Wessel Bakker

Cost reduction potential of demand response from a system perspective

A statistical approach to quantify the effect of the participation of demand response on the price of flexible capacity in balancing markets of the Netherlands and Great Britain

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A statistical approach to quantify the effect of the participation of demand response on the price of flexible capacity in balancing markets of the Netherlands and Great Britain

Utrecht University, Copernicus Institute of Sustainable Development

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Author: Wessel Bakker

Contact: wessel.bakker@me.com

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Supervisors Utrecht University

Dr.ir. Ioannis Lampropoulos (supervisor)

Dr. Elena Fumagalli (second reader)

Utrecht University, Faculty of Geosciences, Copernicus Institute of Sustainable Development, Group of Energy & Resources

Supervisors Sympower

Dirk-Jan Middelkoop, Head of Sales & Expansion, Sympower

Federica Tomasini, Expansion Manager, Sympower

ABSTRACT

In 2021, the European Union (EU) had set the ambitious goal of reaching net-zero greenhouse gas emissions in 2050. To achieve this goal, the way we use energy needs to change radically, and the shift towards renewable energy sources (RES) has to be made. The electricity grid will face significant challenges due to the shift towards RES such as solar and wind energy, as electricity production will be increasingly intermittent, volatile, and unpredictable. Therefore, one of the main challenges of the energy transition is to constantly keep the balance between the demand and supply of electricity, as this is essential to have a reliable and safe electricity system. Demand response (DR) can potentially provide a cost-efficient alternative for balancing the electricity grid. In contrast to the traditional way of balancing the grid which adjusts the production of electricity, with DR, the demand of electricity is adjusted to match it with the supply.

Electricity grid operators buy flexible capacity on balancing markets to balance the grid. When DR can offer flexible capacity for a lower marginal cost, it has the ability to bid a lower bid price on these markets. This enables grid operators to reduce costs in buying flexible capacity, which can lower the cost of the electricity system.

This research aims to quantify the cost reduction potential of DR from a system perspective. Historical data of balancing markets in Great Britain and the Netherlands are analyzed using regression, correlation, and average bid price analysis to quantify the effect of the participation of DR on the price of flexible capacity. Next to that, opportunities and barriers have been identified in sharing more detailed data of balancing markets to enable this quantification.

The results show that for most balancing markets included in the scope, a significant price reduction is estimated due to the participation of DR. It is estimated that DR bids on average 35% lower than the market average. Next to that, the regression analysis estimated that a 1% higher participation of DR in balancing markets on average leads to a 2.7% lower price for flexible capacity. Looking at the current average participation of DR in the markets included in the scope, it is estimated that the price in these markets has dropped by 10%-20% due to the participation of DR. By extrapolating this, it is estimated that the price reduction of flexible capacity in balancing markets in 2030 ranges from 43% to 71% compared to a situation without the participation of DR.

The results also show that the main opportunities of sharing more detailed data of balancing markets are lower barriers for new market entrants, increased market efficiency, improved reputation for grid operators, and easier identification of DR potential. The main barriers are the extra burden for grid operators, harm of privacy of business, risk of collusion, the political view on regulation and transparency, and the lobby of the industry.

PREFACE AND ACKNOWLEDGEMENT

This research is conducted in a context and would not have been possible without all the people and organizations that contributed to the project. I would like to thank them individually.

This research has been conducted as part of the master's program of Energy Science at the University of Utrecht. The master's program of the university provided the theoretical background for this research. Next to that, my university supervisors helped shape the research scope and methodology. Therefore, I would like to thank Utrecht University, with special thanks to my supervisors Ioannis Lampropoulos and Elena Fumagalli, for providing feedback and being a great sparring partner.

The context of this research was given by the host organization Sympower, a demand response aggregator with an international presence in balancing and electricity markets. This context led to the idea and initiative to start this research. Sympower also provided knowledge about balancing markets and the methodology to calculate the relevant variables for this research. Next to that, Sympower provided the network for finding relevant interviewees and contacts at TenneT, the Dutch transmission system operator, to collect the required data to add the Netherlands as a case study to this research. Therefore, I would like to thank Sympower, with special thanks to my supervisors Dirk-Jan Middelkoop and Federica Tomasini.

TenneT contributed to this research by sharing data of the Dutch balancing markets. Therefore, I would like to thank TenneT, with special thanks to Martijn Ophuis, who helped to provide the data.

Lastly, I would like to thank all the interviewees working at Sympower, Utrecht University, and TenneT for participating in the interviews.

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TABLE 1 LIST OF SYMBOLS

Variable	Symbol	Unit
Flexible capacity	C	MW/h
Share of flexibility source in total accepted capacity	S	%
Price of flexible capacity	P	$\frac{€}{MW/h}$ (NL) or $\frac{£}{MW/h}$ (GB)
Average share in total accepted capacity	$\bar{S}$	%
Average price of flexible capacity	$\bar{P}$	$\frac{€}{MW/h}$ (NL) or $\frac{£}{MW/h}$ (GB)
Relative cost reduction (Regression analysis)	RCR_{RA}	$\%_P/\%_S$
Relative cost reduction (Average bid price analysis)	RCR_{ABA}	$\%_P$
Cost reduction	CR	$\%_P$
Regression analysis	RA	$\frac{£}{\%}$ or $\frac{€}{\%}$
Average bid price analysis	ABA	£ or €
Correction factor	CF	
Sub-script	**Symbol**	**Example value**
Flexibility source	f	Battery, gas turbine, demand response etc.
Balancing sub-market	m	• GB: FFRd (m=1), FFRs (m=2), BM (m=3) • NL: aFRR (m=4), mFRR (m=5)

Reference to an individual bid of party providing flexibility	b	
Tender period	t	Month, day of year, ½ hour
Hour	h	
Demand response	DR	
Year	y	Estimation in the year 2022 or 2030
Average bid price analysis	ABA	
Regression analysis	RA	

List of equations

Equation number	Equation
3.1	$\overline{P_{m,f,t}} = \frac{\sum_{b=1}^{B} P_{m,b,f,t}}{N}$, $(b \in 1, 2, \ldots, B)$
3.2	$\overline{P_{m,t}} = \frac{\sum_{b=1}^{B} P_{m,b,,t}}{N}$, $(b \in 1, 2, \ldots, B)$
3.3	$C_{m,f,t} = \sum_{b=1}^{B} C_{m,b,f,t}$, $(b \in 1, 2, \ldots, B)$
3.4	$C_{m,t} = \sum_{b=1}^{B} C_{m,b,t}$, $(b \in 1, 2, \ldots, B)$
3.5	$S_{m,f,t} = \frac{C_{m,f,t}}{C_{m,t}} \times 100\%$
3.6	$P_t = a - x\, S_{DR} + y\ gas\ price + error$ *(example regression model)*
3.7	$RCR_{RA,DR,m,y} = \frac{RA}{\bar{P}_{m,y}}$ *(Regression analysis)*
3.8	$RCR_{ABA,DR,m,y} = \frac{ABA}{\bar{P}_{m,y}} \times 100\%$ *(Average bid price analysis)*
3.9	$CR_{DR,m,y} = RCR_{RA,DR,m,y} \times \bar{S}_{DR,m,y}$
3.10	$RCR_{DR,ref} = \frac{\sum_{m=1}^{M} RCR_{DR,m,ref}}{M}$ $(m \in 1, 2, \ldots, M)$
3.11	$RCR_{DR,ref} = RCR_{DR,2030}$
3.12	$CR_{DR,2030} = RCR_{DR,2030} \times \bar{S}_{DR,2030}$
4.1	$P_{FFRd} = 7.66 - 0.059\, S_{FFRd,Battery} - 0.12\, S_{FFRd,Load\ response} + 0.055 GP_{GB}$ *(regression model FFRd market)*
4.2	$P_{mFRRda\ Up} = 2.35 - 0.13\, S_{mFRRda\ Up,DR} + 0.15 GP_{NL}$ *(regression model mFRRda Up market)*
4.3	$P_{mFRRda\ Down} = 2.48 - 0.37\, S_{mFRRda\ Down,DR} + 0.16 GP_{NL}$ *(regression model mFRRda Down market)*

List of acronyms

Acronym	Explanation
AC	Alternating current
aFRR	Automatic frequency restoration reserve
BM	Balancing Mechanism
CCGT	Combined cycle gas turbine
DER	Distributed energy resources
DR	Demand response
DSF	Demand-side flexibility
EU	European Union
FFR	Firm frequency response
GB	Great Britain
GHG	Greenhouse gas
IoT	Internet of things
ISP	Imbalance settlement period
IT	Information technology
mFRRda	Manual frequency restoration reserve, directly activated
NL	The Netherlands
OCGT	Open cycle gas turbine
RES	Renewable energy sources
TSO	Transmission system operator
VIF	Variance Inflation Factor
VLP	Virtual Lead Party
V2G	Vehicle-to-grid

1 INTRODUCTION

This chapter starts with an overview of the challenges of the energy transition, after which the (economical) solution to these challenges of demand response is explained. Subsequently, the research gap is identified, forming the basis for the formulation of the research questions and the hypotheses. Lastly, the scope, the introduction to the methodology, and the scientific contribution are presented.

1.1 PROBLEM STATEMENT

In 2021, the European Union (EU) had set the ambitious goal of reaching net-zero greenhouse gas emissions in 2050 (European Commission, 2021a). To achieve this goal, the way we use energy needs to change radically, and the shift towards renewable energy sources (RES) has to be made. Wind and solar power have the highest potential in generating renewable electricity in the EU (IRENA, 2018).

The electricity grid will face significant challenges due to the shift towards RES such as solar and wind energy, as electricity production will be increasingly intermittent, volatile, and unpredictable. Therefore, one of the main challenges of the energy transition is to constantly keep the balance between the demand and supply of electricity, as this is essential to have a reliable and safe electricity system (Aghaei & Alizadeh, 2013).

The traditional way to balance the electricity grid is mainly to adjust the production of fossil-fueled power plants to match the supply with the demand. As these power plants will have a decreasingly important contribution to the electricity supply system in the future, additional methods of balancing the grid should be used by electricity grid operators. A lot of research has been conducted to find solutions to replace fossil-fueled power plants as a flexible source to balance the grid. Besides the support of transmission interconnections between different systems, electricity grids can be balanced by utilising the flexibility of three types of electrical assets: generation, storage, or demand response (DR) (Jabir, Teh, Ishak, & Abunima, 2018; Lotfi, Monteiro, Shafie-Khah, & Catalao, 2018). Balancing the grid with large-scale storage units like batteries is (still) too costly and requires an enormous amount of natural resources (Staffell & Rustomji, 2016). Nowadays, there is a growing consensus among scientists, policymakers and electricity market participants that DR is an essential source of flexibility that needs to be developed to maintain a balanced electricity grid in the future (Hurley, Peterson, & Whited, 2013).

1.2 SOLUTION OF DEMAND RESPONSE

DR is one of the *ancillary services* that grid operators deploy to maintain grid stability, safety, and reliability in response to real-time variances in the power supply and demand (Tomar & Kandari, 2021). Balancing the supply and demand is a crucial purpose of ancillary services. Imbalances can occur in moments of unexpected events on the grid, like an outage of a power plant or unexpected high electricity consumption.

DR programmes, as part of demand-side management (DSM) which also includes energy efficiency measures, has the potential to (partly) replace power plants as a flexibility source to balance the grid (Oconnell, Pinson, Madsen, & Omalley, 2014). In contrast to the traditional way, with DR, the imbalance in the electricity system is solved by adjusting the demand of electricity to match it with the supply (Lampropoulos, Kling, Ribeiro, & van den Berg, 2013). The used definition of DR is "*The process through which final consumers (households or businesses) provide flexibility to the electricity system by voluntarily changing their usual electricity consumption in reaction to price signals or to specific requests, while at the same time benefiting from doing so*" (Eurelectric, 2015).

Apart from the technical functionality of DR, the economic aspect plays a vital role in developing this balancing method. Focusing on cost-effective solutions is crucial in the energy transition. DR could lower the costs of the electricity system in multiple ways (Bradley, Leach, & Torriti, 2013). An important example of this is that DR can lower the cost of balancing the supply and demand on the grid (Oconnell et al., 2014).

In countries that allow DR, flexibility suppliers can periodically offer their demand-side flexible reserve capacity on balancing markets to transmission system operators (TSO) for a particular bid price. TSOs are responsible for the high-voltage transmission grids that transport electricity over long distances. The bid price represents the financial remuneration if they get accepted (van der Veen & Hakvoort, 2016). These balancing markets consist of multiple sub-markets, with the most important difference being the reaction speed, the supplier's financial remuneration, and the number of activations that occur. Based on the need for flexibility in the electricity system, TSOs buy flexible capacity on multiple balancing markets in the most cost-efficient way. Having purchased this flexible capacity allows the TSO to adjust the consumption or production of electrical devices to bring back the balance on the grid on moments of unexpected behaviour of the production or consumption of electricity which causes an imbalance (Ocker, Braun, & Will, 2016).

In this research, it is investigated whether DR can reduce costs for balancing the electricity system by having a lower marginal cost than alternative balancing methods. The balancing markets of the Netherlands (NL) and Great Britain (GB) are used as case studies. The assumption is that when DR has a lower marginal cost, DR capacity will therefore be offered on the balancing markets for a lower price due to competition on the markets. When more flexible capacity is available for a lower bid price, the price for flexible capacity will decrease. A lower price for flexible capacity will lower costs for TSOs to balance the grid.

1.3 RESEARCH GAP

The economic benefits from a system perspective of DR are often discussed in academic literature. The literature review in Appendix Table 20 summarises the different ways of how DR can reduce costs for electricity. It shows that it has been extensively studied how DR can reduce costs in avoiding investments in grid and production capacity, and on the wholesale electricity markets by lowering electricity price. However, less focus is on estimating the cost reduction of DR in balancing the grid. Academic literature and TSO reports that do look at this cost reduction of DR are discussed.

In a report of the European Commission, Bertoldi (2009) states that DR can offer *"cheaper and "cleaner" solutions to balancing the grid"*. However, no research methodology is presented in this report. Studies like Vlachos & Biskas (2013) simulate the costs made by grid operators on balancing markets by comparing the cost-effectiveness of different balancing market designs for a specific region and include demand response. Nevertheless, the study has not specifically estimated the effect of the participation of DR on the balancing costs. Dietrich, Latorre, Olmos & Ramos (2016) find that there are system cost reductions of implementing DR for balancing the grid and that it "*may be economically reasonable*" from the system operator point of view. A modelling approach was used as a methodology. Strbac (2008) takes a different approach and estimates a small economic benefit of DR providing flexibility to the system by looking at the operational cost of DR compared to a gas turbine. Bradley et al. (2013) give a good overview of the different system cost reductions of DR, but state that *"it was not possible to provide an average annual estimate of the value of DR to avoid the need for generation capacity to provide a reserve for emergencies/unforeseen events"*.

To summarise, existing academic literature has focused on estimating the cost reduction of DR in balancing markets based on simulation models or by comparing operational costs. In contrast, literature that uses observational data to estimate the relationship between the participation of DR in balancing markets and the cost of flexible capacity for TSOs has not been found. Observational data means here *''Data obtained by observing actual behavior outside an experimental setting"* (Stock & Watson, 2019). In the context of balancing markets, observational data refers to the balancing markets' historical data.

In many countries, DR is not allowed to participate in balancing markets due to regulation. Therefore, no relevant data is available for this research in these countries. In TSO market reports of countries that do allow DR, some insights have been given on the effect of the participation of DR on the balancing costs. Fingrid, the Finnish TSO, reports the share of DR in the total capacity of the balancing markets (Fingrid, 2020). A price drop can be seen at the moment DR started participating in the balancing markets. However, the data is not detailed enough to do analysis on and to isolate the effect of the participation of DR. Next to that, the *Annual Market Update 2019* of Dutch TSO *TenneT* states that the prices for flexible capacity had dropped on the balancing market due to increased offered capacity when DR was allowed to participate. However, this does not say something about DR specifically, but rather about the effect of increased competition on these markets. In the *Power Responsive* reports of *National Grid*, the TSO of GB, insights have been given on the average bid prices of DR on balancing markets. It shows that DR bid prices are usually lower than traditional flexibility sources. These reports form a sound basis for both the hypothesis and the analysis of the bid prices of DR. However, the depth of analysis is limited and external factors on prices have not been taken into account. Therefore, a more in-depth analysis is needed to estimate the cost reduction of DR on balancing markets.

1.4 Research questions and hypothesis

The scope of this research and related research questions are based on the identified research gap. This study focuses on the cost reduction from a system perspective that DR can realize on balancing markets. In contrast to the approach of most existing literature, the focus of this research is on using observational data of balancing markets to quantify the effect of the participation of DR on the prices of flexible capacity.

The underlying hypothesis of this study, which is based on the described literature, is that higher participation of DR on balancing markets will result in a lower price for flexible capacity, as DR has a lower marginal cost than other competitive technologies (Bradley et al., 2013; Strbac, 2008). As a result, this would lead to lower costs for TSOs. This hypothesis is tested in this research.

This leads to the main research question:

What is the cost reduction potential of demand response participation in balancing markets from a system perspective?

To quantify this effect, the relationship is statistically measured between the two main variables: the price of flexible capacity on balancing markets and the share of DR in the total accepted capacity on balancing markets.

This research also aims at consulting TSOs on which data should be shared to perform the analysis that is conducted in this research. Next to that, the aim is to consult TSOs on the question of whether they should share this data. This is done by identifying the barriers and opportunities of sharing data that support similar analyses. This qualitative part of the study is included, because a limitation to the quantitative methodology of this research is that the required data is not always publicly available. Therefore, this approach can only be applied to a limited number of countries. If this data is available, it is usually shared by TSOs that collect this data. There can be justified reasons why TSOs do not share this data, such as protecting the privacy of businesses participating in balancing markets. On the other hand, sharing this data makes it possible to do analyses and bring more transparency to these markets.

Lastly, this research looks at how a potential cost reduction of DR will change towards the year 2030 and how this will affect the incurred costs for TSOs to balance the grid.

To answer the main research question, the following sub-questions have been formulated:

1) *Which data are (or should be) shared by transmission systems operators and national regulators to support analyses on the potential of cost reduction on system balancing through the participation of demand response?*

2) *What is an appropriate method for performing analyses on the potential of cost reduction on system balancing through the participation of demand response?*

3) *What are the opportunities and barriers to publicly sharing data on balancing markets?*

4) *What is the (quantitative) relationship between the share of demand response in the total accepted capacity and the price of flexible capacity on balancing markets?*

5) *How will the participation of demand response in balancing markets change towards 2030 and how will this affect the incurred costs for TSOs to balance the grid?*

The hypothesis that is tested in this research is as follows:

- Hypothesis: ***A higher participation of DR in balancing markets organised by TSOs will lead to lower prices for flexible capacity.***

1.5 RESEARCH SCOPE AND INTRODUCTION TO THE METHODOLOGY

The first and second sub-question is answered by proposing calculational steps to translate data from balancing markets to variables that can be used for analysis to test the hypothesis of this research. To answer the third sub-question, interviews have been conducted to identify opportunities and barriers for TSOs and national regulators to share detailed data on balancing markets to support such analyses.

Data that has been collected to answer the fourth sub-question are for the countries GB, via public data, and the NL, via undisclosed data of TenneT which was made accessible specifically for this research. These countries will be used as case studies. The *automatic frequency restoration reserve* (aFRR) and the *manual frequency restoration reserve* (mFRR) balancing markets/products of the Netherlands (NL) and the *firm frequency response* (FFR) and *balancing mechanism* (BM) sub-markets/products in Great Britain (GB) are included in the scope. The results of the auctions on these markets are used to statistically identify a trend between the share of DR in the total accepted capacity, and the price of flexible capacity. This is done using regression analysis, correlation analysis, and by comparing the average bid prices of different flexibility sources. As there are multiple balancing sub-markets that are not harmonised in every country, the results of this research cannot be directly translated to different countries. To improve the external validity of the results of this research, a cross-market and cross-country comparison is conducted after the results are collected for the two case studies.

To answer the fifth sub-question, scenarios are presented that forecast or represent the share of participation of DR on the balancing markets in NL and GB up to the year 2030. These scenarios have been constructed based on academic literature and reports of research institutions that give predictions on how the participation of DR in balancing markets will change in the future. Consequently, the scenarios are used to predict how the change in the share of participation of DR will affect the costs incurred by TSOs to balance the grid up to the year 2030. This is done by extrapolating the results found in the fourth sub-question.

1.6 SCIENTIFIC CONTRIBUTION

The results of this research will help the decision-making in choosing cost-effective solutions for the energy transition and to make it more affordable for society. This research has scientific relevance, as it provides a generic methodology which is applied to two case studies thus contributing to existing literature.

DR still represents a small share of the flexible capacity that grid operators use, mainly due to regulatory and technical barriers. It is estimated that a tenfold increase is needed in the flexible capacity of DR to reach the EU 2030 sustainability goals (IEA, 2021). TSOs and national regulators play an important role in the development of DR. If this quantification of this research will support the hypothesis that DR is a cost-effective way of balancing the grid, then this result can convince TSOs and national regulators to accelerate the development of DR.

2 THEORETICAL BACKGROUND

This chapter provides the theoretical background for this research. The chapter starts with a historical background of DR, after which balancing markets are introduced. Subsequently, the difference between flexible capacity and flexible energy is explained. Next to that, the different types of price settlements are explained, which are used for determining the prices in balancing markets. Afterward, the (marginal) cost of providing DR is explained. Lastly, the different balancing market designs of the countries included in the scope are introduced.

2.1 HISTORICAL BACKGROUND

DR and its associated scientific research have evolved over the last decades. At first, DR was enabled at the end of the 20th century by the liberalization of the electricity sector and the establishment of electricity markets. Later, the balancing markets were also established in many European countries. The increased penetration of smaller, and Distributed Energy Resources (DER) stimulated the participation of consumers as active players in the market. Smart Grids and the more recent development of the Internet of Things (IoT), enabled by the advancement of information technology (IT), further helped the growth of DR (Lotfi et al., 2018). The recent exponential increase of the penetration of RES raises the challenges of maintaining a reliable and safe grid and therefore emphasizes the importance of DR programs even more.

2.2 BALANCING MARKETS

Balancing markets are used by TSOs to maintain the balance on the grid. This balance is reflected in the frequency of the alternating current (AC) on the grid. This frequency is 50 Hz in most parts of the world. Having too big deviations from this frequency can cause safety and reliability issues for the electricity grid. Figure 1 shows the effect of consumption and generation (=production) of electricity on the frequency on the grid. When a frequency deviation is measured on the grid, the TSO 'activates' electrical devices that participate in the balancing markets to adjust the consumption or production, according to the needs of the grid. Two directions of flexible capacity regulation can be distinguished: up (increase production or decrease consumption) and down (decrease production or increase consumption).

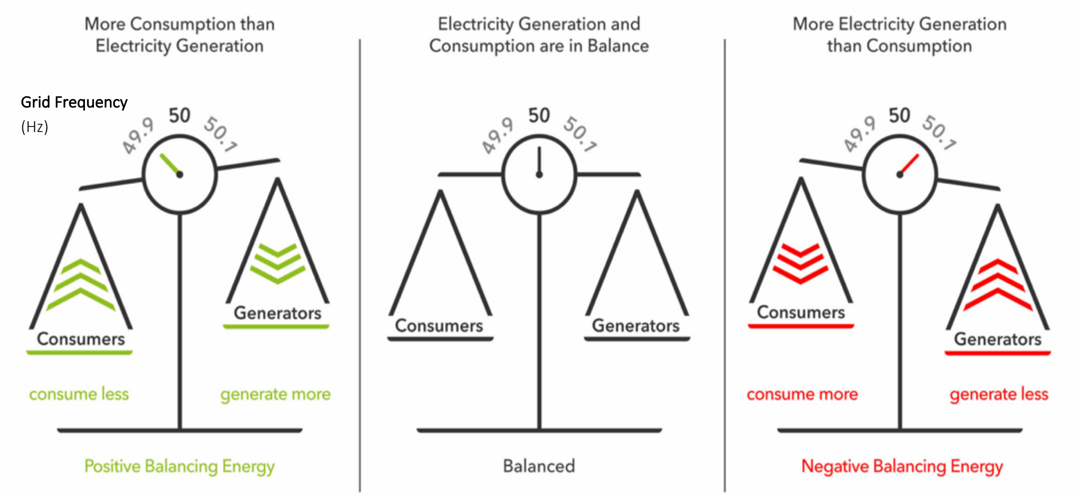


FIGURE 1 THE EFFECT OF CONSUMPTION AND GENERATION OF ELECTRICITY ON THE FREQUENCY ON THE GRID (NextKraftwerke, n.d.)

2.3 PRICES FOR BALANCING CAPACITY AND ENERGY

Two types of flexibility are traded on balancing markets*:* *balancing energy* and *balancing capacity*. If *balancing capacity* is traded, the TSO pays the flexibility provider to have flexible capacity available at any moment during the tender period. In other words, the participants receive a *capacity payment* to be 'stand-by' for moments of an imbalance on the grid. Even though there might not be an activation, they still get paid. In some balancing markets, participants also receive an extra financial *energy payment* when they actually get activated. Some markets only use *balancing energy* remunerations (Emissions-EUETS, 2021).

The amount of remuneration for *balancing capacity* is based on the amount of time and capacity you are accepted for. The unit used for *balancing capacity,* therefore, is MW (10^6 Watt per hour) per settlement period of one hour. The *balancing energy* remuneration is based on the amount of energy that is consumed/produced less/more during an activation. The unit used for balancing energy is therefore MWh.

2.4 PRICE SETTLEMENT

Two main types of price settlements can be distinguished on balancing markets. This is the way prices for flexible capacity are determined per tender period. The two types are *pay-as-bid* and *pay-as-cleared.* Which way is favorable per balancing market depends on how much market information is available for participants, the number of participants, the capacity that is offered, and the level of competition (Elia, 2020). The two types of price settlements can best be explained using an example in Figure 2.

