Europa-Universität Flensburg

Doctoral Thesis

Economics of control reserve provision by fluctuating renewable energy sources

by

Malte Jansen

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Supervisors:

Prof. Dr.-Ing. Olav Hohmeyer - European University of Flensburg

Prof. Poul Ejnar Sørensen - Technical University of Denmark

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“Essentially, all models are wrong, but some are useful.”

George Edward Pelham Box, 1987

Kurzzusammenfassung

In einem Energiesystem mit steigenden Versorgungsanteilen durch Erneuerbare Energien gehört die Bereitstellung von Regelleistung, und damit die Übernahme von Systemverantwortung, zu den zentralen Bausteinen der Energiesystemtransformation. Diese Dissertation weist nach, dass fluktuierende Erneuerbare Energien, wie Onshore- und Offshore-Windparks sowie Photovoltaikanlagen, in der Lage sind, Regelleistung mit gleicher Zuverlässigkeit wie konventionelle Kraftwerke bereitzustellen. Darüber hinaus kann durch die Teilnahme von fluktuierenden Erneuerbaren Energien am Regelleistungsmarkt ein Wohlfahrtgewinn erschlossen werden, welcher zum Teil zu zusätzlichem Einkommen der Anbieter führt und zum anderen Teil zu Kostenersparnissen bei der Regelleistungsbereitstellung. Es wird gezeigt, wie dieser Wohlfahrtsgewinn von den Marktbedingungen abhängt und wie diese angepasst werden müssen um ihn zu maximieren.

Stichworte: Fluktuierende Erneuerbare Energien, Probabilistische Prognosen, Systemdienstleistung, Regelleistung, Energiemärkte, Ökonometrische Analyse, Geschäftsmodell, Wohlfahrtsgewinne

Abstract

The provision of control reserve, and therefore contributing to the secure operation of the power system, is paramount in a future energy system with increasing shares of fluctuating renewable energy sources. This doctoral thesis proves that fluctuating renewable energy sources, such as onshore and offshore wind farms as well as photovoltaic systems, are capable of providing control reserve at the same level of reliability as conventional generators. It is shown that the introduction of fluctuating renewables to the control reserve market can access a welfare gain that could be realized as additional income by the new market participants or as cost saving potential of the control reserve procurement. The dependency analysis between the welfare gain and the regulatory framework leads to recommendations for the development of the control reserve market

Key words: Fluctuating renewable energy sources, probabilistic forecasts, ancillary services, control reserve, energy markets, econometric analysis, business model, welfare gain

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Ich erkläre hiermit an Eides Statt, dass ich die vorliegende Arbeit selbstständig und ohne Hilfsmittel angefertigt habe; die aus fremden Quellen (einschließlich elektronischer Quellen, dem Internet und mündlicher Kommunikation) direkt oder indirekt übernommenen Gedanken sind ausnahmslos unter genauer Quellenangabe als solche kenntlich gemacht. Insbesondere habe ich nicht die Hilfe sogenannter Promotionsberaterinnen / Promotionsberater in Anspruch genommen. Dritte haben von mir weder unmittelbar noch mittelbar Geld oder geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Kassel/London/Flensburg, December 2016

Malte Jansen

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1 Executive Summary

1.1 Problem

Climate change has been identified as a threat to humankind by the Intergovernmental Panel on Climate Change (Pachauri & Mayer, 2014, p. 13). In the wake of these findings, the European Union confirmed the EU 20/20/20 targets that oblige its member states to source 20 % of its energy consumption from renewable sources by 2020 (Directive 2009/28/EC of the European Parliament and of the Council, 2009). The German Renewable Energies Act (EEG) defines the target of 80 % of renewable electricity in the year 2050 (Erneuerbare-Energien-Gesetz, 2014). This will lead to decreasing shares of conventional generation in the future (Nitsch J. et al., 2012, p. 185).

During times with high fluctuating renewable energy sources (RES) instantaneous penetration levels, ancillary services have to be provided by RES generators, since the currently used conventional units become unavailable. Ancillary services are the services in the power system that ensure the security of supply. One of these ancillary services is the provision of frequency regulation service, called control reserve (UCTE, 2009). Alternative generation technologies, such as wind farms and PV systems, will have to be responsible for maintaining the security of supply.

The 2012 revision of the EEG enables RES to deliver energy to the markets and provide ancillary services at the same time. Biomass generators are already integrated into the control reserve markets (Lange et al., 2014, p. 14). Fluctuating RES will follow as soon as the regulatory framework has been adapted for a possible control reserve provision.

Earlier assessments by Brauns et al. (2014) have shown a method for the delivery of control reserve from wind turbines. The findings suggested that the economics of a possible control reserve provision should be investigated further, in order to understand the influence of market design on economic aspects. This doctoral thesis investigates the economics of the control reserve provision from fluctuating RES generators and puts forward the following hypothesis:

