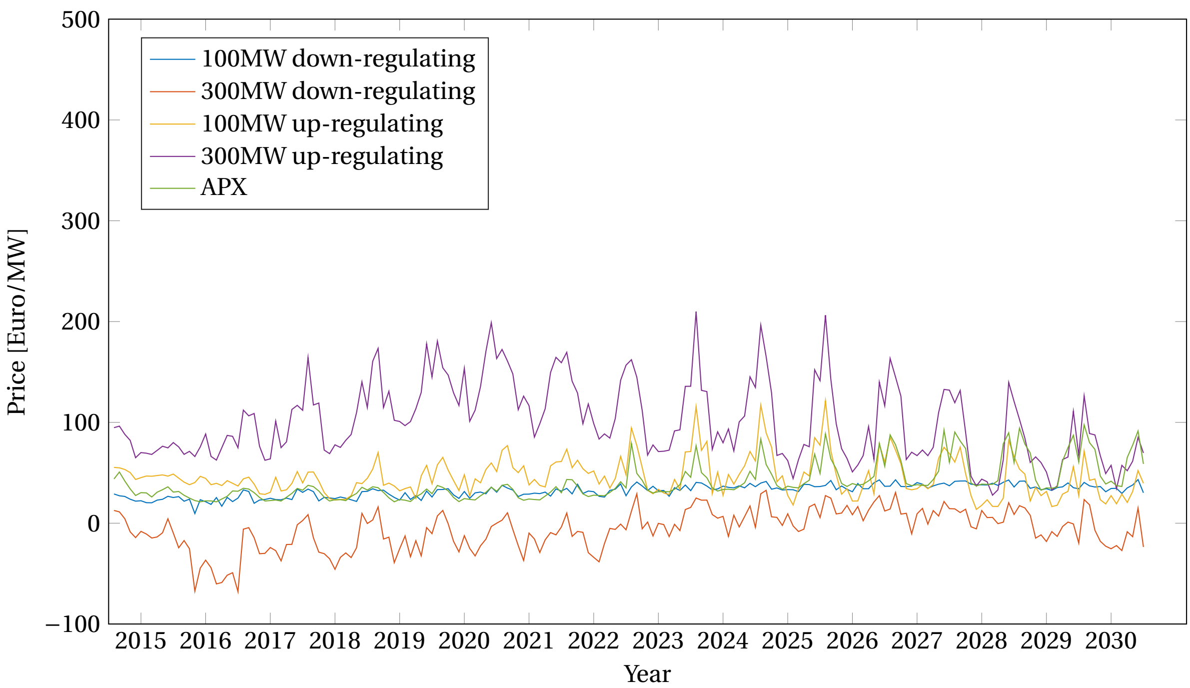


Figure 4.14: Modelled imbalance prices for the large scale storage scenario at 100MW and 300MW up and down combined with the base scenario curve for day-ahead prices.