After all the bids of the market participants have been received by the TSO, they are placed in ascending order on bid price in a *merit order*. A merit order is a graph with on the x-axis the capacity of the bids (MW/h or MWh) and on the y-axis the bid price (€/MWh e.g.). For every tender period, the TSO determines how much flexibility they need and chooses the cheapest combination of bids to buy this capacity.

In the case of the example in Figure 2, the TSO needs 9 MW/h for an hourly tender period. It is the cheapest option to accept Bids A, B, and C and to reject Bid D.

- In the case of *pay-as-cleared*, all the accepted bids (Bid A, B, and C) receive the highest bid price of all the accepted bids: €15/MW/h
- In the case of *pay-as-bid*, every accepted bid receives its bid price: Bid A receives €5/MW/h, Bid B receives €10/MW/h, Bid C receives €15/MW/h.

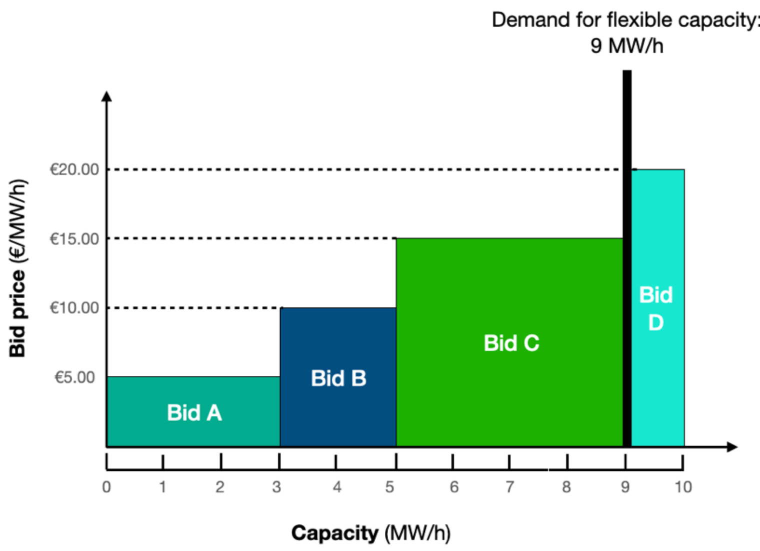


FIGURE 2 EXAMPLE OF MERIT ORDER FOR HOURLY TENDER OF BALANCING MARKET

Depending on the type of price settlement, market participants can choose different bidding strategies. When the flexibility provider has low marginal costs, they want to ensure that they are accepted. Bidding a low bid price is then the best option in a *pay-as-cleared* market, assuming that other participants will bid higher which keeps the price high. This increases the chance that they get accepted and that they make money. In the case of flexible capacity, marginal cost is defined as the cost that arises when the participant offers one extra MWh of flexible capacity. Participants with high marginal costs bid higher and only want to be accepted when the price is high, otherwise, they will lose money by participating.

However, in the case of a *pay-as-bid* market, bidding at a lower price also means that you receive a lower price when your bid is accepted. Therefore, in the case you want to be accepted on a *pay-as-bid* market, it is best to bid just under the highest bid price of the accepted bid. This requires forecasting of what other participants will bid and what the need for flexibility will be (Elia, 2020).

2.5 COST OF PARTICIPATING

When flexibility providers participate in balancing markets, they give up some control over their electrical devices. This cost or inconvenience is what the participating providers receive financial remuneration for. Theoretically, understanding this level of inconvenience for the different types of loads helps to explain the bidding behavior and the marginal cost of participants.

Three types of participants can be distinguished: residential, commercial/business, and industries (Herre, 2020). Table 2 gives an overview of the costs for the different types of participants that relate to an activation on the balancing markets. It distinguishes the costs for increasing (↑) or decreasing (↓) of production or consumption of electricity. Nowadays, flexible DR capacity mainly comes from industries, but it is expected that residential and commercial/business DR will play an increasingly important role in the near future (Wang, Zhong, Ma, Xia, & Kang, 2017).

TABLE 2 COSTS OF PARTICIPANTS TYPE OF PROVIDING FLEXIBILITY ON BALANCING MARKETS (Accenture, n.d.; European Commission, 2021b; Herre, 2020; SmartEn, 2021)

Type of participant	Example type of assets	Type of flexibility		Cost
Residential	Dishwasher, fridge, heat pump, electric vehicle charging	Consumption	↑	• Extra electricity cost • Inconvenience (e.g. too low temperature in room)
			↓	• Inconvenience (e.g. too high temperature in fridge)
	Solar PV, vehicle-to-grid (V2G)	Production	↑	• Increased degradation battery (V2G)
			↓	• Solar energy production loss • Increased degradation battery (V2G)
Commercial /businesses	Air-conditioning, ventilation, electric buses, heat pump	Consumption	↑	• Extra electricity cost • Inconvenience (e.g. too high temperature in building)
			↓	• Inconvenience (e.g. too low temperature in building)
	Solar PV	Production	↑	• Increased degradation battery (V2G)
			↓	• Solar energy production loss
Industry	E boiler, heat pump	Consumption	↑	• Extra electricity cost • Excess heat
			↓	• Production process disturbed • Loss of production
		Production	↑	• Extra fuel cost, excess heat

	Combined heat and power (CHP), gas turbine, wind turbine		↓	• Loss of production

2.6 Marginal cost bidding

Economic theory and academic studies suggest that electricity or balancing markets can be modeled assuming that participants will bid on their marginal costs, with a profit margin (Poplavskaya, Lago, & de Vries, 2020; Son, Baldick, Lee, & Siddiqi, 2004; Vlachos & Biskas, 2013). Although this theory is often discussed and criticized in literature (Cramton, 2004), it is a reasonable assumption that the bid price is, most of the time, an indication of the marginal cost that the participant has. Bidding below your marginal cost would mean that you lose money by participating in the market. Bidding above your marginal cost brings the risk that your bid will not be accepted, even though you would have made money by participating.

As the methodology of this research only includes the balancing market tender results, the bid price is the only data available to estimate the marginal cost of market participants or flexibility sources. Therefore, the assumption is made in this research that the bid price is an indication of the marginal cost. Later in this research, this assumption will be referred to as the *marginal cost bidding assumption*. If this assumption is made, an example of a merit order of a balancing market could look like Figure 3, in which the bid price is equal to the marginal cost of the flexibility sources. In this example, the flexible capacity of a hydropower source bids a lower bid price than a gas-fired power plant, because it has a lower marginal cost of providing flexible capacity. The question asked in this research is where DR could be placed in this merit order by analyzing the relationship between the participation of DR in balancing markets and the price of flexible capacity.

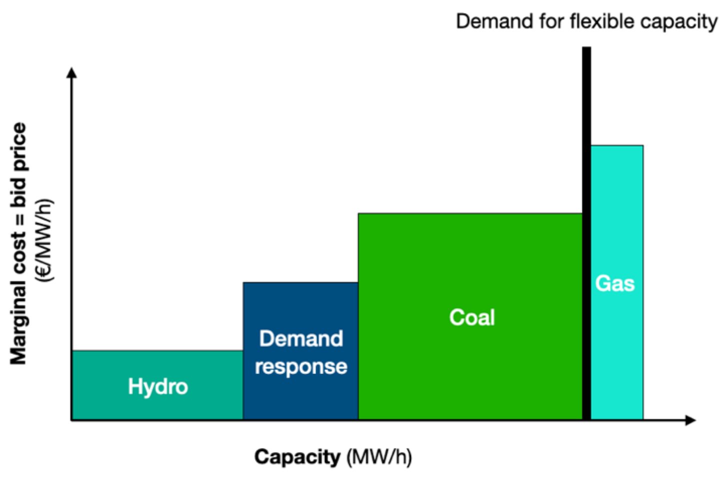


Figure 3 Example merit order of balancing market assuming that flexible capacity is bid with marginal cost as the bid price

2.7 BALANCING MARKET DESIGN

The balancing market design of the two case studies of this research, GB and NL, is significantly different. A reason for this is that the electricity grids of the two countries are part of different synchronous areas, as presented in Figure 4. Countries in the same synchronous area have the same frequency at all times on their electricity grid which makes it possible to trade flexibility across countries.

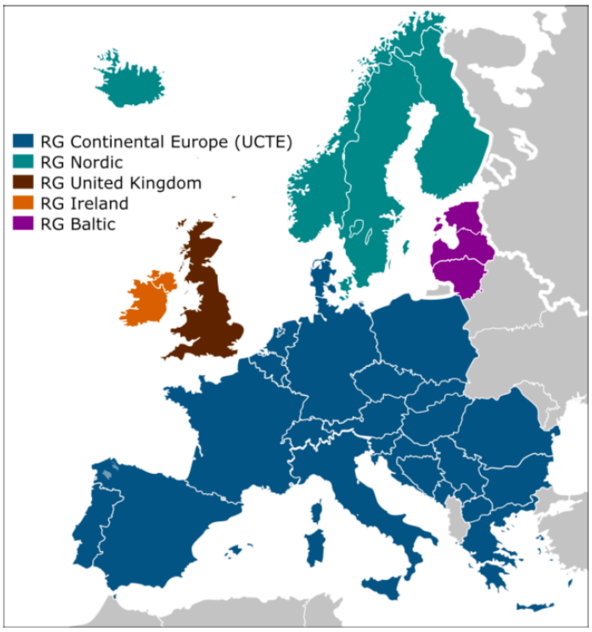


FIGURE 4 SYNCHRONOUS AREAS OF ELECTRICITY GRIDS IN EUROPE (RG: REGIONAL GROUP) (Wikipedia, n.d.)

2.7.1 BALANCING MARKETS IN THE NETHERLANDS: FCR, AFRR, MFRR AND RR

The design of the balancing markets of the Dutch TSO, TenneT, approximately follows the standard of the European Network of Transmission System Operators for Electricity (ENTSO-E) (Roben, 2018), using the following terminology:

- Frequency containment reserve (FCR) (or primary reserve)
- Automatic Frequency Restoration Reserve (aFRR) (or secondary reserve)
- Manual Frequency Restoration Reserve (mFRR) (or tertiary reserve)
- Replacement Reserve (RR)

At the moment of an imbalance, which causes a frequency deviation on the grid, FCR gets activated first. FCR capacity can respond quickly. After that, aFRR takes over FCR, as this type of capacity is able to be activated for a longer time. Subsequently, mFRR takes over aFRR, after which RR can also be activated when this is needed. This process and the role of each of the sub-markets in NL are explained in Figure 5. The requirements to participate are presented in Table 3.

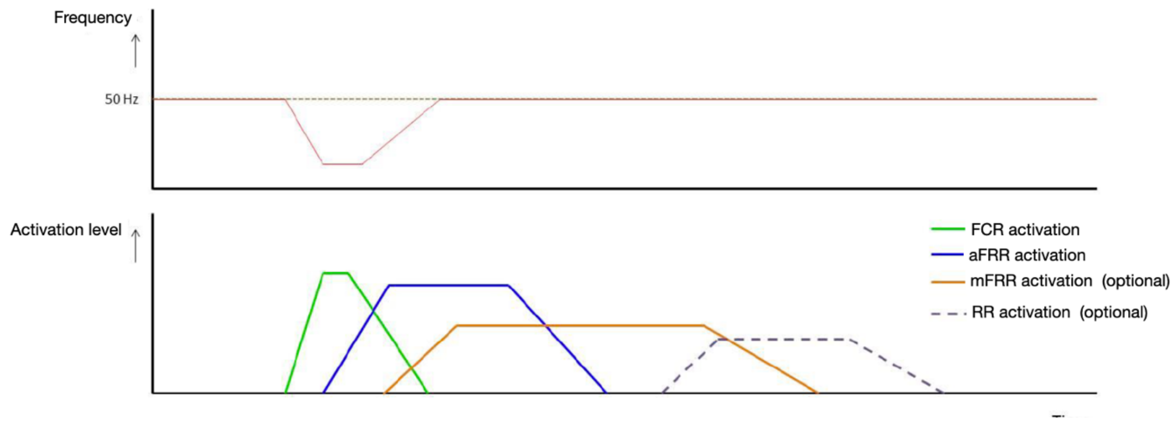


FIGURE 5 THE ROLE OF EACH OF THE SUB-MARKETS IN SOLVING AN IMBALANCE ON THE GRID IN THE NETHERLANDS (Brinkel, 2018)

TABLE 3 MAIN CHARACTERISTICS OF BALANCING MARKETS IN THE NETHERLANDS (Lampropoulos, van den Broek, van der Hoofd, Hommes, & van Sark, 2018).

Balancing sub-market	Full activation time	Frequency activations (Based on ENTSO-E data (ENTSO-E, n.d.))	Type of payment (capacity/energy)	Tender period	Price settlement
FCR	30 s	Continuous	Capacity	Daily	Pay-as-cleared
aFRR	15 min	Tens of times per day up until a few times per year, depending on bid price	Capacity	Daily	Pay-as-bid
			Energy	15 min	Pay-as-cleared
mFRR	10-15 min	1 – 10 per year	Capacity (+ energy, but very low)	Daily	Pay-as-bid

2.7.2 BALANCING MARKETS IN GREAT BRITAIN: FFR AND BM

As the electricity grid of GB is much smaller than the grid of continental Europe, it is more sensitive to imbalances. When one power plants has an outage, a larger share of the electricity in the system needs to be replaced in a small system. This is one of the reasons why GB has a different balancing market design. Another difference of the GB balancing markets is that they are much more transparent than other European countries. This can be explained by the higher need for future flexibility in the GB electricity system, when more RES are added to the system (NationalGridESO, 2020). National Grid (GB's TSO), Ofgem (energy regulator) and Elexon (balancing market administrator) share detailed data on balancing markets, which allows more thorough analyses on DR.

The two balancing markets that are included in the scope of this research, the FFR and the BM markets, are discussed.

The FFR market is a Frequency Response service to maintain a constant frequency of 50 Hz on the grid. On this market, flexible capacity is bought in advance by the TSO on a monthly basis. Activations are based on the frequency deviations and need to occur quickly after the start of the imbalance. FFR is one of the most valuable balancing markets in terms of £/MWh. The FFR market is most similar to to the FCR market in the Netherlands. The FFR market is split into two submarkets: the dynamic (FFRd) and static (FFRs) market. The dynamic is used to maintain the frequency under normal operations. The static market is used by the TSO on moments of large frequency deviations. The requirements of both balancing sub-markets are shown in Table 4.

TABLE 4 SUBMARKETS OF FFR MARKET WITH REQUIREMENTS (Smethurst, Walsh, Hynes, & Rook-Grignon, 2017)

Submarket		Full response time	Grid frequency	Length of response
Primary response	Dynamic		49.8 – 50.0 Hz	
Primary response	Dynamic	10 secs	49.5 – 50.0 Hz	20 secs
Primary response	Dynamic		49.2 – 50.0 Hz	
Secondary response	Dynamic		49.8 – 50.0 Hz	
Secondary response	Dynamic	30 secs	49.5 – 50.0 Hz	30 min
High Frequency Response	Dynamic		50.0 – 50.2	Continuous
High Frequency Response	Dynamic	10 secs	50.0 – 50.5	
Automatic Response	Static	10 secs		
Automatic Response	Static	30 secs		30 min

Besides the FFR market, the *balancing mechanism* (BM) market gives the TSO of GB access to flexibility which can be activated for a longer period than FFR. With BM, the TSO can activate flexibility suppliers for hours instead of minutes with FFR. This reserve capacity is activated on moments of large frequency deviations on the grid, and can take over more short-term markets like FFR. Another difference is that the BM market is an ad-hoc market, which means that participants does not need to make forward commitments to provide flexible capacity. Flexible capacity is bought close to real time (60 or 90 minutes). Participants can set their own requirements on the reaction speed. It is possible to participate through a licensed energy supplier or via a *Virtual Lead Party* (VLP), which is an independent aggregator that bids flexibility on behalf of a third party. Both the FFR and the BM market use *pay-as-bid* price settlements (Proffitt, 2021).

3 METHODOLOGY

In this section, it is explained which methodology is used to answer each of the three sub-research questions. The combination of the answers to these sub-questions answers the main research question.

By answering the first sub-question, it is investigated which different methods can be used to quantify the effect of DR on the price of flexible capacity (section 3.1). This is done by first presenting a generic quantification methodology that explains which data sources can be used, after which the calculation steps are described to create the variables that serve as the input for the analysis. Different quantitative methods are described, which can be applied based on the suitability to the available data.

First, the analysis using a regression model is explained. This type of analysis allows to quantify effects precisely, but it requires sufficient quality of the input data, and it has to comply with the assumptions of the regression model. If the quality of the input data is of less quality or the assumptions cannot be met, alternative, more simple, quantitative analyses are used: correlation and average bid price analysis. These analyses can also complement the regression analysis.

The answer to the first sub-question is supported by the identification of the opportunities and the barriers of TSOs sharing this data (section 3.2). This supports recommendations to TSOs and regulators to support them in the consideration of sharing the balancing market data that is required for the type of analysis in this research. The method of collecting the results for these opportunities and barriers is explained.

By applying the generic methodology to the two case studies of GB and NL, the second sub-question can be answered. As there are differences per country on how to apply the generic methodology, a country-specific methodology is explained (section 3.5). In this section, where the focus is on the extra steps that need to be taken and the adaptations of the generic methodology to the specific case studies.

To answer the third sub-question, the result of the second sub-question is extrapolated to the year of 2030. The input data and the calculation steps for this extrapolation are described (section 3.4). This will provide an estimation of how the potential cost reduction of DR will change in the future.

The methodology diagram, summarizing the methodological steps per research question, is illustrated in Figure 6.

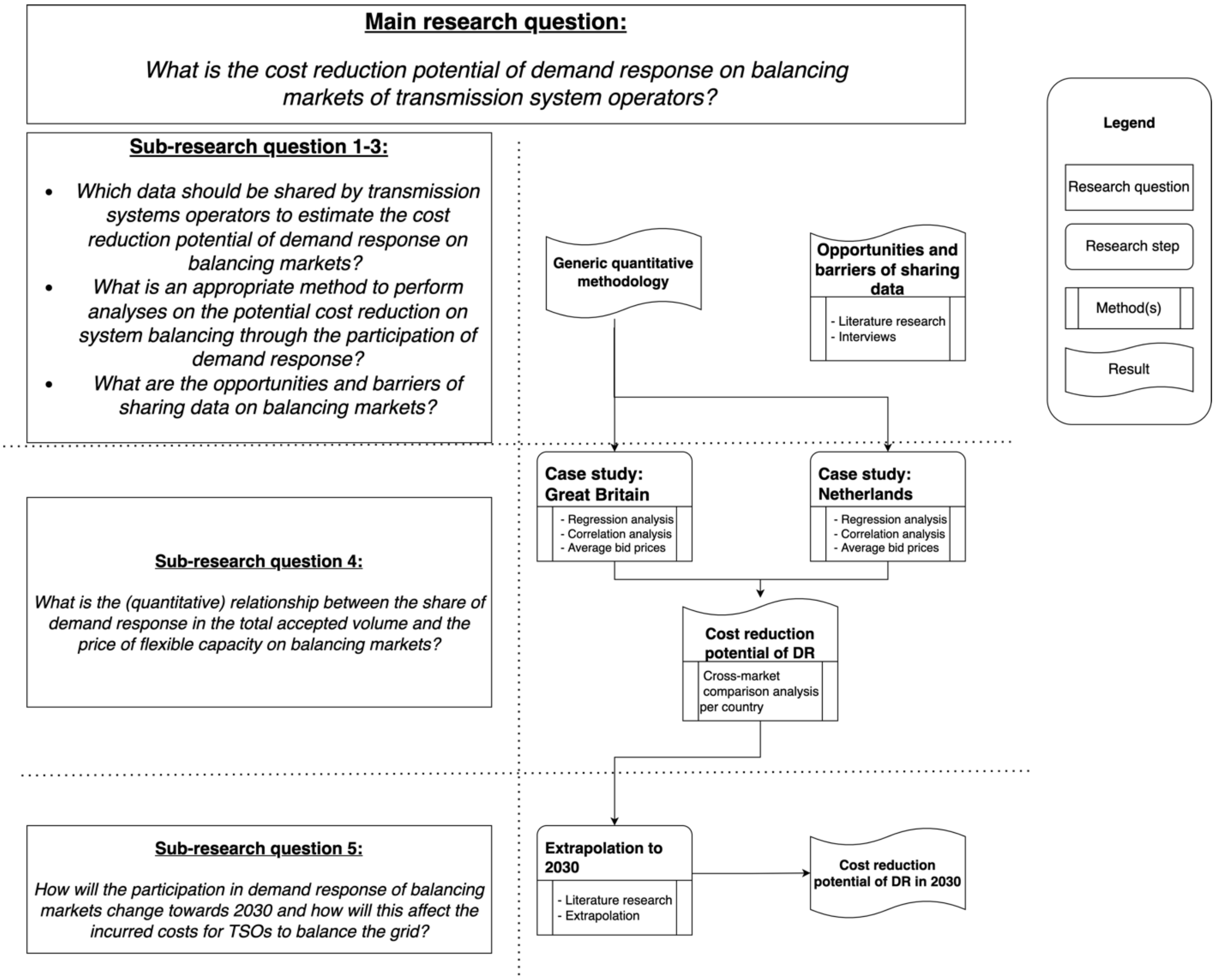


FIGURE 6 METHODOLOGY DIAGRAM

3.1 GENERIC QUANTIFICATION METHODOLOGY

The generic methodology to quantify the current and future effect of the participation of DR on balancing markets on the prices of flexible capacity is illustrated in Figure 9. To explain the reasoning behind the proposed methodology, the diagram is explained in a step-by-step manner. The explanation is linked to the diagram in Figure 9 by referring in (parentheses) to the numbers attached to every step in the diagram.

3.1.1 DATA SOURCES

There are two main types of data sources that can be used for the generical methodology: *Bid offer data (1.1)* or *Aggregated data (1.2).*

Bid offer data should show all the bids of different parties per tender period. To be usable, it should provide information on the accepted capacity (MW, e.g. per settlement period of an hour), the bid price (e.g. €/MW/h) and the technology or flexibility source (e.g. gas, battery, demand response) that offers the flexible capacity. An example of Bid offer data is shown in Table 5.

TABLE 5 EXAMPLE OF BID OFFER DATA

Tender period	Flexibility provider	Capacity (MW)	Flexibility source	Bid price (€/MW/h)	Status bid
January 2021	Company X	3	Demand response	5	Accepted
January 2021	Company Y	5	Gas turbine	10	Rejected

In contrast to the *Bid offer data*, *Aggregated data* does not show the separate bids of the different parties. Instead, it aggregates all the data of the different parties and shows the results for the whole market per tender period. To be usable, it should show information on the total accepted capacity per technology and the average or clearing price per tender period. An example of Aggregated data is shown Table 6.

TABLE 6 EXAMPLE OF AGGREGATED DATA

Tender period	Total Capacity (MW)	Flexibility source	Clearing price (€/MW/h)
20/01/2021 – 21/01/2021	5	Load	5
20/01/2021 – 21/01/2021	10	Generation	10

An important note to make here is that this research focuses on the prices of procured flexible *capacity,* and not *energy*. There are a few reasons why the energy payment is excluded from the scope. First, not all balancing markets have an energy remuneration. When balancing markets do have this in place, data on the volume and prices of these activations is not always available. If this is available, volumes and prices differ per activation which can take place many times per day. This would make the analysis very complex. Only looking at the capacity, therefore, improves the feasibility of the analyses. The unit that is used for the flexible capacity is MW/h, in contrast to MWh, which is usually used for volumes of energy.

3.1.2 MAIN VARIABLES FOR ANALYSES

The described data sources are used to create variables and parameters that can be used for analyses. The symbols used to define these variables are listed in Table 7.

TABLE 7 SYMBOLS USED TO DEFINE VARIABLES AND PARAMETERS FOR ANALYSES

Variable	Symbol	Unit
Flexible capacity	C	MW/h
Share of flexibility source in total accepted capacity	S	%
Price of flexible capacity	P	$\frac{€}{MW/h}$ (NL) or $\frac{£}{MW/h}$ (GB)
Average price of flexible capacity	$\bar{P}$	$\frac{€}{MW/h}$ (NL) or $\frac{£}{MW/h}$ (GB)
Sub-script	**Symbol**	**Example value**
Flexibility source	f	Battery, gas turbine, demand response etc.
Balancing sub-market	m	• GB: FFRd (dynamic), FFRs (static), BM(FRR), BM(RR) • NL: aFRR, mFRR
Reference to an individual bid of participant providing flexibility	b	
Tender period	t	Month, day of year, ½ hour
Hour	h	

To test the hypothesis of this research quantitatively, the following four main variables are created:

- Average bid price per flexibility source per tender period ($\overline{P_{m,f,t}}$) (Variable 3.1)
- The share of each of the flexibility sources in the total accepted capacity per tender period $(S_{f,t})$ (Variable 3.2)
- The (average) price of accepted flexible capacity per tender period ($\overline{P_{m,t}}$ or $P_{m,t}$) (Variable 3.3)
- The total flexible capacity accepted per tender period ($C_{m,t}$) (Variable 2.2)

With the combination of variables 3.2 $(S_{m,f,t})$ and 3.3 ($\overline{P_{m,t}}$ or $P_{m,t}$), the hypothesis can be tested by identifying the trend between the two variables. This is done using a regression analysis or via correlation analysis, where it is tested whether a higher share of DR in balancing markets is associated with a lower price for flexible capacity that can support system cost reduction.

Variable 2.2 (C_t) is used in the regression model to check whether a higher accepted capacity is associated with a higher price for flexible capacity. This increases the accuracy of the regression model.