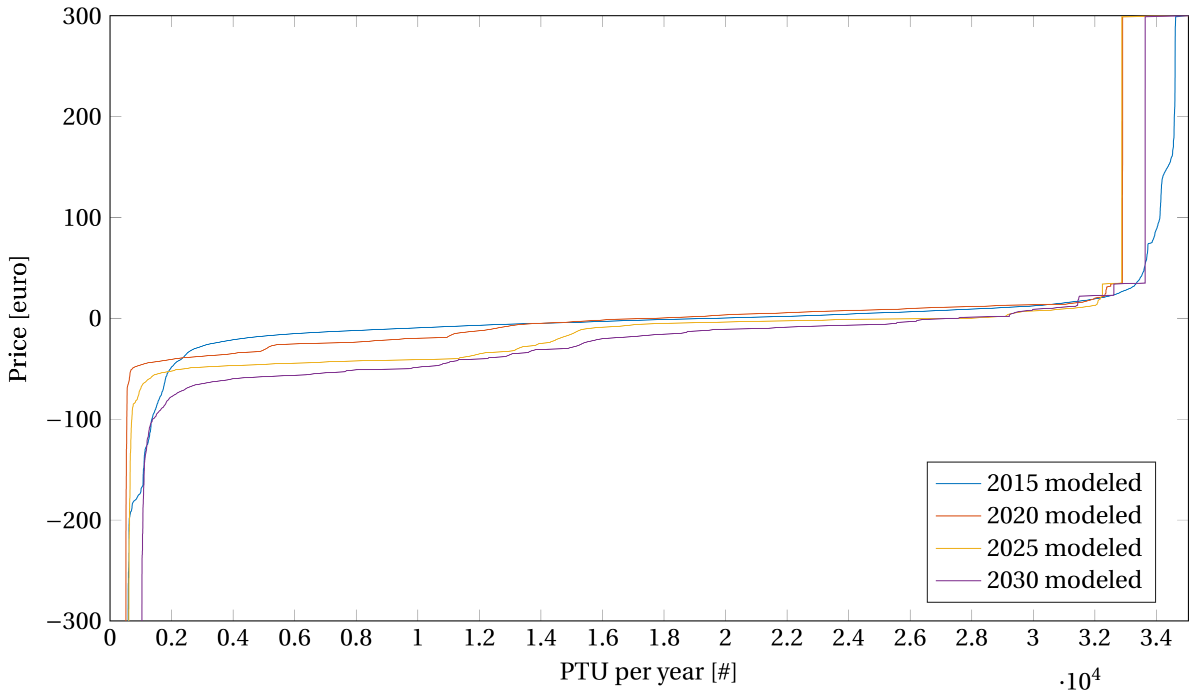


Figure 4.15: Price-duration curve with modelled imbalance prices for the large scale storage scenario.

4.7. Summary

Four different scenarios were used to gain more insight into the future of the FRR market. A base case with no new flexibility options, a wind curtailment case, a large scale storage and an increased forecast accuracy scenario were assessed. The sensitivity of the market to changes and asymmetry in pricing are clearly visible in the results. In the base case, prices quickly rise due to increased imbalance. Introduction of flexibility that is always available, shows that the prices quickly collapse to a much lower level. Wind curtailment can greatly reduce the imbalance costs, but only in the downward direction.

5

Discussion

Uncertainty is the only certainty there is,
and knowing how to live with insecurity is the only security.
- John Allen Paulos

In this chapter assumptions, market design uncertainties and potential improvements are reviewed. Firstly, the main assumptions for modeling of the FRR market and possible improvements are given. Secondly, uncertainties in future market design are discussed. Finally, a short overview of propositions for future modeling and research is given.

5.1. Assumptions

In this paragraph the most important assumptions, possible improvements and their expected impact are highlighted. In Appendix A, a full list of assumptions can be found.

5.1.1. Imbalance volume

For simplicity, wind and solar were taken as uncorrelated and demand and solar to be fully correlated. The shape of the error distribution was taken as double exponential function based on [28, 30]. Both simplifications, of correlation and shape, could be improved by using more complex distribution functions. In [29] a mixed distribution is proposed, based on a normal and a double exponential distribution for modeling wind forecast errors from day-ahead forecasts.

In the current model, fitting is done between modelled imbalance from imbalance sources and the imbalance volume in the FRR market. To compensate for passive balancing and IGCC contribution, the modelled imbalance was multiplied with a calibration factor. This factor of 0.285 was set at a constant value for all years. When changes to the IDM, discussed later in this chapter, or increased interconnection capacity are applied, this should be reflected by a dynamic imbalance calibration factor.

Due to risk asymmetry between the upward and downward direction, producers tend to take a strategic position for PTUs with a risk of high imbalance volumes. This results in a difference in mean of the imbalance distribution when modelled from sources and observed in the FRR market. As a correction, a static parameter is used in this model for strategic position taking. This parameter could be replaced with a dynamic mechanism, that bases the strategic position taking on an evaluation of imbalance risk in the previous year.

5.1.2. Time granularity & correlation

In its current state the model has a granularity of one PTU. This limits the model to only one regulation state per PTU, either upward or downward regulation. Increasing granularity to a minute base would create the possibility to include the effect of PTUs with both downward and upward regulation, resulting in a dual priced PTU.

Because randomized drawings from the error distribution were done for generating imbalance time series, no dependency between PTUs was preserved. This assumption is limiting when using the model to assess the performance of storage. To assure a sufficient state of charge, it is necessary to have an imbalance time series that correctly depicts the dependency between PTUs. For situations with large prolonged deviations, the usability of storage will be much lower due to the limiting state of charge. This is not shown in the current results.

5.1.3. Flexibility availability

We assumed that BRPs don't the opportunities in the balancing market into account at the day-ahead stage. Therefore, all flexibility available on thermal plants was based on their dispatch from the day-ahead market. We found that if all plants would deliver flexibility based on their theoretical ramp rates, the total volume of flexibility would be much higher than observed in the market. General assumptions were made about participation of certain plant types in the market, to reduce this difference. More detailed research could be done on the capabilities of plants in the Dutch plant stack in delivering FRR.

In reality, some producers take their expectations on prices and volumes on the balancing market and alter their day-ahead bidding accordingly. For example, a weather front moving over their wind farm resulting in a high imbalance risk could result in making reservations on power plants to ensure a low imbalance price. Optimization of expected revenue on the day-ahead and balancing market both at the day-ahead stage would be needed to model this behaviour.

Adding availability profiles for flexibility will be necessary to include DSM, EV and P2H into the model. Their availability profile will play an important role in their usefulness. While a large impact of EV storage on the flexibility of the electricity system is expected by many, the degree of impact will largely depend on the simultaneity of the need for flexibility and the availability of EV to deliver this. During periods of low EV availability, other forms of flexibility might be necessary. Using availability profiles for flexibility would show where the system is tight and prices high and when there is enough. Knowing which flexibility sources are complementary or overlapping would be necessary to predict future investments in flexibility sources. A good understanding of the availability of storage is therefore necessary in order to understand the true value of storage in the FRR market.

5.1.4. Profit optimization

In a situation with a well functioning market, we expect prices determined by the costs of an asset operator. In the case of energy prices, expected prices for balancing would only have a small delta with the day-ahead price. In reality (see also Figure 2.4) price differences are much higher.

For the model we chose to apply profit optimization in order to reconstruct the price difference observed. Inclusion of this adds a specific behavioural effect to the market. It is impossible to represent the complex decision making processes of BRPs with a simple markup.

For the optimization the producers have an assumed imbalance. The size and direction of the imbalance has an impact of the price and volume they choose to offer to the market. Deeper investigations are needed to establish a fundamental relationship between bidding behaviour and imbalance position of producers.

5.1.5. Learning rate

The length of a learning cycle was set to one year. This meant that every year, the producers would get the market prices and volumes of the year before. For the starting year historic data was used. After one year, the model started to use results from the previous year. In reality, not all producers would have the same learning rate, instead a mixed rate could be expected. Furthermore, some producers would use more than one historic year, while other producers would use a shorter data set.

Secondly, further testing should be done on the sensitivity of the model for the starting year. This could either be done by using other years as input or by manually altering the data set.

5.2. Market design uncertainties

Looking at possible future developments in the FRR market, there are many uncertainties. Though a number of flexibility options were discussed in Chapter 2, those were only the ones already existing within the current market structure. It is not unthinkable that in 2030 the market will have a different operating mode, with for example large amounts of consumer peer-to-peer trade. Within this research project the scope was limited to the current market structure. In the following paragraphs, an overview is given of market design uncertainties.

5.2.1. Passive balancing

Changes in prequalification standards (regulatory requirements on ramp rates, availability of flexibility, etc.) could result in a flow from passive steering to actively participating in the FRR market. This flow would add volume to the active market and will increase imbalance with the imbalance that is currently compensated by passive balancing. The main impact will be visible in doubly priced PTUs. In these PTUs, when passive steering can not be used, a conversion to active balancing will futher reduce imbalance. Secondly, more liquidity due to increased market volume could lead to lower prices.

A fast growth of passively acting balancing volume could lead to less stability in the system. While a TSO can measure the response of the passive balancing side when regulating on the active side, it is hard to forecast the availability of passive volume. Especially increased adoption of flexibility with strong volatility in availability would result in less stability. Therefore, prequalifying more volume would be beneficial to the TSO for maintaining a low control error.