With variable 3.1 ($\overline{P_{m,f,t}}$), the hypothesis can also be tested by comparing the average bid price of the flexibility source that is associated with demand response to the overall average bid price ($\overline{P_{m,t}}$): the *Average bid price analysis*. When DR bids have on average lower bid prices, TSOs can reduce costs when more flexible capacity can be bought by DR resources. Creating variable 3.1 is only possible if *Bid offer data* is available.

For creating these variables, only the accepted capacity is considered. This is done because capacity that is bided but rejected, does not influence the prices of flexible capacity on balancing markets. This capacity does not affect the costs incurred by TSOs to balance the grid and is therefore not relevant for this research.

The length of the tender period determines the granularity of the data; in the case of a monthly tender on a balancing market, for example, the variables are calculated per month.

3.1.3 Creation of variables for analysis

Depending on the data, some calculation steps need to be taken to create the three main variables, which are explained in this section. Two types of variables can be distinguished: price and capacity variables.

3.1.3.1 Price

$\overline{P_{m,f,t}}$ can only be calculated if *Bid offer data* is available. The variable is calculated by taking the average over all the bid prices of a certain flexibility source in a specific period. Subsequently, $\overline{P_{m,t}}$ is calculated by taking the average over all the bids in a specific tender period.

$$\overline{P_{m,f,t}} = \frac{\sum_{b=1}^{B} P_{m,b,f,t}}{N}\ , (b\ \in 1, 2, \dots, B) \quad \text{(EQUATION 3.1)}$$

There are two ways prices can be settled on balancing markets: pay-as-cleared and pay-as-bid. In the case of a pay-as-cleared market, there is only one price that every participant receives for their flexible capacity ($P_{m,t}$) and no calculation needs to be made. In the case of a pay-as-bid market, every accepted bid receives the specific price that was bid. To calculate a single price per tender period, the average of all the accepted bids is calculated to create $\overline{P_{m,t}}$.

$$\overline{P_{m,t}} = \frac{\sum_{b=1}^{B} P_{m,b,,t}}{N}, (b\ \in 1, 2, \dots, B) \quad \text{(EQUATION 3.2)}$$

(in case of pay-as-bid market)

To improve readability, the (average) price of the accepted flexible capacity in a certain period is denoted as $P_{m,t}$ for the remaining of this report, regardless of whether it comes from pay-as-bid or pay-as-cleared settlement.

3.1.3.2 Capacity

$S_{m,f,t}$ is usually not shared directly by TSOs. Therefore, the accepted capacity per flexibility source ($C_{m,f,t}$) and total accepted capacity ($C_{m,t}$) needs to be calculated per tender period. In the case of *Aggregated data*, these variables can be derived directly. In the case of *Bid offer data* however, some calculational steps need to be taken.

In the case of *Bid offer data,* the total accepted capacity can be calculated per flexibility source ($C_{m,f,t}$) (2.1) by summing the capacity of all the accepted bids ($C_{m,b,f,t}$). By dividing this by the total accepted capacity per tender period ($C_{m,t}$) (2.2), the share of each of the flexibility sources in the total accepted capacity can be calculated per period ($S_{m,f,t}$) (3.3). The formulas for these calculation steps are presented in equations 3.3, 3.4 and 3.4.

$$C_{m,f,t} = \sum_{b=1}^{B} C_{m,b,f,t}\,, (b \in 1, 2, \dots, B)$$ (EQUATION 3.3)

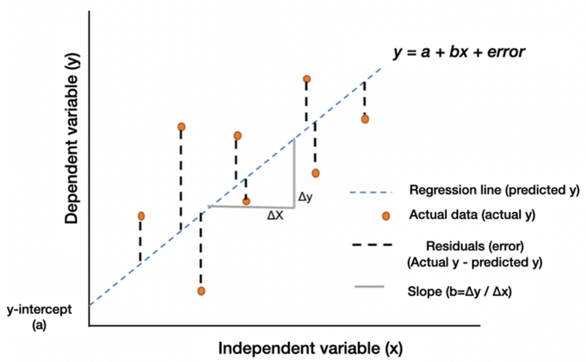
$$C_{m,t} = \sum_{b=1}^{B} C_{m,b,t}\,, (b \in 1, 2, \dots, B)$$ (EQUATION 3.4)

$$S_{m,f,t} = \frac{C_{m,f,t}}{C_{m,t}} \times 100\%$$ (EQUATION 3.5)

3.1.4 REGRESSION ANALYSIS

The regression model (4.2 in Figure 9) uses independent variables ($S_{f,t}$ e.g.) to try to estimate the dependent variable ($P_{m,t}$ e.g.). There are multiple ways to analyze the quantitative relationship between variables. Regression analysis is a set of commonly used methods to quantify the quantitative relationship between variables. In contrast to the related *correlation* method, regression analysis allows to precisely estimate the effect of multiple independent variables on the dependent variable. Correlation can only quantify the relation between two variables. Therefore, regression analysis is a suitable method if there are multiple relevant independent variables. By including the most important relevant variables in the regression model, an *omitted variable bias* is avoided and the effect of each of the independent variables can be isolated. An omitted variable bias occurs when the independent variable correlates with another variable that has been left out of the model. Therefore, the effect of the independent variable is estimated incorrectly (Stock & Watson, 2019).

A visual explanation of the different elements of the results of a regression model is presented is Figure 7. It shows a regression model with 1 (left graph) and with 2 independent variables (right graph).



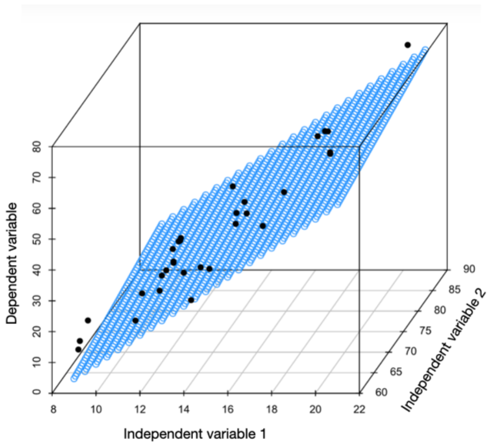


FIGURE 7 VISUAL EXPLANATION OF DIFFERENT ELEMENTS OF REGRESSION MODEL WITH 1 INDEPENDENT VARIABLE (LEFT) AND 2 INDEPENDENT VARIABLES (RIGHT)

3.1.4.1 Approach to build regression model

There are three types of input variables that are used to build the regression models in this research:

- The **dependent variable**:
  - $P_{m,t}$
- The **direct independent variables**. These are the independent variables described up to now and that are collected from the balancing market tender results.
  - $S_{m,f,t}$
  - $C_{m,t}$
- The **indirect independent variables**. These are variables that are not part of the balancing market tender results, but can have an indirect influence on the dependent variable. An example of such an indirect independent variable is the gas price (GP). When the gas price is higher, the operation of gas-fired power plants becomes more costly. They will need a higher compensation for being profitable and therefore they tend to bid a higher bid price on balancing markets. This increases the price of flexible capacity, which can be explained by the gas price. The addition of such indirect independent variables improves the estimation of the effects of the variables of interest: $S_{m,f,t}$

If the hypothesis of this research is true, the regression model shows that there is a negative relationship between the share of demand response S_{DR} and the price of flexible capacity P_t, which suggests that more demand response in the accepted capacity makes the price for flexible capacity go down.

An example regression model in this context could look as follows:

$$P_t = a - \beta\, S_{DR} + \gamma\, GP + \varepsilon \qquad \text{(EQUATION 3.6)}$$

The intercept a and the coefficients β and γ are estimated by the regression model based on the data. The error term ε, or residual, is the difference between the predicted value of the dependent variable and the actual value. The lower the error term, the higher the accuracy of the model. Equation 3.6 can be used to predict P_t by filling in S_{DR} and GP.

There are two main strategies for building regressions models (The Analysis Factor, n.d.):

- <u>Top-down</u>: First add all the independent variables to the model that might explain the dependent variable. Subsequently, variables that have no explanatory value in the model are omitted
- <u>Step-up</u>: Start with an empty model and add independent variables step by step, and only keep them in when they have explanatory value.

The top-down method is favorable when it is clear what the hypothesis is and when the independent variables are already defined. The step-up method is favorable when it is not clear yet which variables will be relevant to add to the model. The approach that is taken in this research to build the regression model is a combination of the two methods:

Top-down:

- Include all the direct independent variables in the regression model
- Omit the independent variables step-by-step that have no explanatory value, until there are only significant variables left

Step up:

- Add an indirect independent variable to the regression model which is expected to be relevant for the model
- When this is the case and the variable has explanatory value, it is kept in the final model.
- These steps are repeated for all the variables that are expected to be relevant.

Which indirect independent variables are considered to be added to the regression model is based on insights found in literature. When literature suggests that a certain factor influences the prices on balancing markets, data of that factor is collected and added to the regression model to check the relevancy of this variable. The list of considered indirect independent variables, with corresponding source, can be found in Table 21. Which indirect independent variables are considered per specific case study is discussed in section 4.

The explanatory value of a variable is measured by the statistical significance of that variable. This can be checked using the *p-value*. In the context of a regression model, the p-value indicates how likely it is that an independent variable has no effect on the dependent variable. Therefore, a low p-value suggests that there is a quantitative relation between the independent variable and the dependent variable. In other words, the p-value is a measure of the confidence level of statements about statistical relations. When the independent variables in a regression model all have low p-value, your results have a high level of internal validity.

A common confidence level used in statistical analysis is 95% (Stock & Watson, 2019). The same criterion for variables to have statistical significance is used in this research and therefore the variables need to have a p-value lower than 0.05. Omitting variables that are insignificant improves the representation of reality by the model.

3.1.4.2 Meeting assumptions of regression model

Before and after building the regression model, it should be checked whether the data complies with the requirements of a regression model. These requirements are a set of assumptions that need to be true about the input data and the results of the model to ensure that the results of the regression model are valid. If this is not the case, the estimated coefficients of the regression model cannot be interpreted, and the results do not represent reality. Before building the model, *outliers* and *multicollinearity* are checked. After building the model, the *Variance Inflation Factor* (VIF), *sample size/number of predictors* ratio, *normality of residuals* and the *goodness of fit* are analyzed. These concepts are explained in appendix 7.3.

3.1.5 Correlation and average bid price analysis

To complement the regression analysis, the *correlation* and *average bid price analysis* are used. This can verify the results of the regression model or it can replace the regression analysis. Building a regression model is not always possible due to a number of reasons, such as lack of data availability or because the assumptions of the regression model cannot be met. The *correlation* and *average bid price analysis* are simpler methods that do not have assumptions that need to be met by the data.

Using correlation analysis, the linear relationship between two variables can be measured. Correlation calculates the level of change in one variable due to the change in the another. When two variables are highly correlated, it suggests that they are strongly related to each other. By calculating the correlation between $S_{DR,t}$ and P_t, the hypothesis of this research can be tested. Figure 8 illustrates some examples of correlations between two variables.

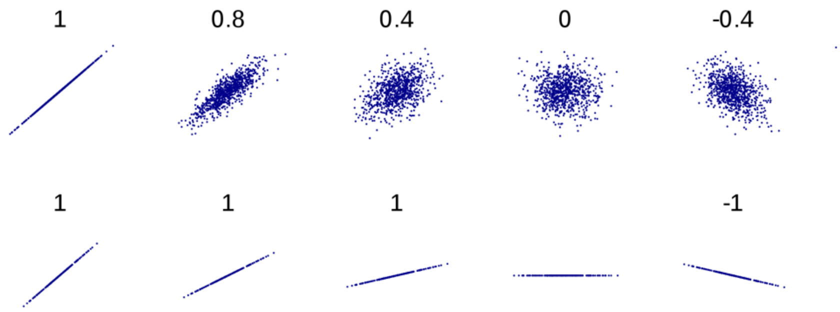


Figure 8 Example of correlations between two variables

The hypothesis of this research can also be tested by looking at the difference between the average bid prices of DR, $\overline{P_{DR}}$, and the overall average bid price, $\bar{P}$. When the data shows that DR bids are lower than the overall average, the data confirms that hypothesis, as lower bid prices lead to a lower (average) price of flexible capacity for TSOs.

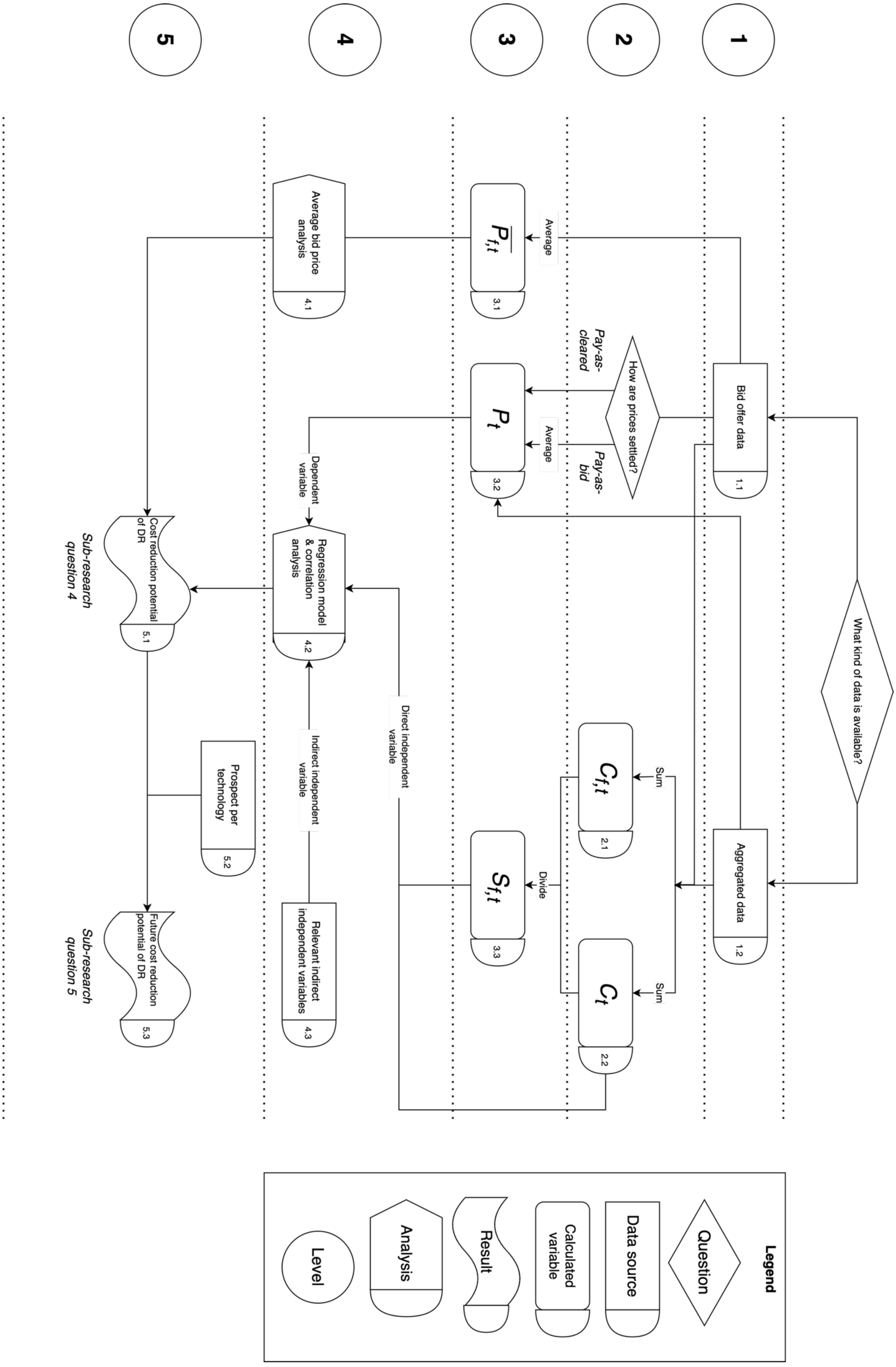


FIGURE 9 GENERIC QUANTIFICATION METHODOLOGY DIAGRAM

3.2 CROSS-MARKET COMPARISON

By applying the generic quantification methodology to the case studies, the cost reduction of DR is quantified in two countries (GB and NL) for 4 balancing sub-markets (FFR, BM, aFRR and mFRR). The result of these analyses are three measures/variables:

- Regression analysis (RA): The difference in the price of flexible capacity that is associated with a 1% increase in the share of accepted capacity of demand response on the balancing markets: $\frac{\Delta P}{\Delta S_{DR}}$ (unit: €/% or £/%)
- Average bid price analysis (ABA): The difference in average bid price: $\overline{P_m} - \overline{P_{m,DR}}$ (unit: € or £)
- Correlation analysis (CA): The correlation between P and S_{DR} (unit: dimensionless)

CA can be used to compare different markets. However, this measure will not be used for quantification, as the unit of CA is dimensionless. RA and ABA can both be used to compare different markets and to quantify the effect. However, the unit of RA and ABA needs to be different to fairly compare the cost reduction between different markets and countries, as the price levels of markets can be significantly different, e.g. a €1/MW/h lower price has a different interpretation in a market with high prices than a market with lower prices. Therefore, a relative number should be used. The calculation to do this is done according to Equation 3.7 and 3.8, with the symbols explained in Table 8.

$$RCR_{RA,DR,m,y} = \frac{RA}{\bar{P}_{m,y}} \quad \text{(EQUATION 3.7)}$$

(Relative cost reduction (RCR) estimated by regression analysis (RA))

$$RCR_{ABA,DR,m,y} = \frac{ABA}{\bar{P}_{m,y}} \times 100\% \quad \text{(EQUATION 3.8)}$$

(Relative cost reduction (RCR) estimated by average bid price analysis (ABA))

$RCR_{RA,DR,m,y}$ and $RCR_{ABA,DR,m,y}$ represent variable 5.1 in Figure 9. $RCR_{RA,DR,m,y}$ can be interpreted as the percentage difference of costs for TSOs to balance the grid due to a 1% increase of the participation of DR in balancing market m in year y. This variable will be the main variable that is used to quantify the cost reduction of DR. By multiplying this variable with the average participation of DR ($\overline{S_{DR}}$), the cost reduction of DR can be calculated (Equation 3.9). This can be interpreted as the percentage difference of costs for TSOs to balance the grid due to the average participation of DR in balancing market m in year y.

$$CR_{DR,m,y} = RCR_{RA,DR,m,y} \times \bar{S}_{DR,m,y} \quad \text{(EQUATION 3.9)}$$

The average bid price analysis is used to complement or replace the regression analysis. $RCR_{ABA,DR,m,y}$ can be interpreted as the percentage difference between the average bid price of DR bids compared to the overall average bid price in market m in year y.

TABLE 8 SYMBOL FOR VARIABLES OF CALCULATION OF COST REDUCTION OF DEMAND RESPONSE

Variable	Symbol	Unit
Regression analysis	RA	$\frac{£}{\%}$ or $\frac{€}{\%}$
Average bid price analysis	ABA	£ or €
Correlation analysis	CA	
Relative cost reduction (Regression analysis)	RCR_{RA}	$\%_P/\%_S$
Relative cost reduction (Average bid price analysis)	RCR_{ABA}	$\%_P$
Cost reduction	CR	$\%_P$
Share of DR in total accepted capacity	ΔS_{DR}	%
Price of flexible capacity	P	$\frac{€}{MW/h}$ (NL) or $\frac{£}{MW/h}$ (GB)
Average price of flexible capacity	$\bar{P}$	$\frac{€}{MW/h}$ (NL) or $\frac{£}{MW/h}$ (GB)
Average share of total accepted capacity	$\bar{S}$	%
Sub-script	**Symbol**	**Example value**
Demand response	DR	
Balancing sub-market	m	• GB: FFRd (m=1), FFRs (m=2), BM (m=3) • NL: aFRR (m=4), mFRR (m=5)
Year	y	Reference year or 2030
Regression analysis	RA	
Average bid price analysis	ABA	

$RCR_{DR,m,y}$ is calculated based on the historical data of the balancing market tender results up until the reference year 2022. Therefore, this variable will be denoted as $RCR_{DR,m,ref}$. This variable will be the input basis the cross-country- and market comparison in section 4.4.

After this comparison, the estimations for the reference year will be consolidated to a single measure for the cost reduction of DR across different markets. This is done by taking the average over the estimations per balancing sub-market (Equation 3.10).

$$RCR_{DR,ref} = \frac{\sum_{m=1}^{M} RCR_{DR,m,ref}}{M} \ (m \in 1, 2, \ldots, M) \qquad \text{(EQUATION 3.10)}$$

3.3 IDENTIFYING BARRIERS AND OPPORTUNITIES OF SHARING DATA ON BALANCING MARKETS

A combination of studies and interviews is used to identify barriers and opportunities of sharing data on balancing markets. By first conducting a literature study, a list of identified barriers and opportunities is made that can serve as input for supporting the semi-constructed interviews. Each potential barrier and opportunity is discussed and the interviewee is asked whether he/she experiences this in the same manner. After discussing the list of barriers and opportunities, the interviewee is asked if he/she experiences another barrier or opportunity that is not on the list. If this is the case, the barrier or opportunity is added to the list.

The specific questions and answers per interview can be found in appendix 7.1. The process used to collect results on opportunities and barriers is shown in Figure 10 with examples. The conducted interviews are listed in Table 9.

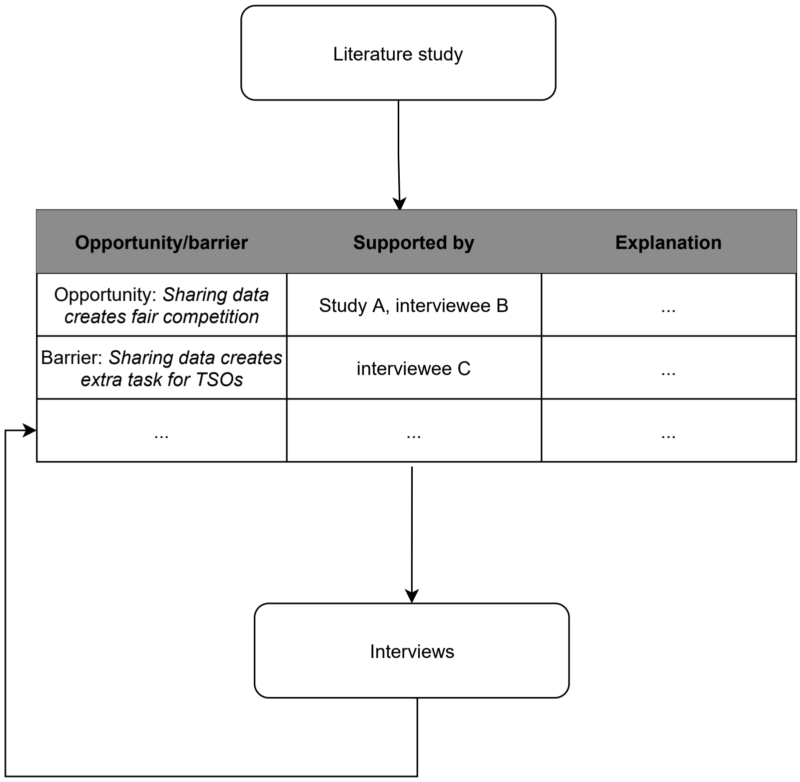


FIGURE 10 METHOD FOR IDENTIFICATION OF OPPORTUNITIES AND BARRIERS OF SHARING DATA ABOUT BALANCING MARKETS

TABLE 9 LIST OF INTERVIEWEES FOR IDENTIFICATION OF BARRIERS AND OPPORTUNITIES OF SHARING BALANCING MARKET DATA

Interviewee	Company	Type of organization
Interviewee A	Energie-Nederland	Industry association for energy companies
Interviewee B	Sympower	Demand response aggregator
Interviewee C	Utrecht University	University
Interviewee D	TenneT	Dutch TSO

3.4 EXTRAPOLATION OF RESULTS TOWARDS 2030

After applying the generic quantification methodology presented in Figure 9 on the two case studies, the cost reduction of DR has been quantified in the current situation with two variables: $RCR_{DR,ref}$ and $CR_{DR,ref}$. The next step is to estimate these variables for the year 2030.

Applying the same estimation method for the year 2030 is not possible, as the historical data is not yet available for this year. Therefore, $RCR_{DR,ref}$ and $CR_{DR,ref}$ will be extrapolated. For this, it is assumed that the relative cost reduction of DR ($RCR_{DR,m,y}$) remains the same for the year 2030 (Equation 3.11). Re-estimating this variable would require the estimation of the marginal cost of all the flexibility sources that participate on the balancing markets in 2030 and the capacity of balancing flexibility that TSOs need in 2030. This estimation falls outside the scope of this research. To correct for uncertain factors, a correction factor CF is taken into account. This factor is used to conduct a sensitivity analysis.

$$RCR_{DR,ref} = RCR_{DR,2030} \times CF \ (CF \in 0.75, 1, 1.25) \qquad \text{(EQUATION 3.11)}$$

The next step is to calculate $CR_{DR,2030}$ using $RCR_{DR,2030}$ and by the extrapolation of $\bar{S}_{DR,ref}$ to $\bar{S}_{DR,2030}$ (Equation 3.12).

$$CR_{DR,2030} = RCR_{DR,2030} \times \bar{S}_{DR,2030} \qquad \text{(EQUATION 3.12)}$$

The estimation of $\bar{S}_{DR,2030}$ is done by forecasting the development of DR on balancing markets based on a literature study. Studies of research institutions and energy companies are included. The list of used literature can be found in Table 10.

TABLE 10 LITERATURE USED FOR EXTRAPOLATION TOWARDS 2030

Study		Organization (Type of organization)
The supply of flexibility for the power system in the Netherlands, 2015-2050	(Alliander & ECN, 2017)	Alliander (Dutch grid operator) ECN (Dutch research institute)
Demand Response Tracking Report	(IEA, 2021)	IEA (International research institute)
Which, where, when and how much flexibility and storage do we need to meet 2030 goals?	(European Commission, 2020)	European Commission

3.5 COUNTRY SPECIFIC METHODOLOGY

The general methodology described in section 3.1 is now be applied to the two case studies of this research. This involves specific data sources, and therefore a specific method. In this section, the required adjustments are explained per country.