5.2.2. Intraday trade

For the German SRL market, it has been shown that, the introduction of an IDM with 15 minute block duration resulted in a significant reduction of quarter to hour shaping imbalance [18]. Reduction of temporal resolution from 60 minutes to 15 minutes for the Dutch IDM could result in the same effect.

There are two important factors that limit the potential of the IDM in the Netherlands. Due to the relatively small size of the Dutch power market, liquidity issues limit its effectiveness in trading. Therefore, it is difficult to trade imbalance and flexibility based on updated production forecasts and dispatch schedules.

With passive balancing BRPs have the possibility to monetize flexibility in the balancing market instead of the IDM. Facilitation of passive balancing therefore contradicts the obligation to balance [12].

5.2.3. Capacity contracts

Currently, capacity is tendered in yearly and quarterly contracts. It is expected that tendering periods will become shorter in the future. Also, differentiation between peak and off-peak or day and night could be introduced to the market. With a yearly capacity contract, producers have to deliver the symmetrical volume year round. Only producers that have a portfolio are willing to take the price risk of running an asset all year round place bids for these tenders. For shorter tender periods, we expect more players to participate in these bids and thus more competition. Shortening tender periods would make it possible to differentiate in volume tendered between seasons. Stochastic sizing optimization by the TSO [51], could further reduce the contracted volume.

5.2.4. International harmonization and integration

In [52], it is shown that a larger region results in some damping effects for solar PV and wind, but a large share remains. Increased border capacity by building new interconnectors (both to synchronous zones and asynchronous zones by High Voltage Direct Current connections [14]), reducing security margins or dynamic line rating would result in reduced imbalance. Extension of the IGGC zone, market harmonization and integration is expected to have positive impact on market liquidity.

5.2.5. Plant stack

Market entry of new players and assets could result in a radical change to the pricing structure of the market. Further closure of thermal plants could result in a weakened grip and market power of a few large BRPs that have a dominant position in the FRR market. More participants and market liquidity could lead to a more efficient pricing regime. Phase out of coal fired power plants due to regulatory restrictions could result in a shift towards CCGT's and other forms of flexibility. Changes in generators bidding strategies due to changing portfolios and optimization choices [53].

5.3. Proposals for future research, modeling & implementation

This study has shown it is possible to model the Dutch FRR market, but still a lot of work has to be done. In this paragraph, an overview is given of a number of directions that could be explored in future research, modeling & implementation.

5.3.1. Scenarios

In this report, only a small number of scenarios were examined. There are a number of other important sources of flexibility that should be included to get a better view of the future landscape of balancing. The following scenarios should be explored:

- Demand response & demand side management: Demand side solutions use different methods to shift demand in time. A BRP could use this capability at customers to reduce its imbalance or sell balancing power to the market. For implementation of this scenario, the availability of demand shifting should be studied in detail.
- EV storage: firstly, the availability of electric cars that can be used is dependent on the behavior of their drivers. Secondly, there are two types of flexibility in EV, vehicle to grid (V2G) and smart charging. While the latter can only deliver flexibility by changing the charging rate, the former can be seen as a decentralized storage option. Thirdly, constraints on charge level and rate set by the car owner or user have to be taken into account. Finally, it is most probable that the storage in EV will be used to do a combined optimization for spot prices, passive balancing and active balancing. Further research has to be done on how to include this multi-market optimization for long term scenarios.
- HVDC flexibility: an important feature of HVDC interconnectors is the ability to control the power flow. In this way, flexibility could be imported from the Nordic countries or the United Kingdom. Adding this to the scenario could lead to increased flexibility, and thus lowered prices.
- Mixed scenarios: In reality we can expect a combination of different technologies delivering flexibility added on top of the base case scenario. It would be interesting to further investigate how those different technologies combine, complement and compete with each other. Therefore, a number of scenarios with different combinations should be tested.

5.3.2. Model extensions

Extensions to the model and scenarios can be made in multiple directions:

- Geographical: currently, the model only looks at the Dutch sources of imbalance and flexibility. Adding more countries to the model would add the possibility to calculate how much of the imbalance could be netted between countries. Effects of geographical spacing in development of wind and solar sites could be examined when this is done. For a successful implementation, the correlation between forecast errors in different geographical regions should be further investigated.
- Contracted FRR: contracted FRR sizing and pricing. For a thermal asset the costs of providing balancing power are lowest when their profits on the day-ahead market are the lowest. This results in a direct coupling to fuel prices for conventional power plants. Storage has only a binding with the costs of cycle losses. And thus, the coupling with dark- and sparkspread will become weaker as storage grows in delivery of balancing power. Another change to inspect, would be the impact of changing contract length (quarter, months, weeks or days) of contracted balancing power on contract and voluntary prices.
- External factors: effects of capacity mechanisms and intra-day markets on balancing markets.
- Agent based modeling: further explore the agent based approach as tested in [19] and investigating how system and player optimization models can complement each other.
- System changes: look at the impact of a stochastic market clearing model like implemented in Switzerland could improve the costs of balancing [51] for the Dutch FRR market.
- Computational technology: neural networks and massive parallel computation like CUDA [54] are promising technologies for power price forecasting [55, 56]. It would be interesting to use these technologies for short term forecasting in balancing markets.

5.4. Summary

Due to the complexity of the FRR market, many assumptions had to be made on imbalance, flexibility, market behaviour and their future development. As a next step, it would be important to further investigate these. Next to validation of assumptions and fitting parameters, improvements could be made to the model. Finally, extending the model could lead to new insights.

6
Conclusions

If I have seen further, it is by standing on ye shoulders of giants

- Sir Isaac Newton in a letter to Robert Hooke [57]

In the following paragraphs, answers to the research questions from Chapter 1 will be given. Following the structure of the research questions, we will formulate the conclusions of this project. First, the partial questions are answered and than, these are summarised in the answer for the main research question.

6.1. What are the fundamentals of this market?

Fundamentally, the need for balancing comes from the mismatch between supply and demand. These mismatches are caused by forecast inaccuracies, unforeseen events, system discretization and market participant behaviour.

Discretization imbalance originates from shaping effects when combining discrete trading systems with different temporal resolutions with a continuous need for matching supply and demand. In the Netherlands, there are day-ahead, intraday and balancing markets. On the day-ahead and intraday market, electricity is traded in hour blocks, while in the balancing market 15 minute blocks are used.

Imbalance from forecast inaccuracies are driven by the limited accuracy of weather predictions. When the day-ahead bid is made, a production forecast for the next 12 to 36 hours is used. This results in forecast errors for supply and demand. Within the current system, the need for balancing will grow due to the increased volume of forecast errors for VRES.

Unforeseen events, such as plant or line outages, also cause imbalance due to their unpredictable nature. Lastly, behaviour from market participants, like strategic position taking, can result in imbalance on the FRR market.

The setup of balancing markets is largely defined by ENTSO-E guidelines [22]. Changes to the balancing guidelines at a European level, will impact market volume and pricing. Thus ENTSO-E guidelines, and the implementation within the Dutch control zone by the Dutch TSO Tennet, play a fundamental role for the Dutch FRR market.

In the last decades power procured on the Frequency Restoration Reserve market was largely delivered by thermal plants and cross-border import and export. This resulted in a strong relation between the profitability of thermal plants (dark- and sparkspreads) and balancing prices. When thermal plants are running with high profits, the missed income from reserving bandwidth for balancing increases the prices in the upward direction. In situations with negative spreads, the costs of keeping a plant running are added to the costs of balancing capacity in both directions. Therefore, spreads around zero result in the lowest spread between spot and balancing market capacity and energy prices.

New sources of flexibility from decentralized assets, storage, demand response or management and wind curtailment are being implemented with a growing pace. They differ from the classical sources of flexibility in several ways:

- Availability: storage from EV, demand response or management and wind curtailment are not necessarily available at all times. Their availability is depending on car usage, wind speed and many more exogenous parameters. Thus, a flexible system and good insight on their stochastic behaviour is needed to optimally utilize the flexibility from these sources.
- Cost price: most new forms of flexibility are independent of fossil fuel and CO2 prices. Storage and demand side management have operational costs which are determined by their cycle or shifting losses. Wind curtailment pricing is mainly set by near zero running costs and the applied subsidy scheme.
- Scalability: flexibility from decentralized storage and demand side management has a much smaller granularity. Scaling from hundred EV to thousands of EV would require low additional investments.