3.5.1 GREAT BRITAIN

Data be input for answering the research questions have been found available for two balancing markets: the Firm Frequency Response (FFR) market and the Balancing Mechanism (BM).

3.5.1.1 FFR market

Data about the tenders of this market is publicly available through the website of National Grid ESO, the TSO of GB (National Grid ESO, n.d.). The data is published in their monthly *Post Tender Reports* of the FFR market. This data is available for the period from January 2019 to October 2021. This data provides the variables about all the offered bids in each settlement period (1 month) (*Bid Offer Data*), summarised in Table 11.

TABLE 11 RELEVANT INFORMATION IN POST TENDER REPORTS OF FFR MARKET (NATIONAL GRID ESO, N.D.)

Variable	Explanation	Unit
Status	Bid accepted/rejected	
Company name of flexibility supplier		
Unit ID	Specific registration code per flexibility supplier	
Generation type	Battery, Bio Fuel, Diesel, DSF*: Distributed generation (for export), DSF: Distributed generation (onsite), DSF: Load response, DSF: Storage (for export), DSF: Storage (onsite), Gas, Multiple Fuel Type, Wind * DSF: Demand-side flexibility	
Tendered Period		Month

Availability of flexibility supplier per week		Hours
Nomination fee received by flexibility supplier		£/hour
Bid capacity per submarket	Bid capacity in primary, secondary, high, dynamic and static frequency	MW
Tender reference	Every bid get a unique tender reference number	

- The combination of variables *Bid capacity per submarket* (MW) and *Availability of flexibility supplier per week* (Hours) are used to create the variables $V_{FFR,t}$, $V_{f,t}$ and $S_{FFR,f,t}$
- The combination of variables *Nomination fee received by flexibility supplier* (£/hour) and *Availability of flexibility supplier per week* (Hours) are used to create the variable $P_{FFR,t}$ and $\bar{P}_{FFR,f,t}$.
- The generation type *DSF: Load response* is considered as DR, which has the definition (National Grid, 2017): *'Load shifting or temporary demand reduction or increase (e.g. heating/cooling systems, business operations and appliances)'*
- The *generation types* are used to create the direct independent variables for the regression model $S_{FFR,f}$, with each of the generation types as a flexibility source

3.5.1.2 BM market

Data about the tenders on this market is publicly available through the Balancing Mechanism Reporting Service (BMRS) of Elexon (GB's energy regulator) (Elexon BMRS, n.d.). The relevant data is published in two reports: *Prices of Procured Balancing Reserves (B1730*) and *Accepted Aggregated Offers (B1740)*. This data is available for the period from January 2015 to December 2019. The data provides the aggregated accepted capacity coming from *Load* (consumers) and *Generation* (producers) per settlement period (30 min) with corresponding prices (*Aggregated Data*).

Despite the fact that GB has a different balancing market structure than continental Europe, the data is categorized according to the design of continental Europe. This data is shared in this way by NationalGrid to comply with EU regulation on transparency of balancing markets. Due to the exit of the UK from the EU, NationalGrid stopped sharing this data as of January 2020.

Table 12 shows the relation of the GB balancing markets with the markets categorized in the EU regulation. The data categorized as FCR relates to the FFR market in GB. As the FFR market is separately included in the scope of this research, it is not considered again in the analysis of the data that had to be shared due to EU regulation.

TABLE 12 MAPPING OF GB BALANCING MARKETS TO COMPLY WITH EU REGULATION ON TRANSPARENCY OF BALANCING MARKETS (NationalGridESO, 2018)

Balancing market GB	Service	Relation to market in data EU regulation and terminology in data
FFR	Primary response	FCR
	High response	FCR

	Secondary response	FRR
BM	Delivery < 15 minutes	FRR
	Delivery > 15 minutes	RR

- The data in the B1730 files are used to create the variables: $P_{BM(FRR),t}$ and $P_{BM(RR),t}$
- The data in the B1740 files are used to create the variables with *Load* and *Generation* as flexibility sources (f):
    - $V_{BM(FRR),t}$, $V_{BM(FRR),f,t}$ and $S_{BM(FRR),f,t}$
    - $V_{BM(RR),t}$, $V_{BM(RR),f,t}$ and $S_{BM(RR),f,t}$
- *Load* is considered as DR

3.5.2 THE NETHERLANDS

Data for NL is undisclosed and has been made available by TenneT specifically for this research. The data contains the prices paid via pay-as-bid price settlement (€/MW/h) and the capacity (MW) of the accepted bids per tender period, per balancing sub-market and per flexibility source (*Bid Offer data*). The data include the tender periods between 01/01/2018 and 31/12/2021 for the aFRR and the mFRR balancing markets. The FCR market is not included, because TenneT does not collect relevant information about this market. The flexibility sources and the balancing submarkets that are distinguished in the data are described in Table 13.

TABLE 13 BALANCING SUB-MARKETS AND FLEXIBILITY SOURCES DISTINGUISHED IN DATA OF DUTCH BALANCING MARKETS

Balancing sub-market	Explanation
aFRR Symmetrical	aFRR flexible capacity in up- and down-direction Active period of market in data: 1/1/2018 - 31/12/2020
aFRR Upwards	aFRR flexible capacity in up-direction Active period of market in data: 5/12/2020 - 31/12/2021
aFRR Downwards	aFRR flexible capacity in down-direction Active period of market in data: 19/11/2020 - 31/12/2021
mFRRda Downwards	mFRR flexible capacity in down-direction (directly activated) Active period of market in data: 1/1/2018 – 31/12/2021
mFRRda Upwards	mFRR flexible capacity in up-direction (directly activated) Active period of market in data: 1/1/2018 – 31/12/2021
Flexibility source	**Explanation**
Large scale production	Large scale, centralized generators of electricity, mostly *open cycle gas turbines* (OCGT)
Small scale production	Small scale generators of electricity, mostly *combined cycle gas turbines* (CCGT) and smaller share of coal plants
Mixed portfolio	A combination of generators (CHPs/emergency facilities and DR)
DR	Demand response (mostly industrial loads)

4 RESULTS AND ANALYSIS

In this section, the results of the described methodology are presented in the order of the research questions. First, the qualitative results will be presented to answer the first and second research sub-question on which data should be shared by TSOs or national regulators to support analyses on the cost reduction of DR on balancing markets. To answer the third sub-question, the identified opportunities and barriers of sharing this data are presented. Subsequently, the quantitative results of the two cases studies, GB and NL, are presented to answer the fourth and the fifth research sub-questions. These results will be used to test the hypothesis of this research and to quantify the cost reduction in the present and towards 2030.

4.1 QUALITATIVE RESULTS: OPPORTUNITIES AND BARRIERS FOR SHARING DATA OF BALANCING MARKETS

Parts of the answers to the qualitative sub-questions are already explained in the *Methodology* section. The sections that answer these questions are presented:

- Sub-research question 1: *Which data are (or should be) shared by transmission systems operators and national regulators to support analyses on the potential of cost reduction on system balancing through the participation of demand response?*
    - Answer: Section 3.1.1.
      Both *Bid offer data* and *Aggregated data* can be used for analysis. The data should contain balancing market tender results that provide information on which flexibility source provided flexibility at which moment, and for which price.

- Sub-research question 2: *What is an appropriate method for performing analyses on the potential of cost reduction on system balancing through the participation of demand response?*
    - Answer: Section 3.1 and Figure 9.
      The (quantitative) relationship between the variables *price of flexible capacity* and *share of DR in total accepted capacity* can be estimated using regression, correlation, and average bid price analysis.

- Sub-research question 3: *What are the opportunities and barriers to publicly sharing data on balancing markets?*
    - Answer: This is explained in section 4.1.1.

4.1.1 Opportunities and barriers to sharing data

The results of the literature review and the interviews about the opportunities and barriers of sharing more data publicly on balancing markets are summarised in Table 14.

Table 14 Identified opportunities and barriers of sharing detailed data of balancing markets

Opportunity	Explanation and source
Lower barrier for new participants to enter the market	In (ACER, 2021) (p.103), it is stated that a more transparent balancing market allows new entrants to easily to do analyses to assess the value of entering the market. This is also supported by interviewee A (Energie-Nederland), B (Sympower), interviewee C (Utrecht University) and interviewee D (TenneT).
Increased efficiency of market	In (ACER, 2021) (p.103), it is stated that a more transparent market lowers the information asymmetry of the different parties that participate. This leads to a more economically efficient formation of the price of flexible capacity. This is supported by (ENTSO-E, 2015) (p. 15), interviewee C (Utrecht University) and D (TenneT). Interviewee B (Sympower) believes that transparency will increase market efficiency in the long term, but not in the short-term. Interviewee A (Energie-Nederland) does not believe this will increase market efficiency.
Improve reputation TSO	Interviewee B (Sympower) believes that it can be an opportunity for a TSO to be more transparent and share more data. This can improve the reputation of a TSO. This is supported by interviewee D (TenneT). This opportunity is not discussed with the other interviewees.
Easier to identify DR potential	In (ENTSO-E, 2015) (p.6), it is stated that transparency on balancing markets can improve customer awareness, which makes it easier to identify DR potential. This is supported by interviewee C (Utrecht University). This opportunity is not discussed with the other interviewees.
Barrier	**Explanation and source**
Lack of value of sharing the data	Interviewee A (Energie-Nederland) sees little added value of sharing the detailed data of the balancing markets. The interviewee also does not think it is a right to have this kind transparency. This is not supported by interviewee B (Sympower), C (Utrecht University) and D (TenneT).
Complexity of pooling different devices	Interviewee A (Energie-Nederland) thinks that when participants pool capacity of different devices, it makes the bidding process too complex when participants need to report which assets

	offered flexible capacity on which moment. This is seen as a barrier of sharing this data. This barrier is not supported by interviewee B (Sympower), C (Utrecht University) and D (TenneT).
Extra burden for TSOs, while not being in their interest	Interviewee D (TenneT) and Interviewee C (Utrecht University) see it as a barriers that when TSOs need to share this data, this creates an extra responsibility for them, while it is not in their direct interest. The main interest of TSOs is lowering costs. Sharing this data creates extra costs. This barrier is not discussed with the other interviewees.
Harm of privacy of business	In (ENTSO-E, 2015) (p. 15), it is stated that when detailed information is shared about balancing markets, business participating have less privacy and their portfolio could be deduced from the data. This is something business would like to keep (partly) confidential, as this information can be misused by competitors. This is also seen as a barrier by Interviewee A (Energie-Nederland), B (Sympower) and D (TenneT).
Risk of collusion	When market participants have a lot of market information available, there is the risk on collusion. This means that participants can increase the price of flexible capacity when they have a lot of information. For example, big producers coordinating their bids on electricity markets to increase prices and to increase profit. This is not in the public interest. This risk is seen as a barrier by Interviewee C (Utrecht University). This barrier is not discussed with the other interviewees.
Lobby of industry	According to Interviewee C (Utrecht University), it may be contrary to the interests of some industries so they may be against transparency. Also, it is always difficult for industries when their data is publicly available. This barrier is not discussed with the other interviewees.
Political view on regulation and transparency	According to Interviewee C (Utrecht University), the political view in the Netherlands, for example, is a barrier to more transparency on the markets. Countries like the Netherlands have a more liberal view on regulation and do not believe transparency should be strictly enforced by the government. In contrast, countries like GB believe that governments should use stricter regulation to enforce transparency. This barrier is not discussed with the other interviewees.

Most of the interviewees (partly) agree on the barriers and opportunities of sharing more detailed data of balancing markets. However, a clear difference is visible between the perspectives of the interviewees on this topic.

Interviewee A (Energie-Nederland) mostly argued from the perspective of the liberalized electricity markets, which has to be efficient and for which the barriers and thresholds should be low. Another remarkable observation coming from this interview is that the interviewee does not see a lot of value in sharing more detailed data. All the other interviewees see the added value of this transparency. Interviewee B (Sympower) argued from the perspective of a participant of balancing markets. The interviewee therefore emphasized the importance of sharing this data. The interviewee also saw the harm of the privacy of businesses participating in the markets as a significant barrier. Interviewee C (Utrecht University) saw this topic from a regulation and system perspective. Therefore, the interviewee emphasized the importance of transparency of electricity markets and that the political view on regulation plays an important role in decisions about transparency. Interviewee D (TenneT) argued from the perspective of a TSO and emphasized that sharing the data would create an extra burden for a TSO, which has not the highest priority as they are not obliged to share this data.

4.2 Quantitative results: Great Britain

Quantitative results for the FFR and the BM market are discussed in the next sections.

4.2.1 FFR market results

4.2.1.1 Data description FFR market

The data of the auction results of the FFR market provides information on each individual bid of flexibility suppliers (*Bid Offer Data*). The data that is included in the analysis covers the period of April 2018 until January 2022, as the data source does not provide sufficient information on the auction results before this period. There is no data available for June 2018, so that month is excluded from the analysis. In total, there are 6488 individual bids included in the analysis. Capacity on the FFR market is tendered monthly. Therefore, there are 45 months included in the analysis. However, for the static market there are no prices available for 25% of the months. In these months, no flexible capacity was traded on this market.

In Figure 11, the average share of the accepted capacity per generation type over the whole period (April 2018 until January 2022) is presented for the dynamic FFRd and the static FFRs market.

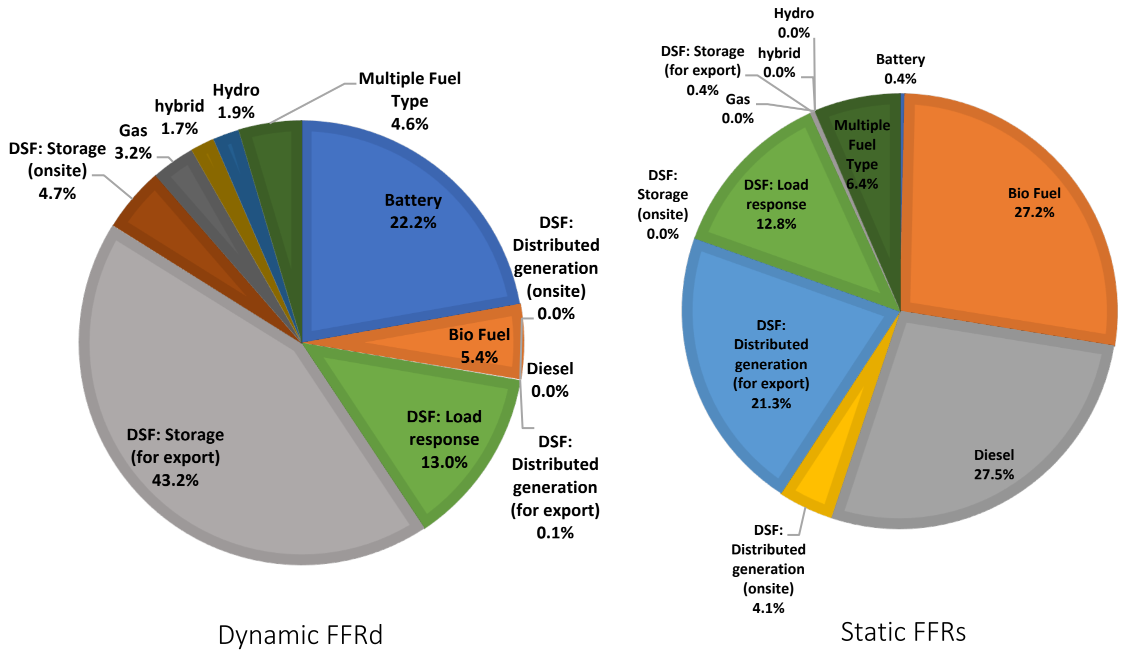


Figure 11 Share of accepted capacity per generation type of dynamic FFRd (left) and static FFRs (right) market over the period April 2018 until January 2022.

Before diving into the results of the different types of analysis, the relation between the two main variables of interest is discussed for both the dynamic as well as the static FFR market. The most remarkable observations of the graphs in Figure 12 and Figure 13 are presented in Table 15 and it is stated whether the observations support the hypothesis of this research. It can be seen that there is high volatility in the two variables and that at some moments the hypothesis of this research is supported by a visible negative trend between the two variables.

It shows that most observations (6/9) support this hypothesis. Note that these observations do not consider external factors. These will be included in the following sections.

Table 15 Observations of relation between share of load response and price on FFR market

Dynamic FFR market (FFRd)		
Period	Observation	Support hypothesis
Aug 2018 – Apr 2019	High S and decreasing P	Yes
Oct 2019 – Apr 2020	High P and decreasing S	Yes
May 2021 – Nov 2021	Increasing P and S	No
	Negative linear trend line between P and S	Yes
Static FFR market (FFRs)		
Period	Observation	Support hypothesis
Dec 2018 – Apr 2019	High S and low P	Yes
Apr 2019 – Aug 2019	Low S and high P	Yes
Nov 2019	High S and Low P	Yes
Apr 2021 – Dec 2021	Increasing S and P	No
	No clear visible trend between S and P	No

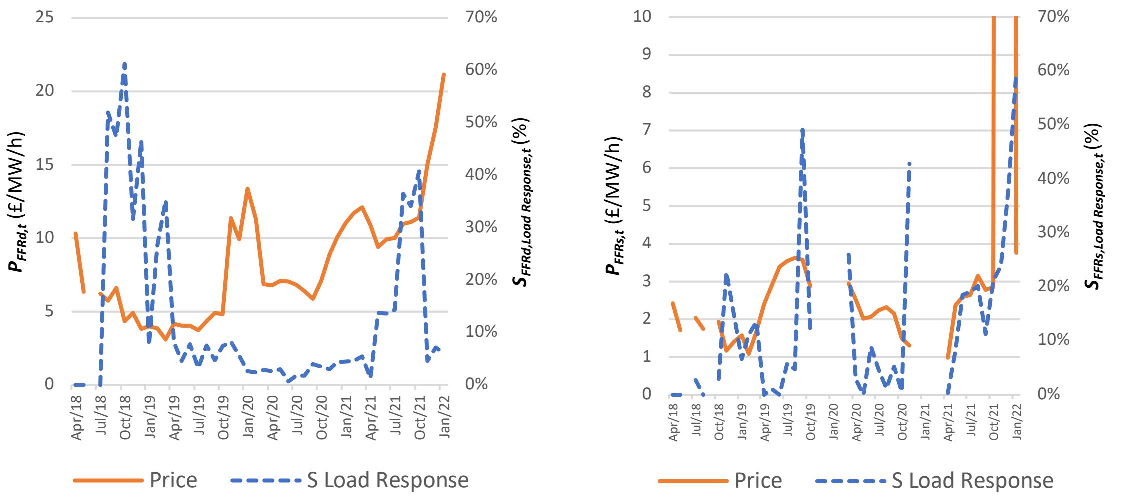


FIGURE 12 PRICE OF FLEXIBLE CAPACITY AND SHARE OF LOAD RESPONSE OVERTIME ON DYNAMIC (LEFT) AND STATIC (RIGHT) FFR MARKET

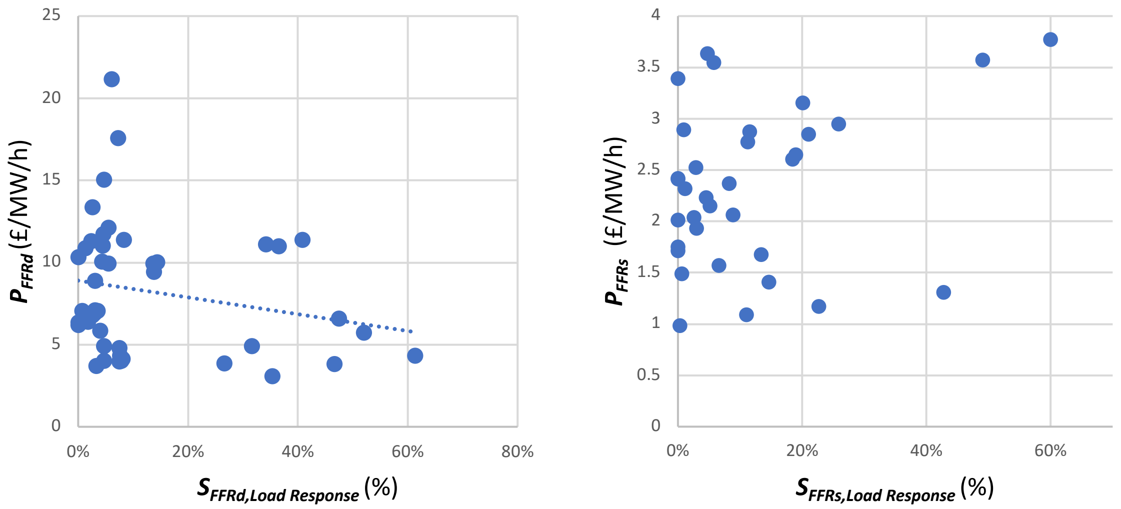


FIGURE 13 SCATTERPLOT AND LINEAR TREND LINE OF PRICE OF FLEXIBLE CAPACITY AND SHARE OF LOAD RESPONSE ON FFRD (LEFT) AND FFRS (RIGHT) MARKET

4.2.1.2 Regression analysis: FFR market

Before discussing the results of the regression analysis, it is tested whether the data is suitable to build a regression model on. This test shows that a regression model is only suitable for the FFRd, and not for the FFRs market. Data of the static FFRs market only contains a price for flexible capacity for 34 months (excluding outliers). In the other months (25%), no static flexible capacity was bought, so no price was settled. The regression model that is built based on these 34 months fails to have statistically significant results, as shown in appendix Table 23. It shows that only the participation of the generation type *Diesel* has a significant effect on the price, that the *observations/number of predictors ratio* is too low and that the predictive value of the model is low (R^2=0.28). Therefore, only the regression results of the FFRd market are analysed further.

The results of the dynamic FFRd regression model can be found in appendix Table 22. The direct independent variables that have shown to be statistically significant are $S_{FFRd,Battery}$ and $S_{FFRd,Load\ Response}$. The variables of the other flexibility sources have shown to be statistically insignificant. The indirect independent variable that has shown to be significant is the GB gas price GP_{GB}. All the indirect independent variables that are considered can be found in appendix Table 21.

In appendix Table 24, it is checked whether the FFRd regression model complies with the assumptions/checks of a regression model. It shows that the model complies with every assumption. However, a strong correlation of 0.69 has been found between GP_{GB} and P_{FFRd}. This is just below the critical value of 0.7 above which multicollinearity in the data is suggested. Multicollinearity could cause problems for the estimation of the coefficients in the regression model. On the other hand, the VIF analysis suggests that there is no collinearity, so the multicollinearity assumption is not violated. Therefore, the regression model is accepted.

Figure 14 and the regression statistics show that the regression model predict the price of flexible capacity P_{FFRd} reasonably well (R^2=0.69 and MAPE=24%). It shows a negative relationship between P_{FFRd} and $S_{FFRd,Load\ Response}$ (-0.116 $\frac{£/MW/h}{\%_S}$) and $S_{FFRd,Battery}$ (-0.059 $\frac{£/MW/h}{\%_S}$), which supports the hypothesis of this study. A positive relationship has been found between GP_{GB} and P_{FFRd}, which is according to expectations. For the gas price in GB, the unit *£/therm* is used, which is a conventional unit for natural gas companies (Wright, 1987). Therefore, many data providers also use this unit. A *therm* is approximately equal to 29.3 kWh.

The plots show that the price is predicted more accurately at high values than at low values of the independent variables ($S_{FFRd,Battery}$, $S_{FFRd,Load\ Response}$ and GP_{GB}). Especially high values for GP_{GB} show a clear effect on P_{FFR}. It also shows that the accuracy of the model increases over time, and that it follows the up moving trend of P_{FFRd}. This can be explained by the effect of GP_{GB} on P_{FFRd}. The peak of P_{FFRd} in January 2020 is clearly not predicted well.

The final regression model of the FFRd market is presented in Equation 4.1.