6.2. How can we model the Dutch Frequency Restoration Reserve market?

This question proved to be helpful in the process of understanding this market both qualitative and quantitative. We choose to build the model bottom up, around the fundamentals found in the previous research question. Imbalance sources were categorized by their origination.

6.2.1. System discretization

- Hour to PTU shaping: imbalance due to the difference in block duration between the FRR and day-ahead market. The shaping was implemented as a sawtooth multiplied with the difference in demand between two adjacent hours.
- Sub PTU variations: variations in demand and supply within a FRR market block of 15 minutes. For the long term scenarios, sub PTU variations were left out of scope. Inclusion of sub PTU variations would require combining the random nature of imbalance on a longer timescale with the correlation between smaller time steps.

6.2.2. Forecast errors

- Wind forecast errors: the difference between day-ahead wind forecast and realization of power. This was modelled as the multiplication of a series of random samples from a double exponential distribution with the generated power.
- Solar forecast errors: the difference between day-ahead solar forecast and realization of power. Modeling took place similarly to the wind forecast errors, but with an independent random sample from the double exponential distribution.
- Load forecast errors: the difference between day-ahead load forecast and realization of demand. For the load forecast error the same sampling as for solar was taken, leading to fully correlated errors.

6.2.3. Other

- Outages: a combination of asset and line outages within the system, resulting in large amounts of imbalance in the upward direction. These can be implemented with randomized probability distribution.
- Strategic position taking: a choice of producers considering the price risks in both directions. Some

producers prefer a certain position due to the reliability of their forecasts and the differences in price risks in both directions. The total effect was added as a static delta to the imbalance for all time steps.

Summing all these sources, we generated a time series for the total imbalance. This time series was then multiplied with a correction factor, to account for the imbalance volume that is absorbed by IGCC and passive balancing, to derive the imbalance in the FRR market.

Flexible capacity of conventional assets were derived from the difference between their run level and minimal and maximal run level for each hour. For wind turbines with a curtailment option installed, the flexibility available was taken equal to the generated power output. In the storage case, the battery was assumed to be at a 50 % filled state at the start of every PTU. A more realistic model for storage availability should be a next step in further research.

Due to the large differences between cost prices and observed market prices, we chose to add revenue optimization based on historic prices and volumes. By combining historic market results with real time knowledge of producers about their flexible capacity and cost price, an optimized bid was made by weighing multiple scenarios. This implementation reflects market power exercised due to the low amount of market participants and market volume.

6.3. How will imbalance develop in the future in terms of volume and price?

A substantial growth of imbalance is expected. This growth is caused by a growth of the total volume of VRES day-ahead forecast errors due to a growth of VRES sources.

Looking at the long term, the market is highly sensitive to adoption of new technologies. While the base case showed increased prices, all scenarios showed a strong decrease in prices. A further reduction in price can be expected when more market participants will become active.

Looking at only FRR in the Netherlands is not sufficient for accurate modelling of this market. For more accuracy an integral approach should be taken for balancing and flexibility, expanding its view to the whole synchronous area. This makes the presented model in this report less appropriate for the use in business applications. Nonetheless, it proved to be useful in assessing the impact of different scenarios on the market.

6.4. What is the impact of improved wind forecast accuracy, large scale storage and wind curtailment on this market?

To get a clear view on the sensitivities of some important market developments, three scenarios were selected. These scenarios isolate one specific development to get a good understanding on its relative impact.

The wind curtailment case is especially interesting, because of the fixed cost price uncoupled from commodity prices. Due to the low cost price and large volume of wind curtailment, the prices on the negative side quickly flatten out. We expect a second order effect, resulting in default curtailment or a larger amount of static position taking by producers, to compensate for the asymmetric price risk.