(EQUATION 4.1)

$$P_{FFRd}\ \left[\frac{£}{MW/h}\right] = 7.66 - 0.059\ S_{FFRd,Battery}[\%] - 0.12\ S_{FFRd,Load\ response}[\%] + 0.055 GP_{GB}\ \left[\frac{£}{therm}\right]$$

(regression model FFRd market)

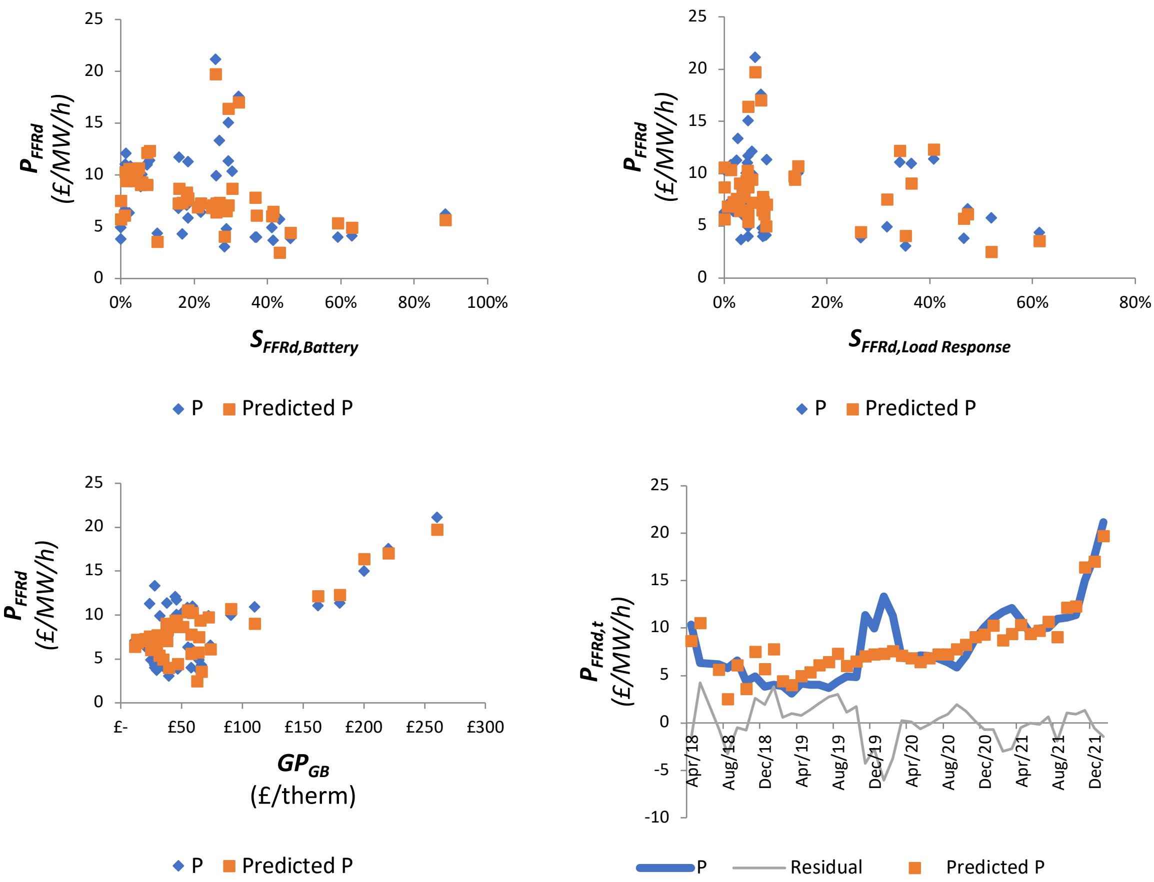


FIGURE 14 REGRESSION PLOTS FFRD MARKET

4.2.1.3 Capacity and price analysis of FFRd market

The results of the FFRd regression model are supported by an analysis of the capacity and prices on this market. This helps understanding the unexplainable observations.

Figure 15 shows the capacity and prices per flexibility source per tender period. In these graphs, the generation types that have an insignificant contribution (≤1%) are not shown to improve readability. The graphs show high volatility in the accepted capacity over the years. There seems to be a seasonal trend with a higher accepted capacity at the start of the winter. The ongoing high demand for flexibility takes place at the same time as the start of the Covid-19 pandemic, which can could be a possible explanation for it. The increased demand for flexibility was mainly covered by a big increase in flexibility coming from storage.

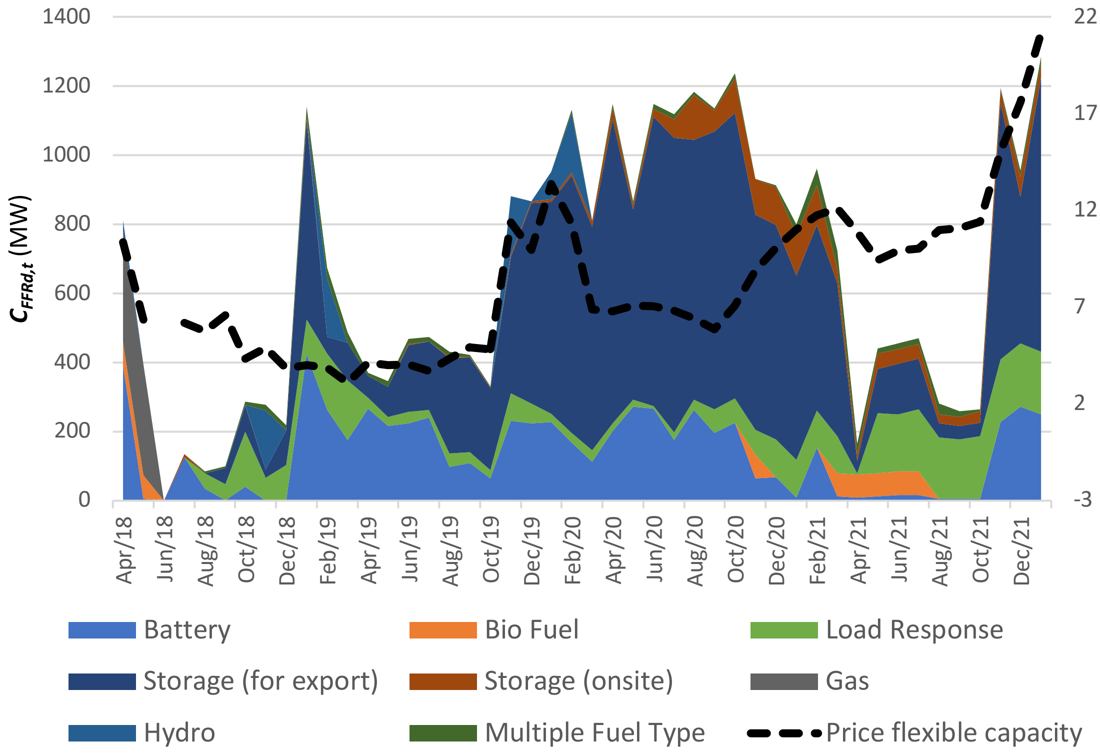


FIGURE 15 ACCEPTED DYNAMIC CAPACITY AND PRICES PER TENDER PERIOD PER GENERATION TYPE ON FFR MARKET (£/MW/H)

It can be seen in Figure 15 that there are significantly higher prices at the start of the winter in 2019, 2020 and 2021. This can be explained by an increase in the demand for flexibility in these periods. The prices stabilize again at a lower price in Spring. The high price in December 2021 can be explained by the high gas-price crisis in GB (Rabobank, 2021; The Guardian, 2021).

4.2.1.4 Average bid price and correlation analysis: FFR market

Figure 16 and Figure 17 show that *Load Response* bids lower on the static FFR market than in the dynamic FFR market. The figures also show that *Load Response* bids on average a lower price than the market average on both the dynamic (£7.10 vs. £8.24, -14%) and the static (£2.50 vs. £8.42, -70%) market. This supports the hypothesis of this research.

The correlation between P_{FFRd} and $S_{FFRd,Load\ Response}$ is -0.21 for the dynamic market. This supports the hypothesis of this research. For the static market this correlation is 0.28. This does not support the hypothesis of this research. A possible explanation for this is that the correlation analysis does not take external factors into account.

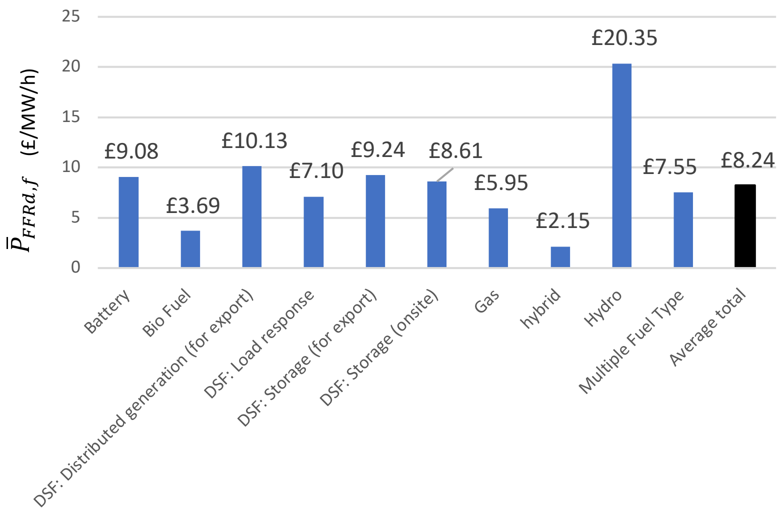


FIGURE 16 AVERAGE BID PRICE ON DYNAMIC FFR MARKET PER FLEXIBILITY SOURCE

FIGURE 17 AVERAGE BID PRICE ON STATIC FFR MARKET PER FLEXIBILITY SOURCE

4.2.2 BM MARKET RESULTS

4.2.2.1 Data description

The data of the auction results of the BM market provides information on an aggregate level on the capacity and prices per settlement period (30 min in GB). Therefore, the data is categorized as *Aggregated data*. The data that is included in the analysis covers the period of January 2015 until December 2019, as the data source does not provide sufficient information on the auction results before and after this period. In total, there are 87,274 settlement periods included in the dataset, each providing information on the capacity and prices of two balancing BM sub-markets: BM(FRR) & BM(RR).

Figure 18 shows the average share per flexibility source on the BM(FRR) and BM(RR) market.

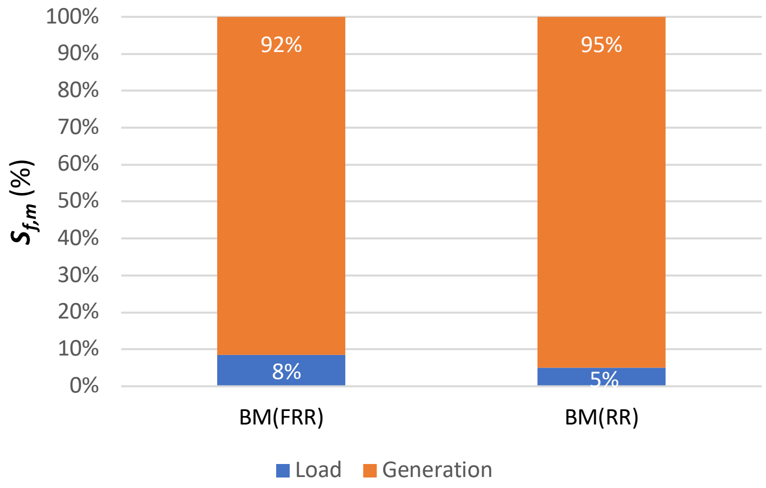


FIGURE 18 AVERAGE SHARE PER FLEXIBILITY SOURCE ON BM(FRR) AND BM(RR) MARKETS

Before presenting the results of the different types of analysis, the relation between the two main variables of interest is discussed to give context to these analyses. The most remarkable observations in Figure 19 and Figure 20 are presented in Table 16, which shows that the high volatility of the share of *Load* is not reflected in the price of flexible capacity.

Table 16 shows that most observations (7/8) do not support the hypothesis. It seems that an external factor is missing to explain the high volatility in the prices. The significant price drop in July 2018 cannot be explained by the share of *Load*. In addition, the extremely high prices from Jan 2015 until Jun 2015 (122 £/MW/h, outside of the graph) can also not be explained according to the model.

TABLE 16 OBSERVATIONS OF RELATION OF PRICE OF FLEXIBLE CAPACITY AND SHARE OF LOAD ON THE BM(FRR) AND BM(RR) MARKETS

BM(FRR) market		
Period	**Observation**	**Support hypothesis**
All periods	High volatility in S but low volatility in P	No
April 2018	Big decrease in P, while S does not significantly decrease	No
All periods	Overall trend is a decreasing P and S	No
All periods	No visible trend between P and S	No
BM(RR)		
Period	**Observation**	**Support hypothesis**
All periods	High volatility in S but low volatility in P	No
Oct 2017	High P and high S	No
Nov 2018 – May 2019	Increasing P and decreasing S	Yes
All periods	No visible trend between P and S	No

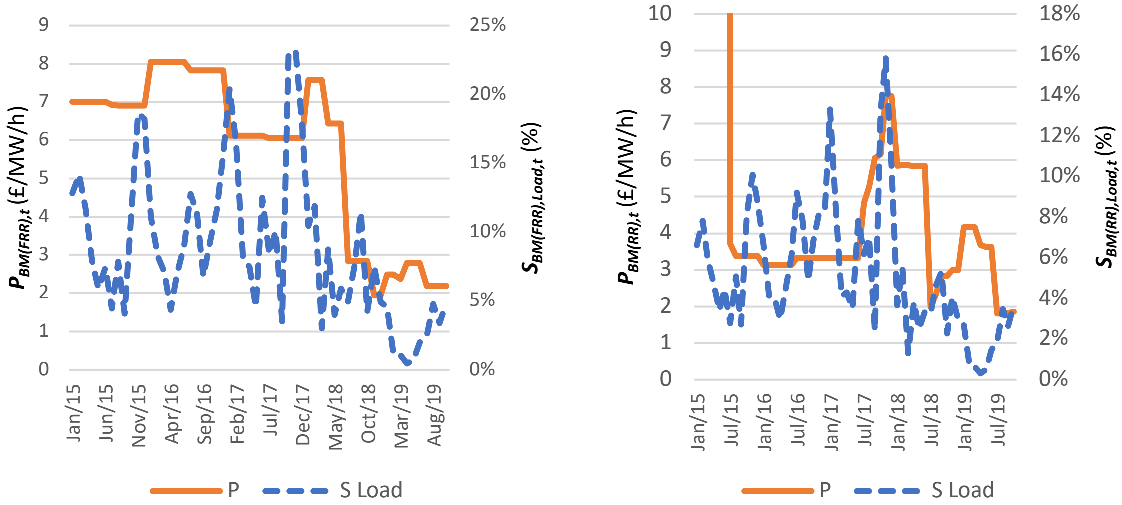


FIGURE 19 PRICE OF FLEXIBLE CAPACITY AND SHARE OF LOAD ON BM(FRR) (LEFT) AND BM(RR) (RIGHT)

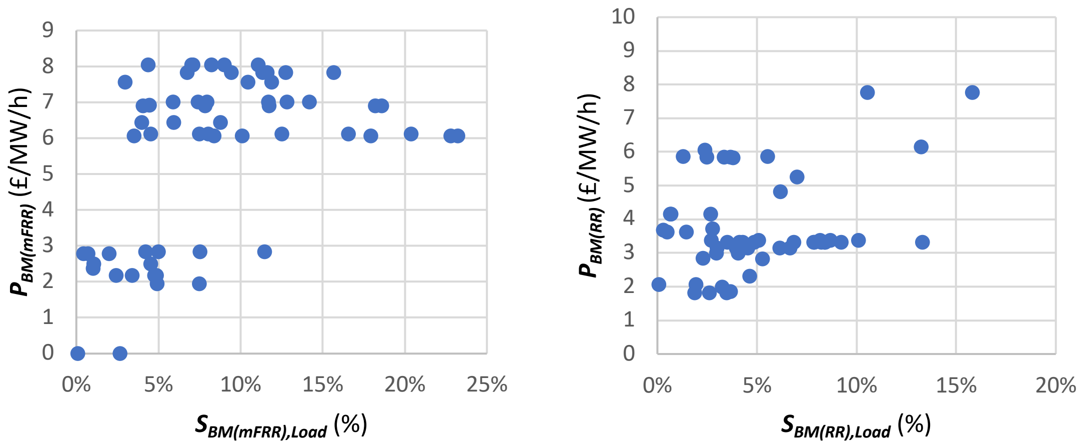


FIGURE 20 SCATTERPLOT OF SHARE OF LOAD IN TOTAL ACCEPTED CAPACITY AND PRICE FOR FLEXIBLE CAPACITY ON BM(MFRR) (LEFT) AND BM(RR) (RIGHT) MARKET

4.2.2.1 Regression analysis: BM market

The regression model of the BM(FRR) market in appendix Table 25 shows that no statistically significant effect have been found between $S_{BM(FRR),Load}$ and $P_{BM(FRR)}$ on the BM(FRR) market. Next to that, appendix Table 26 shows that the model does not comply with the assumptions of a regression model, as the residuals are not normally distributed. This is an indication that the regression model cannot estimate the coefficient of the independent variables.

The regression model of the BM(RR) market in appendix Table 27 also show that no statistically significant effect have been found between $S_{BM(RR),Load}$ and $P_{BM(RR)}$ on the BM(RR) market. Next to that, appendix Table 28 shows that the model does not comply with the assumptions of a regression model, as the residuals are not normally distributed. Lastly, the regression model has a very low predictive value (R^2=0.10). Based on these results, it is concluded that for both the BM(FRR) and the BM(RR) market it is not suited to use a regression model to estimate the effect of DR on the price of flexible capacity.

4.2.2.2 Average bid price and correlation analysis: BM market

An *average bid price analysis* is not possible on the data of the BM market, as it is *Aggregated data* and the separate bid prices are not specified per flexibility source.

The correlation between the variables $S_{BM(FRR),Load}$ and $P_{BM(FRR)}$ is 0.44 for the BM(FRR) market. For the BM(RR) market this correlation is 0.32. Both correlations do not support the hypothesis of this research.

4.3 Quantitative results: The Netherlands

Quantitative results have been collected for five Dutch balancing sub-markets: aFRR Symmetrical, aFRR Upwards, aFRR Downwards, mFRR Downwards and mFRRda Upwards. The dataset of the mFRRda market includes 12,400 individual bids submitted in 551 auctions in the period between 01/01/2018 and 31/12/2021 (*Bid offer data*). The average shares of the different flexibility sources in the total accepted capacity are shown per balancing sub-market in Figure 21.

It shows that *Large scale production* takes the majority of the share, followed by *Mixed Portfolio*. DR takes a small share in the total accepted capacity on the markets, especially in the aFRR balancing market for which S_{DR} is 0. The aFRR markets are therefore excluded from this analysis, as DR takes an insignificant share in the total accepted capacity.

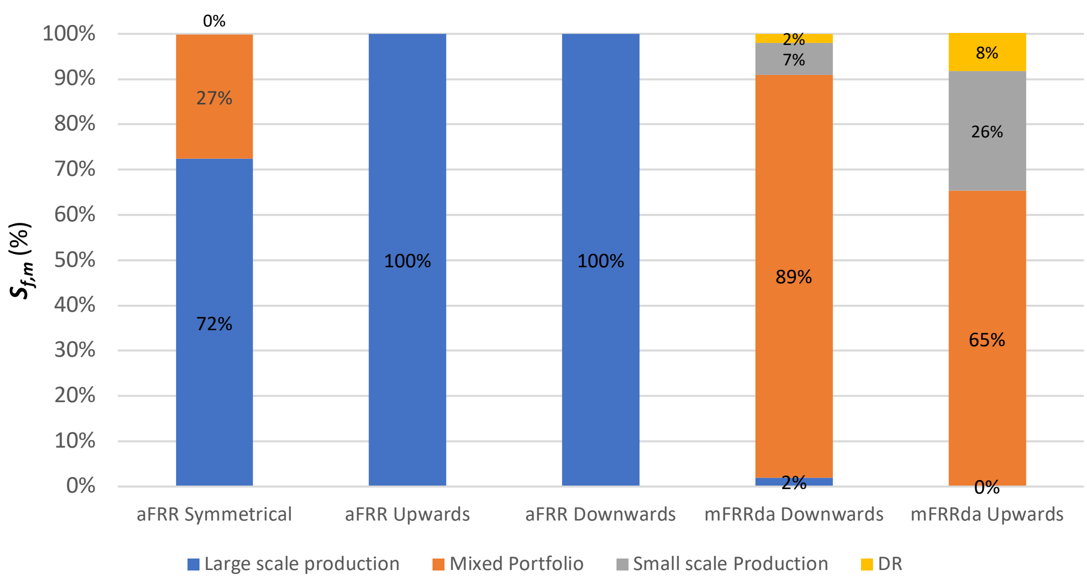


Figure 21 Average share of accepted capacity per flexibility source per balancing sub-market

4.3.1 mFRRda market results

4.3.1.1 Data description

Before diving into the results of the different types of analysis, the relation between the two main variables of interest is discussed for both the mFRRda Up and Down market. The most remarkable observations of the graphs in Figure 22 and Figure 23 are presented in Table 17 where it is stated whether the observations support the hypothesis of this research.

It shows that most observations (7/9) support this hypothesis. Note that these observations do not consider external factors. These will be included in the following sections.

Table 17 Observations of relation between share of demand response and price on mFRRda market

mFRRda Down market		
Period	Observation	Support hypothesis
Jan 2020 – Aug 2020	High S and steady P	No
May 2021	High P and Low S	Yes
	Negative linear trend line between P and S	Yes
mFRRda Up market		
Period	Observation	Support hypothesis
Jun 2018	High S and decreasing P	Yes
Feb 2019 – May 2019	High S and decreasing P	Yes
Dec 2019	High S and low P	Yes
Nov 2020 – Jun 2021	Increasing P and S	No
Aug 2021 – Dec 2021	Low S and high P	Yes
	Negative linear trend line between P and S	Yes

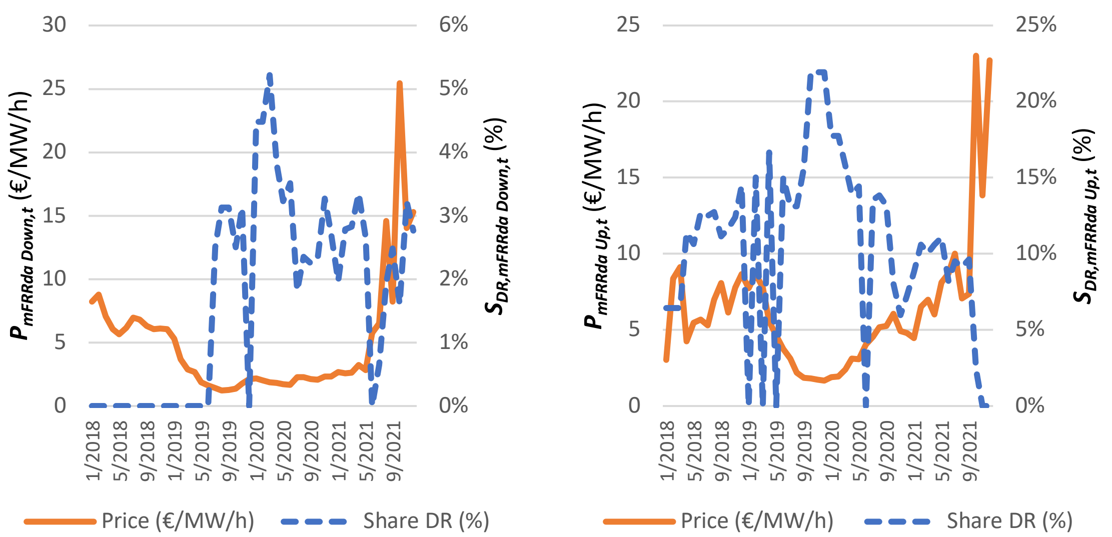


Figure 22 Price of flexible capacity and share of demand response over time on mFRRda Down (left) and mFRRda Up (right) market

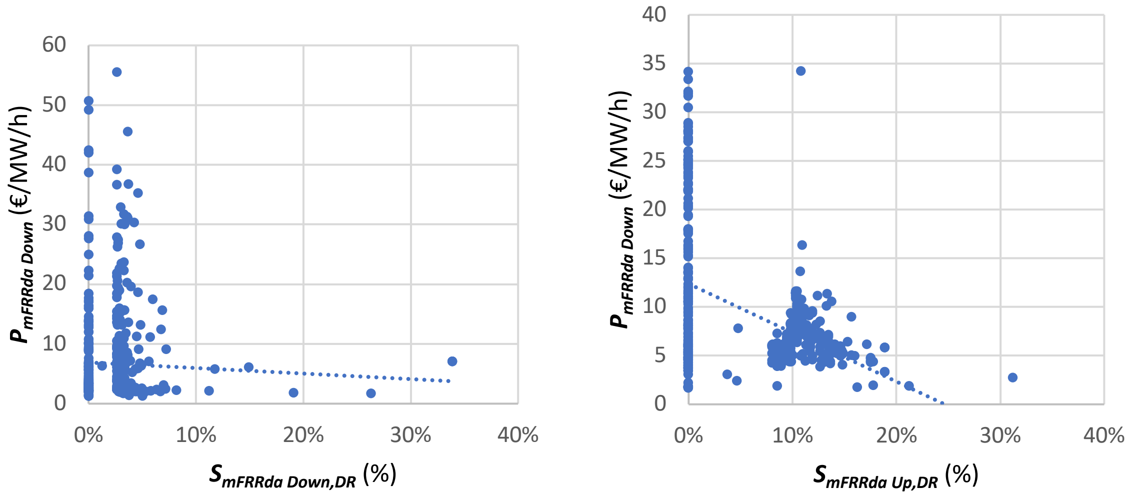


Figure 23 Scatterplot and linear trend line of price of flexible capacity and share of demand response on mFRRda Down (left) and mFRRda Up (right) market

4.3.1.2 Regression analysis: mFRRda Up market

The results of the regression model of the mFRRda Up market can be found in appendix Table 29. The direct independent variable that have shown to be statistically significant is $S_{mFRRda\ Up,DR}$. The indirect independent variables that have shown to be significant is the NL gas price GP_{NL} (unit: €/MWh).

In appendix Table 30, it is checked whether the mFRRda Up regression model complies with the assumptions/checks of a regression model. It shows that a strong correlation between GP_{NL} and $P_{mFRRda\ Up}$ has been found of 0.83, which makes sense as a high gas prices causes high marginal costs. The VIF analysis shows that this high correlation does not cause multicollinearity. Multicollinearity could cause problems for the estimation of the coefficients in the regression model. On the other hand, the *normality of residuals assumption* is violated by the regression model. This suggests that the coefficients of the model cannot be estimated accurately.

To understand why the residuals are not normally distributed, the relation between the residuals and the independent variables is investigated in Figure 24. Two main things are remarkable, which can explain the violation of the normality of residuals assumption. There are many different residuals for 0% $S_{mFRRda\ Up,DR}$. This is due to the fact that in many auctions DR did not participate and different prices were settled. When the DR participants join the auction, they win and provide a significant share on the auction. Next to that, residuals are higher for moments when GP_{NL} was around €100/MWh. This can be explained by the market instability caused by high gas prices.

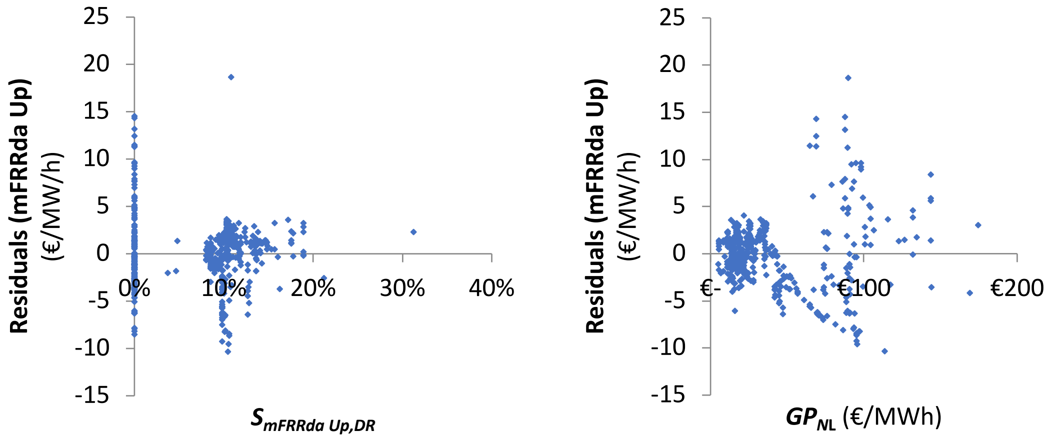


FIGURE 24 SCATTERPLOT OF RESIDUALS OF REGRESSION MODEL AND INDEPENDENT VARIABLES OF REGRESSION MODEL MFRRDA UP MARKET

The violation of the *normality of residuals assumption* makes the estimation of the coefficient less accurate. However, the 95% confidence range of the coefficient is between -0.184 $\frac{€/MW/h}{\%_S}$ and -0.083 $\frac{€/MW/h}{\%_S}$ (both negative), the independent variables show a significant effect on the dependent variable and the violation of the normality of residuals assumption is explainable. Therefore, the results of the mFRRda Up regression model will be accepted and used for the conclusion. The inaccuracy caused by the violation of the assumption can be compensated by combining the results of multiple markets.

Figure 25 and the regression statistics show that the regression model predict the price of flexible capacity $P_{mFRRda\ Up}$ well (R^2=0.70 and MAPE=30%). It shows a negative relationship between $P_{mFRRda\ Up}$ and $S_{mFRRda\ Up,DR}$ (-0.13 $\frac{€/MW/h}{\%_S}$), which supports the hypothesis of this study. However, the relationship looks non-linear. This can make the estimation of the effect less accurate. A positive relationship has been found between GP_{NL} and $P_{mFRRda\ Up}$, which makes sense. Especially high values for GP_{NL} show a clear effect on $P_{mFRRda\ Up}$. This relation does looks like to be linear.

The final regression model of the mFRRda Up market is presented in Equation 4.2.

(EQUATION 4.2)

$$P_{mFRRda\ Up}\left[\frac{€}{MW/h}\right] = 2.35 - 0.13\ S_{mFRRda\ Up,DR}[\%] + 0.15 GP_{NL}\left[\frac{€}{MWh}\right]$$

(regression model mFRRda Up market)

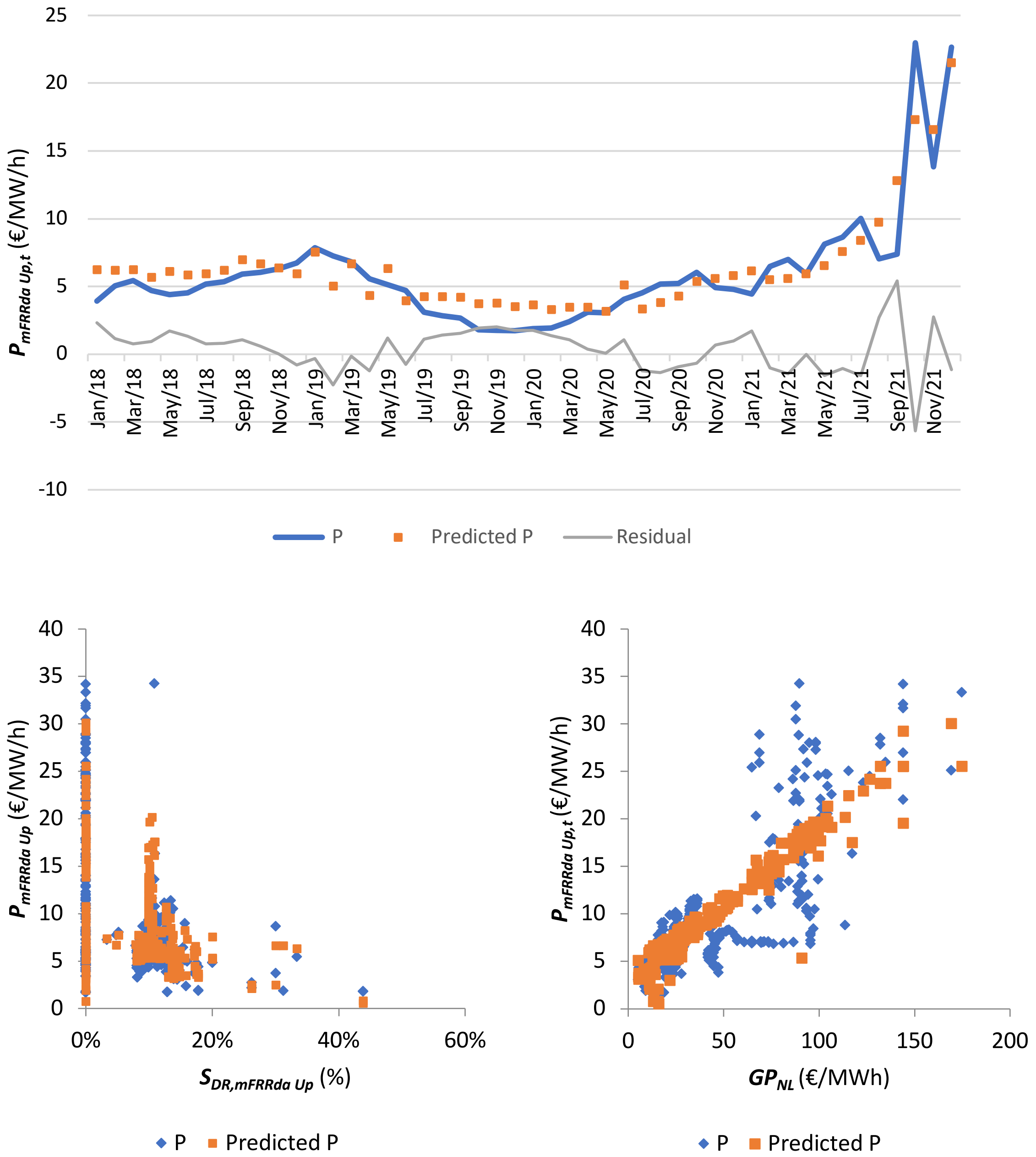


FIGURE 25 REGRESSION PLOTS MFRRDA UP MARKET

4.3.1.1 Regression analysis: mFRRda Down market

The results of the regression model of the mFRRda Down market can be found in appendix Table 31. The direct independent variable that have shown to be statistically significant is $S_{mFRRda\ Down,DR}$. The indirect independent variables that have shown to be significant is the NL gas price GP_{NL} (unit: €/MWh).

In appendix Table 32, it is checked whether the mFRRda Down regression model complies with the assumptions/checks of a regression model. It shows that all of the regression model assumptions are met, except that the *normality of residuals assumption* is violated by the regression model. This suggests that the coefficients of the model cannot be estimated accurately.

To understand why the residuals are not normally distributed, the relation between the residuals and the independent variables is investigated in Figure 26. Two main things are remarkable, which can explain the violation of the normality of residuals assumption. There are many different residuals for 0% $S_{mFRRda\ Down,DR}$. This is due to the fact that in many auctions DR did not participate and different prices were settled. When the DR participants join the auction, they win and provide a significant share on the auction. Next to that, most of the residuals of GP_{NL} are positive. When the residuals would have been normally distributed, there would have been as many positive residuals as negative residuals. This can be explained by the large volatility of the gas prices during the gas prices, which causes the regression model to estimate the effect less accurate. These arguments can partly explain the violation of the normality of residuals assumption.

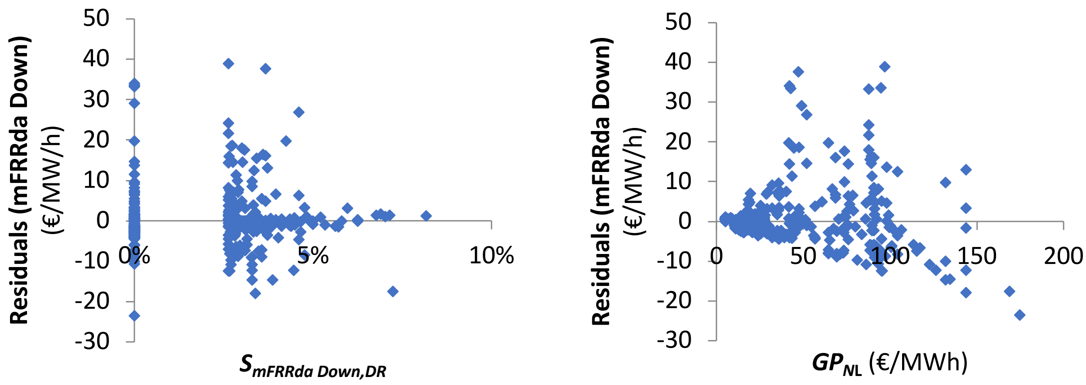


FIGURE 26 SCATTERPLOT OF RESIDUALS OF REGRESSION MODEL AND INDEPENDENT VARIABLES OF REGRESSION MODEL MFRRDA DOWN MARKET

The violation of the *normality of residuals assumption* makes the estimation of the coefficient less accurate. However, the 95% confidence range of the coefficient is between -0.678 $\frac{€/MW/h}{\%_S}$ and -0.0568 $\frac{€/MW/h}{\%_S}$ (both negative), the independent variables show a significant effect on the dependent variable and the violation of the normality of residuals assumption is explainable. Therefore, the results of the mFRRda Down regression model will be accepted and used for the conclusion. The inaccuracy caused by the violation of the assumption can be compensated by combining the results of multiple markets.

Figure 27 and the regression statistics in Table 31 show that the regression model prediction accuracy is acceptable (R^2=0.40 and MAPE=54%). It shows a negative relationship between $P_{mFRRda\ Down}$ and $S_{mFRRda\ Down,DR}$ (-0.37 $\frac{€/MW/h}{\%_S}$), which supports the hypothesis of this study. However, the relationship looks non-linear. A positive relationship has been found between GP_{NL} and $P_{mFRRda\ Down}$, which makes sense. This relation does looks like to be linear.

The final regression model of the mFRRda Down market is presented in Equation 4.3.

(EQUATION 4.3)

$$P_{mFRRda\ Down}\left[\frac{€}{MW/h}\right] = 2.48 - 0.37\ S_{mFRRda\ Down,DR}[\%] + 0.16GP_{NL}\left[\frac{€}{MWh}\right]$$

(regression model mFRRda Down market)

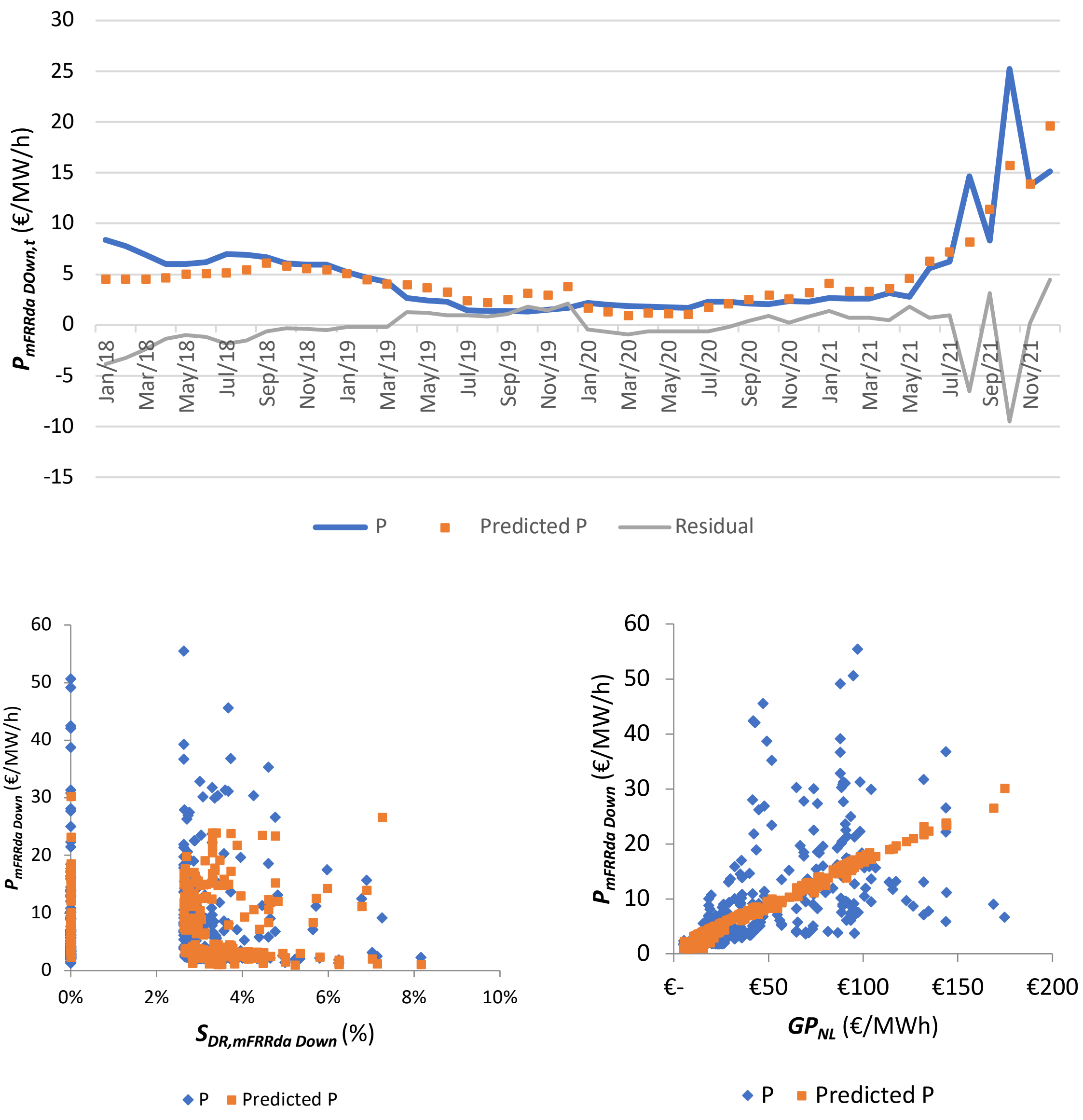


FIGURE 27 REGRESSION PLOTS MFRRDA DOWN MARKET

4.3.1.2 Capacity and price analysis: mFRRda Up and Down market

The results of the mFRRda regression models are supported by an analysis of the capacity and prices on this market. This helps understanding the unexplainable observations.

Figure 28 shows that the total accepted capacity of the mFRRda Up market is steadily increasing over time from around 500 MW to almost 1,000 MW. It does not look like the total accepted capacity has a significant effect on the price. The accepted capacity of DR is steady with a few exceptions. Significant volatility is visible in the price of flexible capacity. The peak in the price of flexible capacity can be explained by the gas crisis. The low accepted capacity of DR at the end of 2021 can also be explained by the gas crisis, which caused large industries to shut down due to high operational costs.

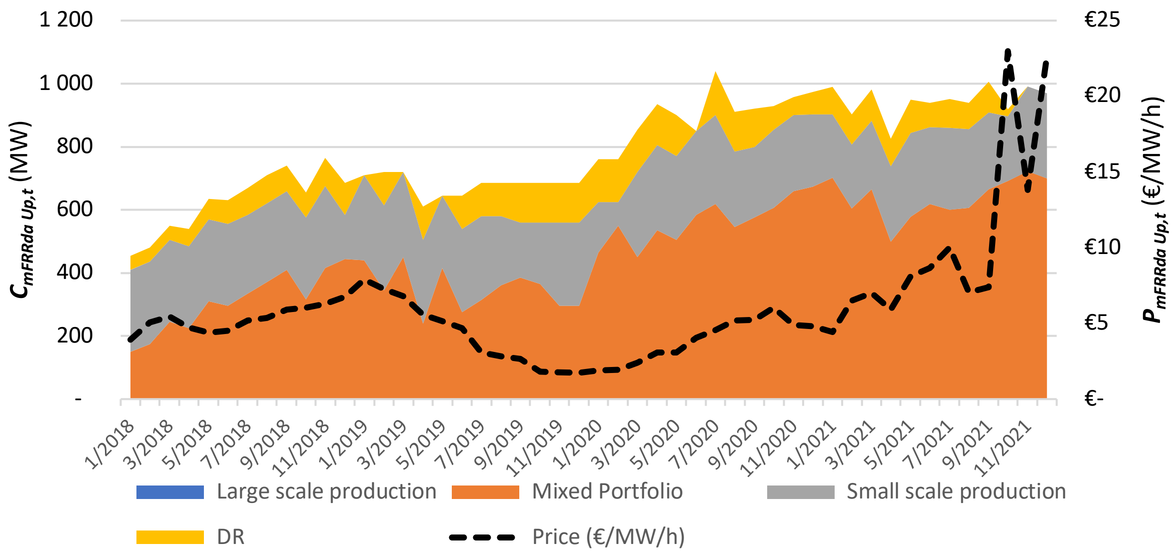


FIGURE 28 ACCEPTED CAPACITY PER FLEXIBILITY SOURCE OVER TIME ON MFRRDA UP MARKET

Figure 29 shows that the total accepted capacity of the mFRRda Down market is steady around 600 MW. The total accepted capacity does not seems to be effected by the prices, or vice versa. DR provides no flexible capacity until July 2019. From that moment, DR start providing a steady small amount of the accepted capacity with a few excepts where no DR is provided. Significant volatility is visible in the price of flexible capacity. The peak in the price of flexible capacity at the end of 2021 can be explained by the gas crisis.

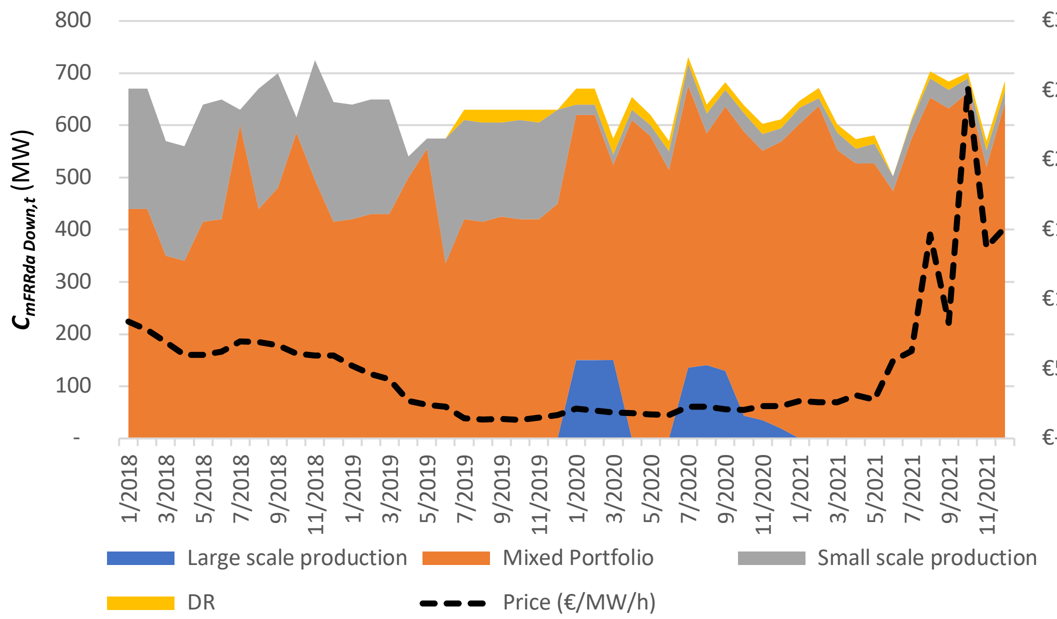


FIGURE 29 ACCEPTED CAPACITY PER FLEXIBILITY SOURCE OVER TIME ON MFRRDA DOWN MARKET

4.3.1.3 Average bid price and correlation analysis: mFRR markets

Figure 30 shows that DR bids are lower than the market average on the mFRRda Down market (€4.92/MW/h vs. €7.06/MW/h; i.e., 30% lower) and mFRRda Up market (€6.71/MW/h vs. €8.98/MW/h; i.e., 25% lower). Both observations support the hypothesis of this study. The aFRR market is excluded from the analysis, because DR provides an insignificant amount of the accepted capacity.

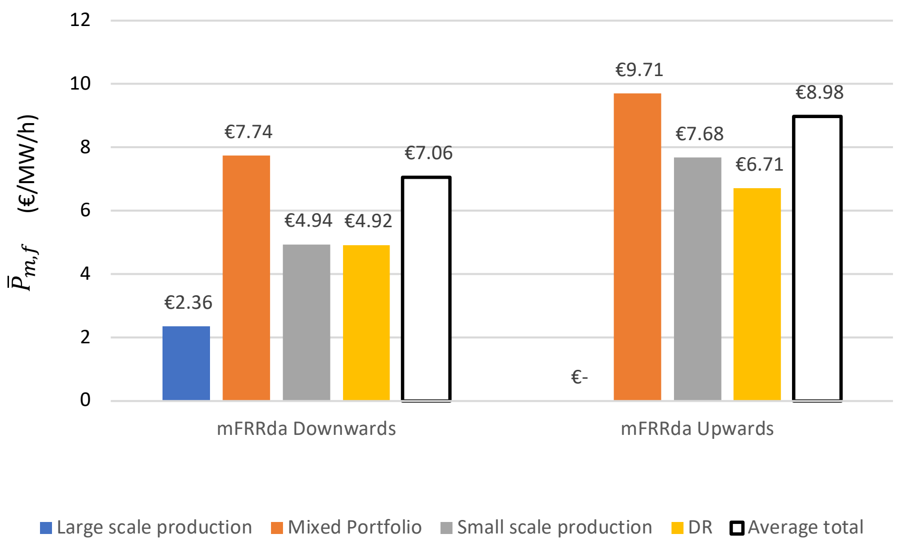


FIGURE 30 AVERAGE BID PRICE PER FLEXIBILITY SOURCE PER DUTCH SUB-BALANCING MARKET

The correlation between $P_{mFRRda,Up}$ and $S_{mFRRda\ Up,DR}$ is -0.49 for the mFRRda Up market. The correlation between $P_{mFRRda,Down}$ and $S_{mFRRda\ Down,DR}$ is -0.050 for the mFRRda Down market. Both observations support the hypothesis of this research.

4.4 Quantitative results: Cross-market comparison and analysis

In this section, the results of the different analyses and markets are consolidated to conduct a cross-market comparison and analysis.

4.4.1 Regression analysis

The results of the regression models provide an estimation of the change in price caused by a 1% increase of the share of DR ($\frac{\Delta P}{\Delta S_{DR}}$). To fairly compare markets with different price levels and currencies, the relative cost reduction (RCR) is calculated by dividing this number by the average price per market, $\overline{P_m}$. This results in a measure for the percentage change in P caused by a percentage change in S_{DR} ($\frac{\Delta P}{\Delta S_{DR}}$).

Figure 31 shows the relative cost reduction of DR across the different markets for which a regression analysis was possible. It shows that the relative cost reduction of the FFRd and the mFRRda Up are both around -1.5%. The relative cost reduction of the mFRRda Down market is significantly higher at -5.24%. The average of the different estimations is -2.71%.

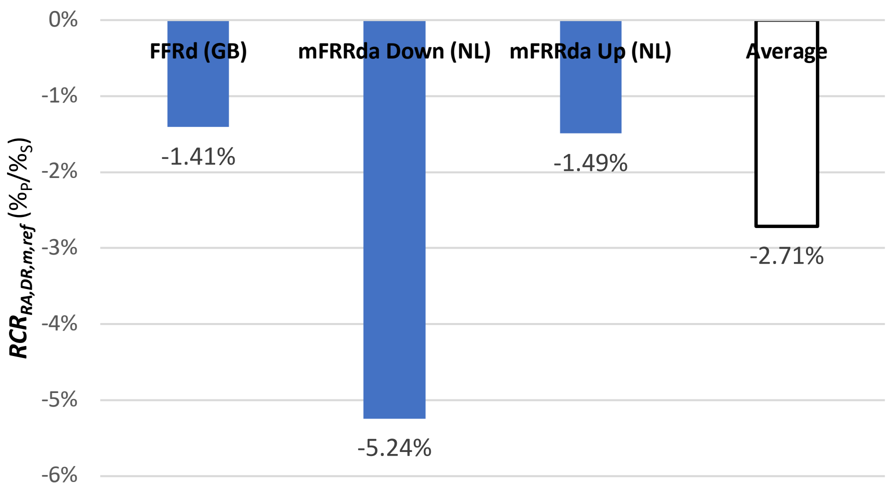


Figure 31 Overview of results from regression analysis

Figure 32 shows the estimated price reduction of DR in the reference year per balancing market. This calculated by multiplying the relative cost reduction of the regression analysis ($RCR_{RA,m,ref}$) with the average share of DR per market ($\bar{S}_{DR,m}$). This result can be interpreted as the cost reduction for TSOs due to the participation of DR in balancing markets. This cost reduction ranges from -11% to -18%.