An important limitation of wind curtailment is its availability. Subsequently, the number of hours with high price deltas for downward regulation will still grow, but with a smaller rate than in the base case scenario.

For the wind curtailment case, no default curtailment was added. In a scenario with an extreme difference between price deltas in upward and downward direction, profits could be improved by changing this curtailment strategy. Always curtailing a percentage of wind power, to be able to also deliver flexibility in the upward direction, could be an option. Currently, many wind farms in the Netherlands are subsidized. The current SDE subsidy scheme limits the use of curtailment. An increasing number of wind farms, that are out of their subsidized period, could increase the use of curtailment.

Immediately visible in the large scale storage case is the enormous impact on pricing. It is noticed that the increased number of high price PTUs, follows the base case until 2019. With an increasing volume of storage, the prices quickly stabilize and decrease towards the spot prices. When looking at the price duration curve, the number of high price PTUs become significantly lower, reaching 2015 levels in 2030. A small number of highly priced hours remain, when spot prices and imbalance prices are both high.

One of the main differences with wind curtailment, is the availability for both directions. Storage decreases prices in both directions, but the largest effect can be expected in the upward direction. Interestingly, due to the lower opportunity in the downward direction, storage is not offered to the market for every PTU. Moreover, in a combined curtailment and storage case, the value of storage will mostly be in the upward direction.

Further investigation is needed to determine the impact of the assumption that the storage returns to a 50 % charge level after every PTU. Secondly, the intertemporal independence between PTUs should be investigated. In the current implementation, the impact of large scale storage on the FRR market is high.

The impact of increased forecast accuracy is outpaced by the growth of imbalance caused by increased installment of VRES. Still, the 22 % reduction in imbalance, results in significantly lower price levels in the upward direction.

6.5. How will the Dutch Frequency Restoration Reserve market develop till 2030 in the Netherlands?

Combining the partial answers, we can answer the main research question. Through capacity contracts the Dutch TSO ensures capacity to provide both upward and downward regulating energy. Moving towards smaller periods for contracting, could enable more participants to become active in the market.

Storage and wind curtailment were shown to have an enormous impact on the availability of flexibility to the market and to market pricing. Wind curtailment will limit prices on the down regulating direction. While its availability coincides with wind production, it was shown in Chapter 4 that its availability is less than for storage. Improvements in VRES forecasting will have a much smaller impact.

The most important uncertainties for the future development of the FRR market are international harmonization and integration and liquidity of intraday and balancing markets as reviewed in Chapter 5. Combined with new forms of flexibility, this could lead to a different pricing regime than observed in the current scenarios.

7 Reflection

99 little bugs in the code
99 little bugs in the code
Take one down, patch it around
117 little bugs in the code
- Alex Shchepetilnikov

Finally, we made it to the finish line. Time to wrap up and gather what we learned during the last year of research. Being the first major research project carried out by the author, it proved to be a multifaceted learning experience.

7.1. Iterative non-linear process

At the start of the project, I was probably a bit to optimistic and a newcomer on the trajectory of a research project. At first, I was asked to make a model for both Frequency Containment Reserve and Frequency Restoration Reserve markets (voluntary and contracted parts) for five EU countries including multiple scenarios for the development of flexibility. A few iterations were needed to bring the scope of down to a size doable within a graduation project: the energy market of the Dutch Frequency Restoration Reserve market using a small selections of scenarios.

Still having a very broad and complex assignment, something I did not totally realize at the start, put me in the position of selecting the important bits to include. At first, this felt like being dropped in the midst of a large forest without a map. Bit by bit I figured out all important parts and the interaction between them. Than came the task of selecting what to include and what not. It confronted me with the inability to include everything in one model. I experienced that by being very selective of what to include, I could get far more insights of the effects of those parts.

Experiencing a number of setbacks,k made me realize I should keep a certain flexibility in my planning for an unforeseen learning experience every now and than. For example, the process of writing code for the model. This process could be best described by the little rhyme in the epigraph. Being largely an autodidact with Matlab, this meant hours of debugging and searching solutions via Google and StackOverflow. Main learning points will be trivial to the more experienced programmers, document the code and work modular. It resulted in some extended evening sessions and headaches, but also made me learn a lot of new tricks with Matlab. For a next project I plan to switch to using R or Python due to them being open-source having both large communities of active users.