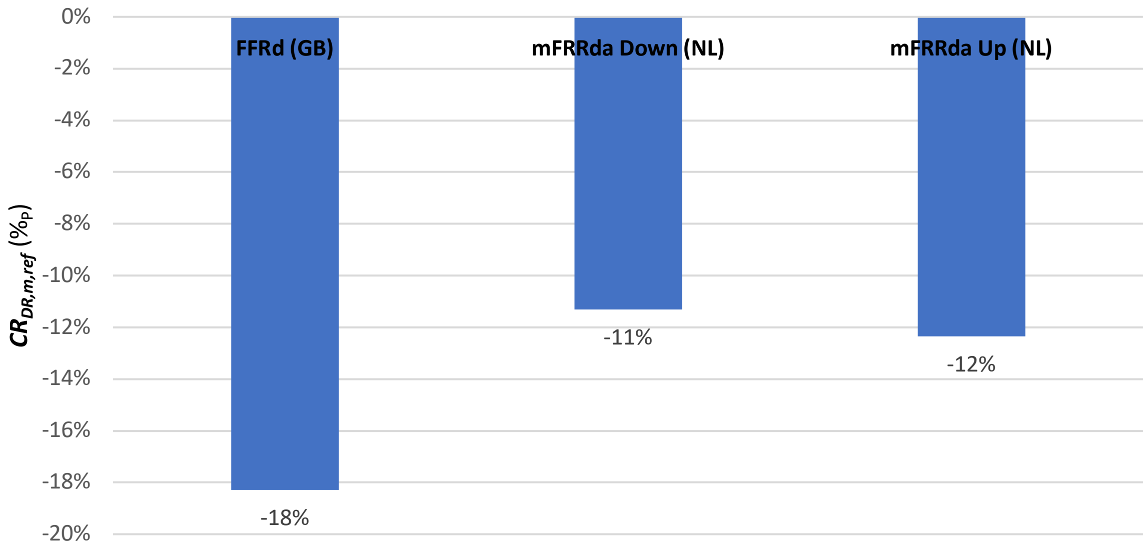


FIGURE 32 ESTIMATED COST REDUCTION OF DEMAND RESPONSE IN REFERENCE YEAR PER BALANCING SUB-MARKET

4.4.2 AVERAGE BID PRICE ANALYSIS

The measure of the average bid price analysis should be interpreted differently than the regression analysis. The relative cost reduction of the average bid price analysis ($RCR_{ABA,m,ref}$) shows the percentage difference between the average bid price of DR and the overall average bid price on the market (ΔP in $\%_P$).

Figure 33 shows the relative cost reduction for which the average bid price analysis was possible. It shows that the different markets show significantly different results, ranging from -14% for the FFRd market to -70% for the FFRs market. The average of the results is -35%.

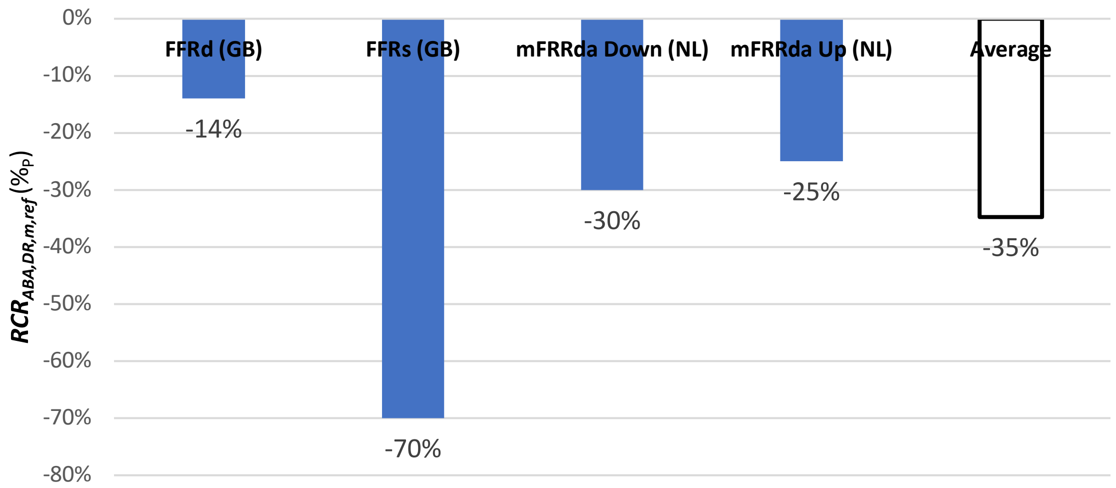


FIGURE 33 OVERVIEW OF RESULTS FROM AVERAGE BID PRICE ANALYSIS

4.4.3 Correlation analysis

Figure 34 shows the results of the correlation analysis. For three of the six sub-markets a negative relationship is estimated between P and S_{DR}, ranging from -0.05 to -0.49. For the other three markets a positive relationship is estimated, ranging from 0.28 to 0.44.

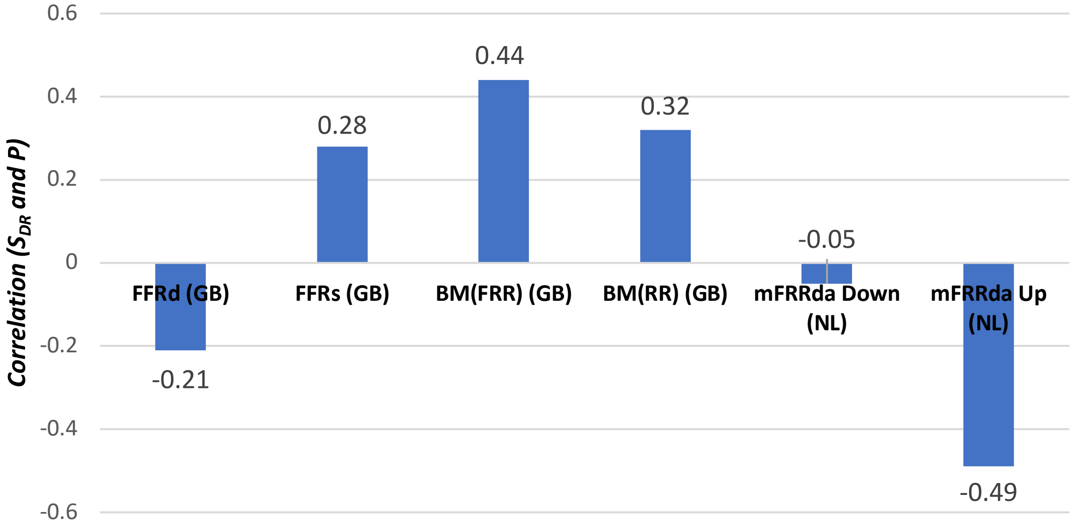


Figure 34 Overview of results from correlation analysis

4.4.4 Comparison analyses

The average bid price analysis show similar results to the regression analysis, as all the result suggest a negative relationship between P and S_{DR}. However, the two types of analyses show different quantifications of this effect, as the highest and the lowest estimations are not the same per balancing market in the analyses. The correlation analysis shows significantly different results than the other two analysis. It suggests a positive relationship for the BM and FFRs markets, while this is not suggested by the other two analyses.

4.5 Extrapolation towards 2030

In this section, the results for the extrapolation of $CR_{DR,ref}$ towards 2030 are presented. First, different studies that estimate the participation of DR in balancing markets are discussed. Second, an estimate for $S_{DR,2022}$ is made based on these studies. This estimate is used for the extrapolation to estimate $CR_{DR,2030}$.

The studies that provide relevant information for this extrapolation are presented in Table 18. The studies present different measures for estimating the role of DR in providing flexibility to the electricity system in 2030. IEA (2021) estimates that the share of DR in the electricity system flexibility will grow from 1.6% in 2020 to 22% in 2030 for advanced economies. The European Commission (2020) takes a different approach and estimates the total need for flexibility based on the penetration of RES in the European electricity system over time. This study estimates that the need for 'short term flexibility' will not change significantly towards 2030, but that the need for 'multi-hour flexibility' will increase from

110 TWh in 2015 to 140 TWh in 2030, which will be covered by storage systems and demand response for 38 TWh (27%) in 2030. Alliander & ECN (2021) estimate that DR will provide 13% of the electricity grid flexibility in 2030 using a modelling approach with the Netherlands as case study.

TABLE 18 LITERATURE USED TO ESTIMATE THE PARTICIPATION OF DEMAND RESPONSE ON BALANCING MARKETS IN 2030

Study		Organization (Type of organization)	Estimation of $\bar{S}_{DR,2030}$
The supply of flexibility for the power system in the Netherlands, 2015-2050	(Alliander & ECN, 2017)	Alliander (Dutch grid operator) ECN (Dutch research institute)	13%
Demand Response Tracking Report	(IEA, 2021)	IEA (International research institute)	22%
Which, where, when and how much flexibility and storage do we need to meet 2030 goals?	(European Commission, 2020)	European Commission	27%

Taking an average over these studies result in an estimate of the share of DR in balancing markets in 2030 of 21%. By using the extrapolation explained in methodology section 3.4, the estimate of the cost reduction of DR in 2030 ($CR_{DR,2030}$) is 56%. To correct for uncertain development towards 2030, a sensitivity analysis is conducted using correction factor CF, which takes the values 0.75, 1, and 1.25. The sensitivity analysis is presented in Figure 35. By taking the correction factor into account, it is estimated that the cost reduction in 2030 due to the participation of DR ($CR_{DR,2030}$) ranges from 43% to 71%.

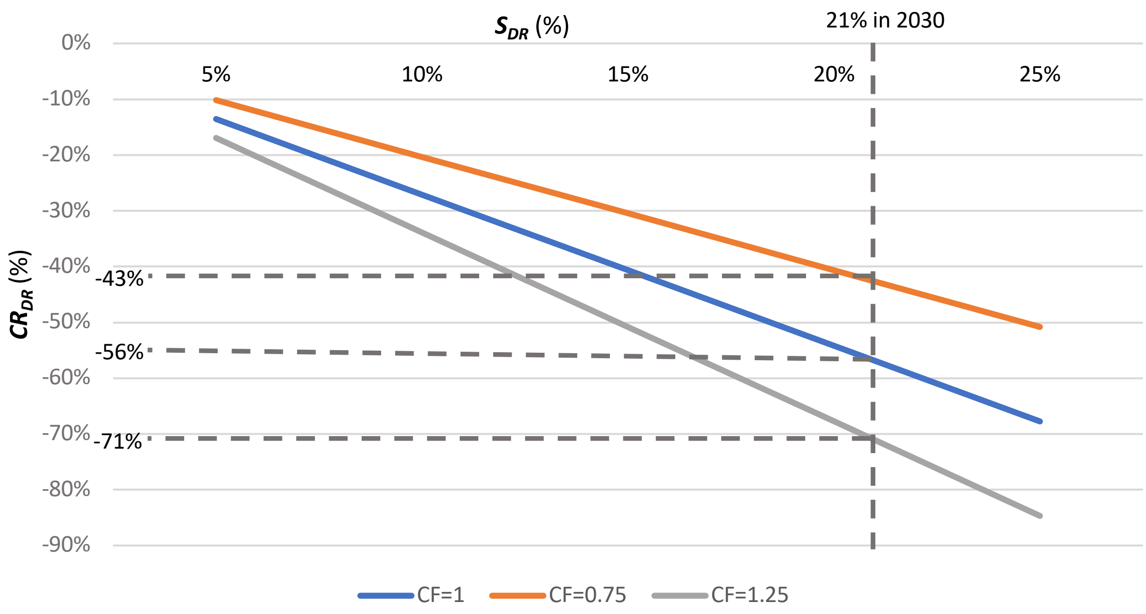


FIGURE 35 SENSITIVITY ANALYSIS OF EXTRAPOLATION COST REDUCTION POTENTIAL OF DEMAND RESPONSE TOWARDS 2030

5 DISCUSSION

This chapter reflects on the methodology, the assumptions, and the results of this research. It is also discussed how the results can be interpreted. By examining the strengths and weaknesses of the study, it is determined how the results can be interpreted for drawing the conclusion.

First, the internal validity of the qualitative results is discussed. By doing this, it is assessed how appropriate an overview is provided of the opportunities and barriers to sharing more detailed data of balancing markets to enable the quantification of the cost reduction of DR. Second, the internal validity of the quantitative results is discussed. This is done by critically assessing the methodology and the results in their ability to identify the cause-effect relationship between the participation of DR and the price of flexible capacity in balancing markets. Subsequently, the extrapolation of these results towards 2030 is discussed.

The external validity of this research is discussed to assess to which extent the results can be generalized. This is done by examining the country selection bias of the case studies, the assumptions of the (marginal) costs of DR, other factors to the costs of DR, and by comparing the results of this research with results found in existing literature which also estimates the cost reduction of DR. Lastly, recommendations for future research are provided based on the limitations of this research.

5.1 INTERNAL VALIDITY

5.1.1 INTERVIEWS ON THE IDENTIFICATION OF OPPORTUNITIES AND BARRIERS FOR SHARING DATA

Literature research was used as preparation input for the interviews to collect the qualitative results. The number of opportunities and barriers found in the literature was limited. However, the experience and knowledge of the interviewer formed a good contextual basis for the interviews.

The interviews show that results have been collected from experts with a diverse spectrum of perspectives. The results also show that the interviewees agreed on most of the opportunities and barriers, which indicates that a complete overview of the opportunities and barriers is presented. However, there are some opportunities and barriers that are only supported by one interviewee, while the other interviewees do not agree on these opportunities and barriers. These are therefore not considered for the conclusion.

The number of interviewees is limited. Next to that, the interviewees were selected based on the researcher’s network and they work for Dutch organizations. This could have created a selection bias in the results.

5.1.2 REGRESSION, AVERAGE BID PRICE, AND CORRELATION ANALYSIS

Different types of analyses were used to test the hypothesis of this study and quantify the relationship between the participation of DR and the price of flexible capacity in balancing markets. Multiple balancing sub-markets are included in the scope of the two case studies, GB and NL. The results of the different analyses are discussed per balancing sub-market, after which the different outcomes are compared.

5.1.2.1 FFRd (GB)

Regarding the FFRd data, a clear negative relationship is visible between the participation of DR ($S_{Load\ response,FFRd}$) and the price of flexible capacity on the FFRd market (P_{FFRd}). This observation is supported by the regression analysis, which provides estimates of a significant effect. The results of the average bid price and correlation analysis also support this. All these observations support the hypothesis of this research.

5.1.2.2 FFRs (GB)

For the FFRs market, a contradiction between the results of the different types of analyses is observed. It is remarkable that DR bids are significantly lower on the FFRs market than the market average (-70%), while the regression analysis cannot support the hypothesis, as it cannot identify a significant effect of $S_{Load\ response,FFRs}$ on P_{FFRs}. Next to that, a positive correlation (0.28) has been found between $S_{Load\ response,FFRs}$ and P_{FFRs}.

When assuming the validity of the hypothesis of this study - a negative relationship between the variables of interest - the positive correlation can be explained by the fact that this type of analysis does not consider any other factors. It could be the case that on moments of high $S_{Load\ response,FFRs}$, an external factor (e.g. the gas price) accidentally was also high which increased P_{FFRs}. This leads to a positive correlation. If the external factor causes this correlation could have been tested with a regression analysis. However, this was not possible due to the limited number of observations as input to the regression model. This limitation can also explain why no significant effect was estimated of $S_{Load\ response,FFRs}$ on P_{FFRs}.

When not assuming the validity of the hypothesis - there is an insignificant, or a positive relationship between the two variables of interest - the contradiction on the FFRs market can be explained by the fact that the result of the average bid price analysis is caused by the extreme outlier in the average bid price of the flexibility source *DSF: Distributed generation (for export)*. This flexibility source bid 47.58 £/MW/h compared to the market average of 8.42 £/MW/h. Excluding this flexibility source, *Load Response* bids the third-highest average bid price on this market, of the seven flexibility sources participating in this market.

5.1.2.3 BM (GB)

Looking at the BM(FRR) and the BM(RR) market data, no trend is visible between the variables of interest. Next to that, the regression models for these markets show that no significant effect can be measured. The correlation analysis for the BM(FRR) and the BM(RR) estimate a positive correlation of 0.44 and 0.32, respectively. An average bid price analysis was not possible for these markets, due to a lack of detail in the input data.

As explained in *Methodology* section 3.5.1.2, the data combines tender results of different balancing sub-markets of GB, which had to be shared due to EU regulation in the format of the markets distinguished by ENTSO-E. Therefore, the data does not represent GB's markets individually. Both markets show sudden significant price drops in the data, which is remarkable. This can be explained by the lack of data quality.

Due to the lack of data quality, and because only the correlation analysis could be conducted on the data, little can be said about the relationship between S_{DR} and P on the BM(FRR) and the BM(RR) markets.

5.1.2.4 mFRRda (NL)

For both the mFRRda Up and Down market, there is a visible negative trend between the variables of interest. This trend is supported by all three types of analysis, which support the hypothesis of this research.

However, there are two main weaknesses in the regression analysis of the mFRRda markets. First, the regression analysis of the mFRRda Down market is based on a low participation of DR of 2.3%. Therefore, a limited number of DR participants are represented by these results. Next to that, the regression models of both the mFRRda Up and Down market violate the normality of residuals assumption. This leads to less accurate estimations of the coefficients, in this case $RCR_{RA,DR,mFRRda\ Up,ref}$ and $RCR_{RA,DR,mFRRda\ Down,ref}$. This inaccuracy can (partly) be corrected for by taking the average over the estimations of multiple regression models.

5.1.3 CROSS-MARKET COMPARISON

The cross-comparison for the two case studies shows that the highest price reduction due to the participation of DR is estimated in the mFRRda Down market by both the regression analysis as well as the average bid price analysis. However, the correlation analysis does not show the strongest negative correlation for this market.

The results of the FFRd market similarly show that in this market, the lowest price reduction is estimated by the regression and the average bid price analysis. Also in this case, the correlation analysis does not show the weakest negative correlation for the FFRd market.

As explained earlier, the deviating result of the correlation analysis can be explained by the fact that this type of analysis does not include external factors.

Remarkably, the regression analysis shows a similar result for the FFRd market to the mFRRda Up market (-1.41 $\frac{\%_P}{\%_S}$ vs. -1.49 $\frac{\%_P}{\%_S}$, respectively), while the results of the average bid price analysis are significantly different (-14$\%_P$ vs. -25$\%_P$, respectively). This can be explained by the difference in the approach of the two types of analyses in estimating the price reduction. The average bid price analysis does not consider the share of the flexible capacity provided by DR. The regression analysis does take this (indirectly) into account.

One thing that is clearly noticeable in the FFR and mFRRda markets is the extreme increase in the price of flexible capacity at the end of 2021, caused by the high gas prices. High volatility of the dependent variable in a regression model leads to less accurate estimations of the regression model (Stock & Watson, 2019).

5.1.4 EXTRAPOLATION TOWARDS 2030

The cost reduction in the reference year is extrapolated towards 2030 by making two assumptions. The first assumption is that relative cost reduction in the reference year is the same as in 2030. This is a rough estimation that cannot be factually justified. Next to that, it is assumed that the cost reduction of DR will linearly increase with the increase of the participation of DR. This assumption can neither be justified, nor is unlikely to be true. This can be seen in the regression plots, which show that the price reduction decreases with higher participation of DR (e.g. Figure 25). This suggests that fitting an exponential or logarithmic model would be more suitable. Justifying both assumptions, or using a more complex approach, lies outside of the scope of this research. To correct for these uncertainties, the sensitivity analysis is conducted, based on a correction factor.

5.2 EXTERNAL VALIDITY

5.2.1 COUNTRY SELECTION BIAS

Studies like this are only possible for countries that allow DR and for which the appropriate data is available. This creates an inherent selection bias. Only countries that meet these criteria can be included in the scope of the analysis, which is not a good representation of countries.

5.2.2 COSTS OF DR FOR TSOS

This study mainly focuses on the cost reduction that the participation of DR can realize for TSOs, and therefore the cost reduction from a system perspective. When a price reduction is found using this research methodology, it is suggested that this will directly lead to lower balancing costs for TSOs. However, other potential costs will likely be increased due to a higher participation of DR. When there are more small DR participants, TSOs will need to spend more money on the internal operations like billing, metering, verification, settlement, communication, software and administration (Bradley et al., 2013). The quantification of these extra costs has already been researched in the existing literature, and therefore lies outside the scope of this research.

5.2.3 Marginal costs bidding assumption

An important assumption in this research is the *marginal cost bidding assumption*, explained in section 2.6, which assumes that the bid price reflects the marginal costs of providing flexibility for a particular flexibility source.

It is unlikely that flexibility sources will bid lower than its marginal cost in the long term, as participation then will lead to financial losses. However, it is likely that participants sometimes bid significantly higher than their marginal cost. This strategic bidding is possible when participants have enough market information available to know that they can bid higher, while being sure that their bid will still be accepted in the market. Following the economic theory, it is not possible to structurally bid higher than your marginal costs when there is enough competition, as competitors will push you out of the market. However, these perfect economic market assumptions do not always hold. Therefore, the marginal cost bidding assumption also does not always hold. When this is the case, the estimations in this research do not reflect the marginal costs of DR, but rather the bidding strategy.

5.2.4 Comparison with relevant literature

As mentioned in the *Research gap*, section 1.3, there is relevant literature that presents (an indication of) a cost reduction of DR. Now that the results of this research are shown, it is interesting to compare these results with the existing literature.

The only source that provides enough detailed information is the annual *Power Responsive reports* of NationalGrid, GB's TSO (NationalGridESO, 2020).

First of all, this report confirms the calculational method to calculate the capacity and average bid prices per flexibility source on the FFR market (Figure 15, Figure 16, and Figure 17), as this report show the same results. Second, the results of the average bid price analysis can be confirmed by the report, as it shows that *Load Response* bids structurally lower than the market average. The report does not give information to support the regression and correlation analysis. The report also does not provide information to confirm the results of the BM market.

5.3 Recommendations for future research

Now that this research's most important strengths and weaknesses have been identified, the recommendation for future research can be given. This recommendation is mainly based on the weaknesses and the part of the research gap that has not been addressed.

For the opportunities and barriers of sharing more detailed data of balancing markets, it is recommended to extend this research by including a more diverse selection of interviewees, also working for organizations outside of the Netherlands.

Looking at the weaknesses of the quantitative results, it would be good to include a broader range of balancing markets in different countries. Next to that, including data of a more extended period can increase the accuracy of the regression models. Additionally, it is recommended to look at the cost reduction of DR in balancing markets with a high share of DR, as this was not the case for all the markets included in the scope of this research. Next to that, it would be relevant to study the impact of the high gas prices on the balancing markets individually to isolate this effect from the other effects that have been studied on the price of flexible capacity.

It is also recommended to challenge the two main assumptions made for the extrapolation towards 2030. This can be done by proposing a new method to estimate the relative cost reduction of DR in the future. Next to that, it is recommended to test whether non-linear models, like exponential or logarithmic models, better explain the relationship between the participation of DR and the price of flexible capacity in balancing markets. This can increase the accuracy of the estimations for both the reference year and the extrapolation towards 2030.

It is also recommended to conduct a study that combines the results of this and similar studies, using historical data of balancing markets, with studies that estimate the cost reduction of DR in a different way, like the study of Strbac (2008), which looks at the operational costs of DR assets. The combination of these methodologies can challenge the *marginal cost bidding assumption*. Lastly, it is recommended to combine the results of a study like this with a study that includes other factors which can lead to extra (or less) costs for TSOs. This shall provide a complete overview of the cost reduction of DR from a system perspective.

6 CONCLUSION

This chapter formulates the conclusion of this research by answering the following main research question:

What is the cost reduction potential of demand response participation in balancing markets from a system perspective?

The hypothesis of this research, which is based on existing literature, is that a higher participation of DR can reduce costs for balancing the electricity grid. The main research aim was to test this hypothesis by using a novel quantification methodology that contributes to the existing literature.

The main research question was answered by analyzing historical data of balancing markets to identify the (quantitative) relationship between the share of DR in the total accepted capacity and the price of flexible capacity in balancing markets. The markets included in the scope were the FFR and the BM market of GB, and the mFRRda market of NL, looking at data within the period from 2015 up to 2021. This research also presents opportunities and barriers to sharing more detailed data to enable this quantification.

6.1 QUANTIFICATION OF COST REDUCTION OF DR FROM A SYSTEM PERSPECTIVE

The results show that for most balancing markets that were included in the scope, a significant price reduction is estimated due to the participation of DR. This leads to lower costs for TSOs for balancing the electricity grid.

It is estimated that DR bids are on average 35% lower than the market average. Next to that, the regression analysis estimated that a 1% higher participation of DR in balancing markets leads on average to a 2.7% lower price for flexible capacity. Looking at the current average participation of DR in the markets included in the scope, it is estimated that the price in these markets has dropped by 10%-20% due to the participation of DR. By extrapolating this, it is estimated that the price reduction of flexible capacity in balancing markets in 2030 due to the participation of DR ranges from 43% to 71%.

6.2 Opportunities and barriers to sharing data

The opportunities and barriers of sharing more detailed data of balancing markets to enable the quantification of the cost reduction of DR that have been identified are presented in Table 19.

Table 19 Opportunities and barriers of sharing more detailed data of balancing markets

Opportunity
Lower barrier for new participants to enter the market
Increased efficiency of market
Improve reputation TSO
Easier to identify DR potential
Barrier
Extra burden for TSOs, while not being in their interest
Harm of privacy of business
Risk of collusion
Lobby of industry
Political view on regulation and transparency

7 APPENDIX

7.1 INTERVIEWS

In this appendix, a summary is presented of the questions and answers of the conducted interviews. The question/statements of the interviewer are shown underlined and the answers of the interviewee are shown in *italic*.

7.1.1 INTERVIEWEE A (ENERGIE-NEDERLAND)

Date: 07-01-2022

Organisation (Type of organisation): Energie-Nederland (Industry association for energy companies)

Role: Electricity market expert

Location: Online meeting

- In my thesis, I try to estimate the effect of the participation of DR on the price of flexible capacity on balancing markets. To do this, I need detailed data on the market tender results. There are opportunities and barriers to sharing this data. This is what I like to discuss with you. How do you see transparency on electricity/balancing markets?
  - *Transparency on balancing markets is not a right of participants. I am in favour of transparency, but this does not mean that all detailed information (like bid prices) should be published. It is part of the risk of participating that you don't know everything about what is happening on the market. It is nice for you, as a master's student, to be able to access this data so that you can do this kind of analyses, but why should TSOs share this data? Consultants and analysts could help bring more transparency to the market. It is also hard to share this data, when aggregators pool different types of technologies. Then you don't know what is behind a specific bid.*
- If we look at the opportunities of sharing more detailed data about balancing markets, would you agree that more transparency lowers the barriers for new players to enter the market?
  - *I don't really see the added value of more transparency. Of course, more information makes it easier to enter the market. But the most important information, about the prices for example, is already shared by TSOs. This allows entrants to do business case calculations. I don't think you need more information.*
  - *New entrants or small companies can always contract a knowledgeable market participant to allow for integration of new flexible, decentralized assets in the balancing market. There is sufficient competition between such market participants. In addition, one has to realize that the balancing market is much wider than just the market as operated by the TSO. Market participants (Balance Responsible Parties) are active in*

balancing their portfolio (system support balancing or "passief meeregelen") and are interested to add more positions (for third parties) in their portfolio. In essence, competition between these market participants means that entrance barriers for new entrants are removed.

- Do you agree that more transparency makes the market more cost-efficient?
  - *I do agree that market barriers should be removed. For example, the minimum bid size on Dutch balancing markets should be lowered. This leads to more efficient markets. However, I think sharing more detailed information on balancing markets is redundant. I don't see why there should be more transparency.*
- Having more insights into the market can help decision making. For example, when more and more capacity can be offered by a battery, but the capacity offered remains low, maybe the TSOs should make it more attractive for batteries to participate. In this way, the transparency helps TSOs and regulators in having this insight.
  - *You should never make it more attractive for specific technologies to participate. You should have a fair level playing field so that different technologies can compete. If there are barriers, you should remove them. The market then determines which technologies win and which lose.*
- If we look at the barriers, there are a few which I found in literature which I would like to discuss with you. The first one is about business privacy. Do you see it as a barrier that sharing this data would harm the business privacy of participants, and that it is not desirable for these parties that everyone knows how big their portfolio is?
  - *Yes, I agree. I think it is unnecessary to share this data.*
- Another barrier that I found was that it is not in the interest of a TSO to share this data. Doing this would bring up a new task and therefore extra costs. This could be a barrier.
  - *I do think TSOs have an interest. TSOs buy flexible capacity on the balancing markets and they have an interest in competition, because it brings the price down. Therefore they want to remove barriers. However, it is not the responsibility of a TSO to promote demand response or other technologies. That is up to the market.*
- Do think it is also a barrier that TSOs don't share this data to keep power over the market? Having more information available than the participants gives them more power?
  - *No, I don't see it like this. TSOs buy flexible capacity when needed. The amount of capacity they buy is approximately unsensitive to price changes. Of course, they buy this capacity in the most cost effective way, because they are also a company that can make a profit. I don't see why it would be in the interest of a TSO to make the market untransparent.*
- Would you agree that the absence of a suitable data platform is a barrier of sharing this data?
  - *I see that differently. There is not a single platform for the electricity market. There are multiple platforms. The different platforms compete with each other. The idea that there should be a separate platform for demand response is a wrong idea.*
- That is not exactly what I meant with a platform. What I meant is that it could be the case that they need a platform on which they can easily share this data, the ENTSO-E data transparency platform for example. The absence of this platform could be a barrier.
  - *The ENTSO-E platform was a good idea. The platform could also be used to share this data, so I don't think the absence of such a platform is a barrier in this case.*
- Do you see other opportunities or barriers of sharing this data?

- *Again, I don't really see the value of sharing this data.*
- This could be a barrier on itself. Because it has no value, it is not sharing by TSOs for example.
  - *Yes, I agree. That could be the case. Next to that, I already mentioned that the pooling is a barrier. It is really important that participants can offer the flexibility by pooling different assets. This makes it complex to find out what is behind the pooled bid.*
  - *What I think is missing, is a good description on how these market works, this can be complex to understand. This would really help market participants to enter the markets.*

7.1.2 Interviewee B (Sympower)

Date: 10-01-2022

Organisation (Type of organisation): Sympower (Demand response aggregator)

Role: Sales Engineer & bidder of flexible capacity

Location: Office Sympower (Prinsengracht 437, Amsterdam)

- In my thesis, I try to estimate the effect of the participation of DR on the price of flexible capacity on balancing markets. To do this, I need detailed data of the market tender results. There are opportunities and barriers to sharing this data. This is what I like to discuss with you. Which opportunities and barriers do you see?
  - *I doubt whether there are opportunities for a TSO like TenneT. As a participant, like Sympower, you can try to understand the bidding behavior of competitors to always bid a little lower than them. Then you have high revenues and low risk of getting rejected. Having more transparency makes it easier for participants to have a higher profit margin and therefore it is not in the interest of TenneT. This could be one of the reasons for TenneT to not share this data.*
- Do you see a reason for a TSO to share this data?
  - *It could help them to improve their reputation. When they share this data, they could use it for PR purposes and say that they are transparent.*
- Do you see it as a barrier that sharing the data harms the privacy of business?
  - *Yes, if we look at Sympower, it can become hard to attract new customers when you don't have a portfolio of capacity in a certain country. So if you're a small player, you don't want other to know that you don't a lot of capacity that you bid. So it can be a barriers for new entrants of the market.*
  - *The point you mentioned earlier, I do think that in the long run it is in the interest of TenneT to share this data as it makes it easier for new entrants to enter the market. When there are more parties participating, there is a higher level competition which decreases the price. For new entrants is very valuable to have this data, because it is then easier to calculate the potential business case. If you know that a certain industry bids at a certain level, it is easier to convince people in the same industry to join the portfolio.*

7.1.3 INTERVIEWEE C (UTRECHT UNIVERSITY)

Date: 18-02-2022

Organisation (Type of organisation): Utrecht University (University)

Role: Expert

Location: Online

- In my thesis, I try to estimate the effect of the participation of DR on the price of flexible capacity on balancing markets. To do this, I need detailed data of the market tender results. There are opportunities and barriers to sharing this data. This is what I like to discuss with you. Which opportunities and barriers do you see?
    - *First of all, I think it's a right of consumers and producers of electricity to have transparency on electricity markets, because electricity is a utility good. More transparency for such goods is always better. Everybody is very dependent on electricity.*
    - *I believe it's improves the efficiency of the electricity market if this data is publicly available. Otherwise, you need to hire expensive consultants who have this knowledge about the market. No need for that, if the data is available.*
- Would you agree that sharing the data also lower the barrier for new participants on balancing markets?
    - *Yes, for new entrants it can be quite difficult to enter the balancing markets if you don't have the expert in-house yet. So having more data certainly makes it easier to enter the market. Having more participants on the markets is good for competition.*
- Up until now, we only discussed opportunities of sharing the data. Do you also know arguments why this data should not be shared?
    - *When market participants have a lot of market information available, there is the risk on collusion. This means that participants can increase the price of flexible capacity when they have a lot of information. For example, big producers coordinating their bids on electricity markets to increase prices and to increase profit. This is not in the public interest. However, there are ways to prevent this.*
    - *Next to that, sharing the data could be hindered by lobby groups of big industries that do not want that competitors know what they are bidding on the markets.*
- What is interesting to see is the difference in transparency of different markets. For example in the UK, this data is publicly shared with even the name of the company that bided the capacity. Do you know why they do that in the UK?
    - *The UK uses a more Anglo-Saxon view on regulation than the Netherlands, for example. In the Netherlands, we believe more in a liberal/French view in which we let market participants more free on the market. In the UK, there is strict regulation to improve transparency on the electricity markets.*
- Do you see any other barriers of sharing this data?

    - *I think TSOs like TenneT do not share this data because they are not obliged to do that. You need regulation to stimulate that TSOs share this data. Another reason this data is not shared is because it may be difficult to share data, when it can be traced to individual parties. A legal obligation would be better, since those parties can not complain.*
- <u>Some people see pooling as a limiting factors to sharing data. When an aggregators pools different assets, they bid this pool in a single bid. Having to provide information on how this pool looks like can make it more complex. Do you see this as a barrier?</u>
    - *No, you can just show the pool then, right? Of course, sometimes it can be very difficult to trace back what the pool looked like, but there are certainly ways to solve this.*
- <u>Do you see any other barriers or opportunities of sharing this data?</u>
    - *No, not really. I think we discussed the most important points.*

7.1.4 Interviewee D (TenneT)

Date: 25-02-2022

Organisation (Type of organisation): TenneT (Dutch TSO)

Role: Contractor ancillary services

Location: Online

- As you are the last interviewee, I propose that we discuss the opportunities and barriers that already have been identified. You can say if you agree with them or not.
    - *That sounds like a good plan, let's do that.*
- Do you agree that sharing the data lowers that barriers for new participants on the market?
    - *Yes, agree. However, there need to be some threshold, because we don't want cowboys on the market that take too much risk. But it's important that we don't make these threshold unnecessary high.*
- Do you agree that it can increase the efficiency of the market?
    - *I think liquidity always increase the efficiency of the market. So if there are more participants on the market, the market become more efficient, I think. This is especially the case for marginal pricing markets. Bigger parties are usually better in understanding the market.*
- Would you agree that it is an opportunity for TSOs to improve their reputation?.
    - *There is actually a line in the Clean Energy Package which says that we should share this data. However, there is some disagreement about the interpretation of this line. Personally, I think that at a certain moment we will start sharing this data.*
- Someone said there is no value in sharing this data? Would you agree with that?
    - *No, I don't agree. I think it's important to have more transparency. Big energy companies certainly know the value of flexibility based on their market knowledge. However, all the other participants don't know this and therefore that can estimate the value of participating. It's the goal to give everyone access to a electricity market. Transparency helps doing this.*
- Do you think pooling can be a barrier to sharing more data on these markets. For aggregators it can be more difficult to provide bids when they have to say from which asset it comes.
    - *No I don't think so. For TenneT it can be quite easy to trace back which assets provided the activation.*
- Do you think sharing the data could harm the privacy of businesses?
    - *It depends what is shared. I don't think the name of companies that participate should be shared. There is no need for that anyway. When we only share the type of asset that participates, I don't see a problem for this.*
- Do you see any other opportunities or barriers?
    - *No, I think you covered the most important opportunities and barriers.*

7.2 APPENDIX TABLES

7.2.1 LITERATURE REVIEW

Table 20 provides a literature review of the economic benefits of DR from a system perspective.

TABLE 20 LITERATURE REVIEW OF ECONOMIC BENEFITS OF DEMAND RESPONSE FROM A SYSTEM PERSPECTIVE DESCRIBED IN ACADEMIC LITERATURE

	Economic benefit	Explanation	Source
1	Reduction of required investment in production capacity	When the peaks in electricity consumption are lowered by DR, less electricity production capacity is needed to always be able to cover the demand.	(Bradley et al., 2013; Jabir et al., 2018; Strbac, 2008)
2	Reduction of required investment in grid infrastructure	When the peaks in electricity consumption are lowered by DR, less grid capacity is needed to distribute the electricity	(Bradley et al., 2013; Jabir et al., 2018; Roadmap 2050.eu, n.d.; Strbac, 2008)
3	Reduction of overall electricity prices	Electricity prices can be lowered by using DR, because the use of cost-inefficient production units with high marginal costs is avoided. This is done by making the electricity consumption more stable or by better matching it with the production of electricity. This is particularly important for countries with a high penetration of uncontrollable RES	(Brown & Chapman, 2021; Gils, 2014, 2016; Liu & Tomsovic, 2014; Rashid Howlader, Yousuf Saber, & Senjyu, 2019; Strbac, 2008; U.S. Department of Energy, 2006)
4	Reduction of costs for ancillary services (i.e. balancing the grid, avoiding grid congestion)	When flexible capacity can be offered by DR for a lower price, grid operators make less costs for ancillary services by buying this flexible capacity to maintaining a reliable and safe electricity grid	(Bertoldi, 2009; Bradley et al., 2013; Dietrich, Latorre, Olmos, & Ramos, 2016; Jabir et al., 2018; Liu & Tomsovic, 2014; NI et al., 2017; Strbac, 2008; Vlachos & Biskas, 2013)

7.2.2 Regression models

Table 21 Indirect independent variables regression model

Indirect independent variable	Source
Gas price	Statista
Oil price	Statista
Gross domestic product of GB or NL	Statista
Electricity market prices (day-ahead)	ENTSO-E data transparency platform
Average temperature in country	Statista
Interconnector export and import of electricity per country	ENTSO-E data transparency platform
Average wind speed per country	Statista

7.2.2.1 FFR market

Table 22 Regression model FFRd market

Dependent variable	Symbol	Unit				
Price of flexible capacity	P_{FFRd}	£/MW/h				
Independent variables	**Symbol**	**Unit**	**Coefficient**	**t Stat**	**Standard error**	**P-value**
Intercept	a_{FFRd}		7.661	10.787	0.710	0.000
Battery	$S_{FFRd,Battery}$		-5.87	-3.241	1.812	0.002
Load response	$S_{FFRd,Load\ Response}$		-11.6	-5.421	2.149	0.000
Gas price	GP_{GB}	£/therm	0.0550	9.0331	0.007	0.000
Regression statistics						
R^2	0.71					
Adjusted R^2	0.69					
Mean absolute percentage error (MAPE)	24%					
Standard error	2.19					
F-test (p value)	0.00					
Observations	45					

Table 23 Results regression model of FFRs market

Dependent variable	Symbol	Unit

Price of flexible capacity	P_{FFRs}	£/MW/h				
Independent variables	**Symbol**	**Unit**	**Coefficient**	**t Stat**	**Standard error**	**P-value**
Intercept	a_{FFRs}		2.597	9.3	0.279	0.000
Load response	$S_{FFRs,Load\ Response}$	%	0.305	0.29	1.037	0.771
Diesel	$S_{FFRs,Diesel}$	%	-1.331	-2.68	0.496	0.012
Distributed generation (for export)	$S_{FFRs,DGexport}$	%	-0.917	-1.39	0.662	0.177
Gas price	GP	£/therm	0.00444	1.46	0.003	0.155
Regression statistics						
R^2	0.28					
Adjusted R^2	0.18					
Standard error	4.61					
F-test (p value)	0.04					
Observations	34					

TABLE 24 ASSUMPTION CHECK REGRESSION MODEL DYNAMIC FFRD MARKET

Check	Test	Value	Comply with assumptions/checks
Multicollinearity	Correlation matrix	Strongest correlation between *Gas price* and *Price* of 0.69	Debatable
	VIF test	1.09	√
Sample size/number of predictors ratio		11	√
Normality of residuals	Shapiro-Wilk test	P-value of 0.36	√
	QQ-plot and residual plot	No trend between residuals and independent variables	√
Goodness-of-fit	R^2	0.71	Reasonably high
	F-test	0.0000	√

7.2.2.2 BM market

TABLE 25 REGRESSION MODEL BM (FRR) MARKET

Dependent variable	Symbol	Unit				
Price of flexible capacity	$P_{BM(FRR)}$	£/MW/h				
Independent variables	**Symbol**	**Unit**	**Coefficient**	**t Stat**	**Standard error**	**P-value**
Intercept	$a_{BM(FRR)}$		7.306	33.78	0.216	0.000
Load	$S_{BM(FRR),Load}$	%	-2.976	-1.623	1.834	0.110

Dummy variable*	$d_{BM(FRR)}$		-4.703	-21.05	0.223	0.000
Regression statistics						
R^2	0.91					
Adjusted R^2	0.91					
Standard error	0.65					
F-test (p value)	0.000					
Observations	58					

* *Dummy variable* to correct for significant decrease in price in Jul 2018, which cannot be explained by $S_{BM(FRR),Load}$

TABLE 26 ASSUMPTION CHECK REGRESSION MODEL BM(FRR)

Check	Test	Value	Comply with assumptions/checks
Multicollinearity	Correlation matrix	Strongest correlation between $S_{BM(FRR),Load}$ and $P_{BM(FRR)}$ of 0.44	√
	VIF test	1.37	√
Sample size/number of predictors ratio		19	√
Normality of residuals	Shapiro-Wilk test	P-value of 0.04	x
Goodness-of-fit	R^2	0.92	Low
	F-test	0.019	√

TABLE 27 REGRESSION MODEL BM (RR) MARKET

Dependent variable	**Symbol**	**Unit**				
Price of flexible capacity	$P_{BM(RR)}$	£/MW/h				
Independent variables	**Symbol**	**Unit**	**Coefficient**	**t Stat**	**Standard error**	**P-value**
Intercept	$a_{BM(RR)}$		3.103	9.466	0.328	0.000
Load	$S_{BM(RR),Load}$	%	13.133	2.43	5.404	0.019
Regression statistics						
R^2	0.10					
Adjusted R^2	0.08					
Standard error	1.36					
F-test (p value)	0.019					
Observations	54 (excluding outliers)					

TABLE 28 ASSUMPTION CHECK REGRESSION MODEL BM(RR) MARKET

Check	Test	Value	Comply with assumptions/checks
Multicollinearity	Correlation matrix	Strongest correlation between $S_{BM(RR),Load}$ and $P_{BM(RR)}$ of 0.32	√
	VIF test	1.0	√
Sample size/number of predictors ratio		27	√
Normality of residuals	Shapiro-Wilk test	P-value of 0.00	x
Goodness-of-fit	R^2	0.10	Low
	F-test	0.019	√

7.2.2.1 mFRRda Up market

TABLE 29 REGRESSION MODEL MFRRDA UP MARKET

Dependent variable	Symbol	Unit				
Price of flexible capacity	$P_{mFRRda\ Up}$	€/MW/h				
Independent variables	**Symbol**	**Unit**	**Coefficient**	**t Stat**	**Standard error**	**P-value**
Intercept	$a_{mFRRda\ Up}$		4.35085	11.7286	0.37096	0.000
DR	$S_{mFRRda\ Up,DR}$		-13.36	-5.1967	2.5697	0.000
Gas price	GP_{NL}	€/MWh	0.1474	28.6928	0.005139	0.000
Regression statistics						
R^2	0.70					
Adjusted R^2	0.70					
Mean absolute percentage error (MAPE)	30%					
Standard error	3.35					
F-test (p value)	0.00					
Observations	551					

TABLE 30 ASSUMPTION CHECK REGRESSION MODEL MFRRDA UP MARKET

Check	Test	Value	Comply with assumptions/checks

Multicollinearity	Correlation matrix	Strong correlation between GP_{NL} and $P_{mFRRda\ Up}$ of 0.83	Debatable
	VIF test	1.23	√
Sample size/number of predictors ratio		137.75	√
Normality of residuals	Shapiro-Wilk test	P-value of 0.00	x
Goodness-of-fit	R^2	0.70	√
	F-test	0.00	√

7.2.2.2 mFRRda Down market

TABLE 31 REGRESSION MODEL MFRRDA DOWN MARKET

Dependent variable	Symbol	Unit				
Price of flexible capacity	$P_{mFRRda\ Down}$	€/MW/h				
Independent variables	**Symbol**	**Unit**	**Coefficient**	**t Stat**	**Standard error**	**P-value**
Intercept	$a_{mFRRda\ Up}$		1.4750	2.7922	0.5282	0.005
DR	$S_{mFRRda\ Down,DR}$		-36.72	-2.323	15.803	0.021
Gas price	GP_{NL}	€/MWh	0.1646	19.096	0.00862	0.000
Regression statistics						
R^2	0.40					
Adjusted R^2	0.40					
Mean absolute percentage error (MAPE)	54%					
Standard error	6.36					
F-test (p value)	0.00					
Observations	551					

TABLE 32 ASSUMPTION CHECK REGRESSION MODEL MFRRDA DOWN MARKET

Check	Test	Value	Comply with assumptions/checks
Multicollinearity	Correlation matrix	Highest correlation between GP_{NL} and $P_{mFRRda\ Down}$ of 0.63	√
	VIF test	1.00	√
Sample size/number of predictors ratio		137.75	√
Normality of residuals	Shapiro-Wilk test	P-value of 0.00	x
Goodness-of-fit	R^2	0.40	√
	F-test	0.00	√

7.3 Assumptions and checks regression model

7.3.1 Outliers

The first thing that is checked is whether there are outliers in the data. Outliers are data points that lie outside of the distribution of the rest of the datapoints, because they have either very low or very high values. They usually take these values in exceptional situations or due to measurement errors. Outliers can have a big effect on the estimations of the effects of the independent variables on the dependent variable, while these outliers don't necessarily say something about the trend between two variables. Therefore, it is better to remove them from your dataset. The effect of an outlier on the regression line is shown in Figure 36.

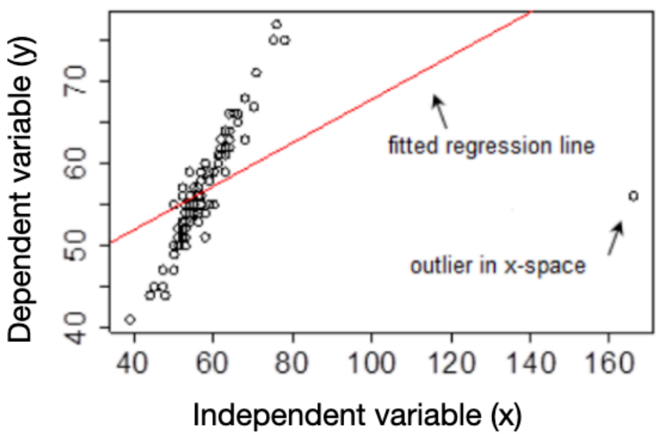


Figure 36 Effect of an outlier on regression line

To remove outliers, the commonly used *1.5 x IQR rule* is applied. Data points are removed if they are either higher than the upper bound or lower than lower bound (Towards Data Science, 2019):

- Lower bound: $Q_1 - 1.5 * IQR$
- Higher bound: $Q_3 + 1.5 * IQR$

Where:

- Q_x Quartile x
- IQR The Interquartile Range: the difference between the third and first quartile

7.3.2 Multicollinearity

The second thing that is checked is *multicollinearity* in the data. Multicollinearity is present in data when variables are highly correlated with each other. A high correlation between two variables suggests that they are associated with each other and move similarly. If this is the case, it becomes difficult for the regression model to estimate the relationship between the independent variables and the dependent variable separately when two independent variables tend to change uniformly (Stock & Watson, 2019).

This would lead to inaccurate estimations of the regression model. Multicollinearity therefore should be ruled out with a test. When there is strong correlation (>0.7 or <-0.7) between two variables in the data, it suggests that there is multicollinearity (O'brien, 2007; Stock & Watson, 2019).

Another statistical measure can be used to rule out multicollinearity: the *Variance Inflation Factor* (VIF). This can be done when the regression model is finalized. When the VIF is higher than 5, there is strong correlation between two variables in the regression model and there seems to be multicollinearity (Stock & Watson, 2019).

7.3.3 Sample size/number of predictors

To ensure that the results are valid, it is important to have enough datapoints compared to the number of predictors (= independent variables). A too small dataset will result in inaccurate estimations of the regression model.

A rule of thumb used in statistics is that the number of datapoints should be at least three times as high as the number of independent variables in the model (Statistics Solutions, n.d.). This is the rule that will be used in this research as well. In the case a final regression model has, next to the dependent variable, three independent variables, the input data should at least 30 datapoints to comply with this rule. This rule will be applied after the regression model has been built and when the number of predictors is determined.

7.3.4 Normality of residuals

Another thing that needs to be checked is how the residuals (the error term) are distributed. If these follow a Normal Distribution, it indicates that the coefficients of the regression model are unbiased, and therefore accurate. Normality of the residuals is one of the most important assumptions of the regression model to have representable results. The Shapiro-Wilk is used to test normality of the residuals. This test uses the p-value to indicate whether data is normally distributed or not. A low-value indicates that the data is not normally distributed.

7.3.5 Goodness of fit

When a regression model has been built, there are multiple ways to check how well it predicts the dependent variable. When is has a high *goodness of fit*, the independent variables explain the variance of the dependent variable well. The main measure that is used to compare the goodness of fit between different models is the R^2, which indicates the percentage of the variance in the dependent variable that the independent variables explain. Figure 37 shows a visual representation of a low and a high R^2.

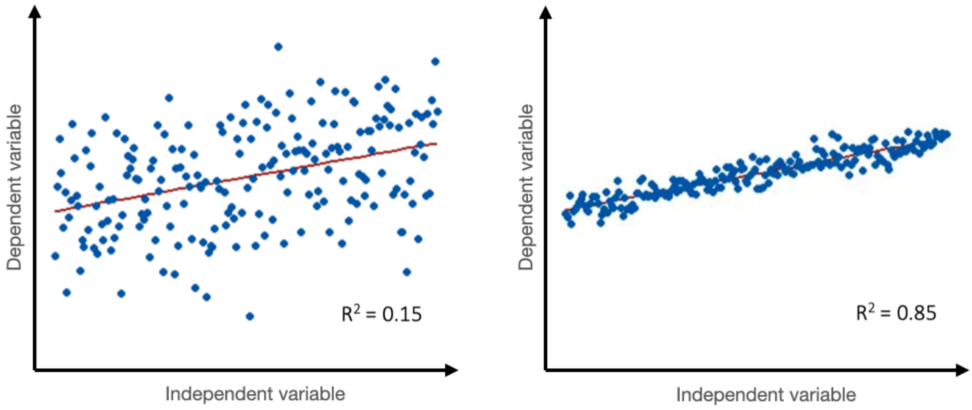


FIGURE 37 VISUALS REPRESENTATION OF LOW (LEFT) AND HIGH (RIGHT) R^2 OF REGRESSION MODEL

7.4 References

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