7.2. Power of peers

Having peers around, for both casual and more in depth discussions, proved to be extremely valuable. Discussions with Remco proved to be especially valuable due to the open minded approach. It brought me a lot of ideas, which I would like to contintue working on.

Bridging academics and business was sometimes challenging but proved to be mostly a source of insight. Especially with a subject where much hands on in depth knowledge exists amongst colleagues. It was good to be challenged on method and implications from both business and academic perspective.

In the finalization of my research project, I already started working as employee for Eneco on other very interesting projects. This slowed down the finalisation of my thesis considerably and placed me in the sometimes stressful position of working on many different topics.

7.3. Handling complexity

This study also confronted me with the quickly growing complexity of energy markets. While, for example the use EV for balancing is an improvement, it is a challenge for those want to integrate it in to their models. Looking at only FRR in the Netherlands, is simply not enough anymore to model this market. To do this we have to integrally look at all forms of balancing and flexibility and expand our view to the whole synchronous area.

I am very thankful that I have been given the opportunity to continue working in this field of research. My goal for the years to come, is to get a better understanding of how we can build frameworks to model this complexity in transitioning flexibility markets.

A

Assumptions

Due to the complexity, scope and time limitations assumptions had to be made for the modeling of imbalance, market operation, future trends and market participant behaviour. Below a comprehensive list of assumptions is given.

A.1. Imbalance sources

- Wind and solar forecast errors are independent
- Solar and load forecast error are fully correlated and only differ in relative size
- Wind, solar and load forecast errors have a double exponential distribution
- A fixed reduction from modelled imbalance to FRR market imbalance as a result of IGCC, passive steering and intraday trade. This was assumed to be a fixed factor for all future years.
- No auto-correlation between PTUs is taken into account

A.2. Markets

- No intra-day markets
- Day-ahead market is solved as a unit commitment problem
- Primary control reserves are out of scope
- Contracted volume of the FRR market is 300 MW for all years
- IGCC is not based on imbalance modelled in surrounding countries
- No feedback loop between balancing market and day-ahead market
- The market is not functioning optimally and producers use their market power in setting higher prices

A.3. Optimization

- All asset owners optimize using the same objective function
- Prize versus market volume relations for the optimization scenarios are update on a yearly base. This implies a slow yearly cycle of the learning effect of producers.
- The producers optimize each asset instead of a whole portfolio at once.

- Cost prices for thermal producers are estimated to be equal to their short run marginal costs

B

Plant parameters

Table B.1 gives an overview of the parameters used per plant type. Ramprates were based on expert opinions and [44]. Note that the ramprates shown here are reduced, to take the delivery of FCR by the same plant into account.

Table B.1: Technical parameters for plant types for FRR included in the model

	Ramprate (%/PTU)	Minimum stable level (%)	Upward participation	Downward participation
CCGT	25	40	10	10
Gas Turbine	25	50	10	10
Solar	100	0	0	0
Coal	10	50	20	20
Nuclear	5	100	0	0
Wind	100	0	0	100
Storage	100	0	100	100

C

Fitting variables

The following fitting variables and values were used:

- Imbalance market share: a factor for the imbalance market share f_{imb} was used to optimize the incentive of offering at a low price of market participants. A value of $0.1 \times (randn + 0.5)$ was used with $randn$ being a random number between 0 and 1.
- Imbalance reduction: the sum of imbalance from various sources was multiplied with 0.285 to come to volume of imbalance in the FRR market.
- Bid volume granularity: for every producer its flexibility volume was linearly split in 6 steps from 0 to $F_{gt,max}$.
- Sample width: for selecting scenarios, a sample width of 100 was used. From the previous year, the 100 PTUs with the smallest absolute difference with the expected day-ahead price were used. This was done to account for the different pricing regimes in the balancing market during day and night and weekday and weekends. From this selection 5 scenarios were drawn at random and used for the optimization process. This was done to reduce the needed calculation time.

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