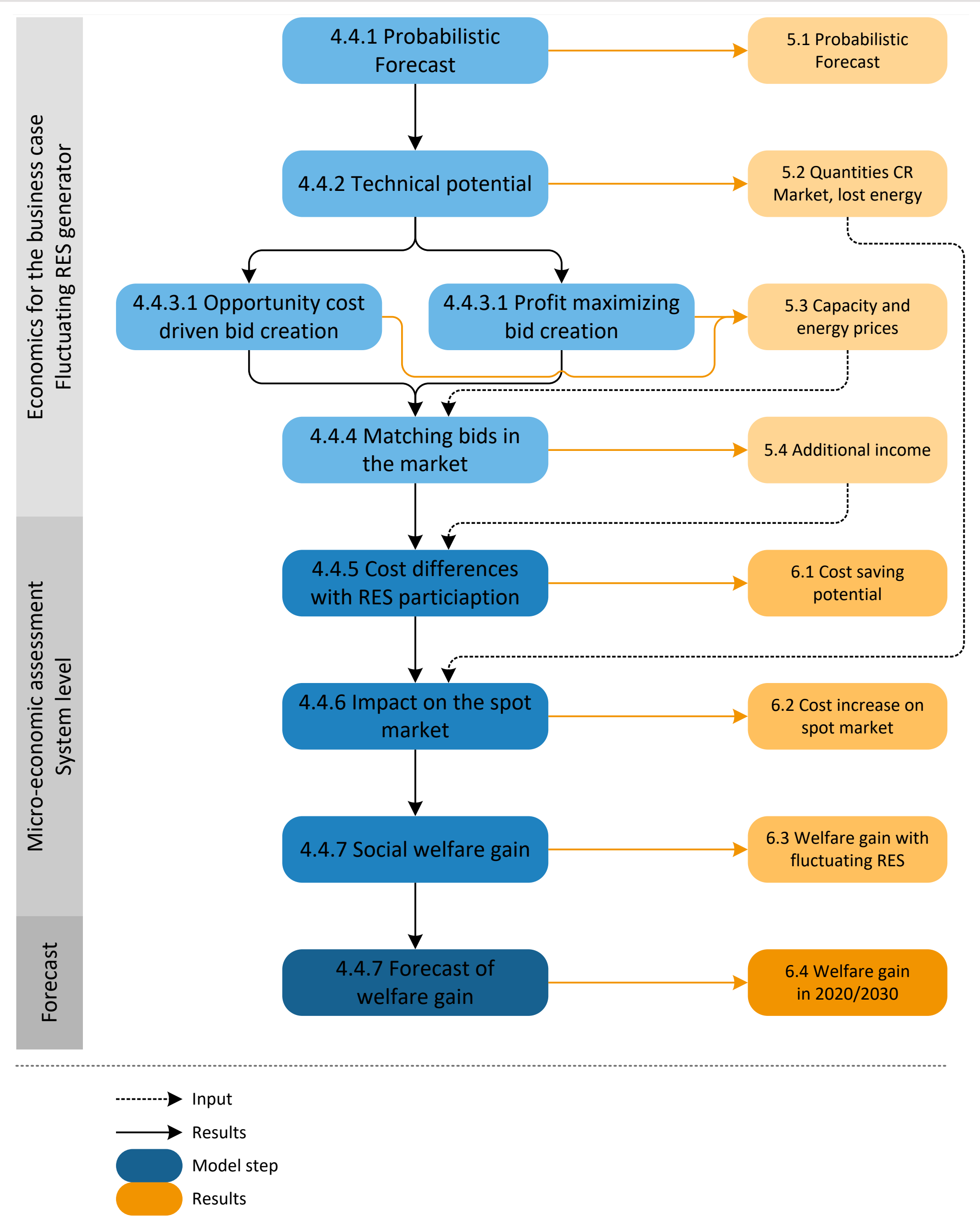
Stochastic units, such as wind farms and PV systems, can provide control reserve to the power system competitively without altering the level of reliability whilst decreasing system costs.

The underlying economics are an essential part of a successful provision of control reserve. If fluctuating RES generators are to have an increasing responsibility for system balancing, regulations will require changes in a non-discriminatory way for all market participants. Therefore, it is necessary to investigate the market rules in the control reserve markets. This thesis presents the economic potentials of a control reserve provision from fluctuating RES as well as the influence of the regulatory framework on these potentials. The assessment is carried out for the German market and its regulations.

1.2 Methodology

The necessity for a new methodology has been identified and therefore the REBal model (Renewable Energy Balancing) has been created. The methodology used in the REBal model provides the answer to the research question by assessing the economics of a control reserve provision of fluctuating RES in detail.

REBal is an econometric model that quantifies the welfare gain of fluctuating RES in the market, thus applying the welfare economics theory. The model provides insight into the economics of control reserve provision of fluctuating RES for both the supply and the demand side. The modelling steps are visualized in the figure below.



Source: Own analysis

Figure 1-1: Flow chart of REBal

The REBal model identifies the economic potentials and constraints for the delivery of control reserve from fluctuating RES generation (onshore and offshore wind farms and PV systems). The model structure is as follows:

1. The offers placed on control reserve markets need to be at least as reliable as offers from the current market participants. Therefore, **probabilistic forecasts** are used.

2. The **technical potential** of the fluctuating RES is calculated for different combinations of restraining factors.

3. The **opportunity costs** for the provision of control reserve by fluctuating RES generators are calculated, resulting in tradable standard market products, i.e. **price/quantity bids**.

4. Simultaneously tradable **profit maximizing price/quantity bids** are created to maximize the possible income on the market.

5. The **bids** are **matched** with existing bids in the merit-order lists. They are accepted if they are cheaper than the bid in the market.

6. The **changes in costs** are calculated, using a **full dispatch simulation** for the capacity and energy bids.

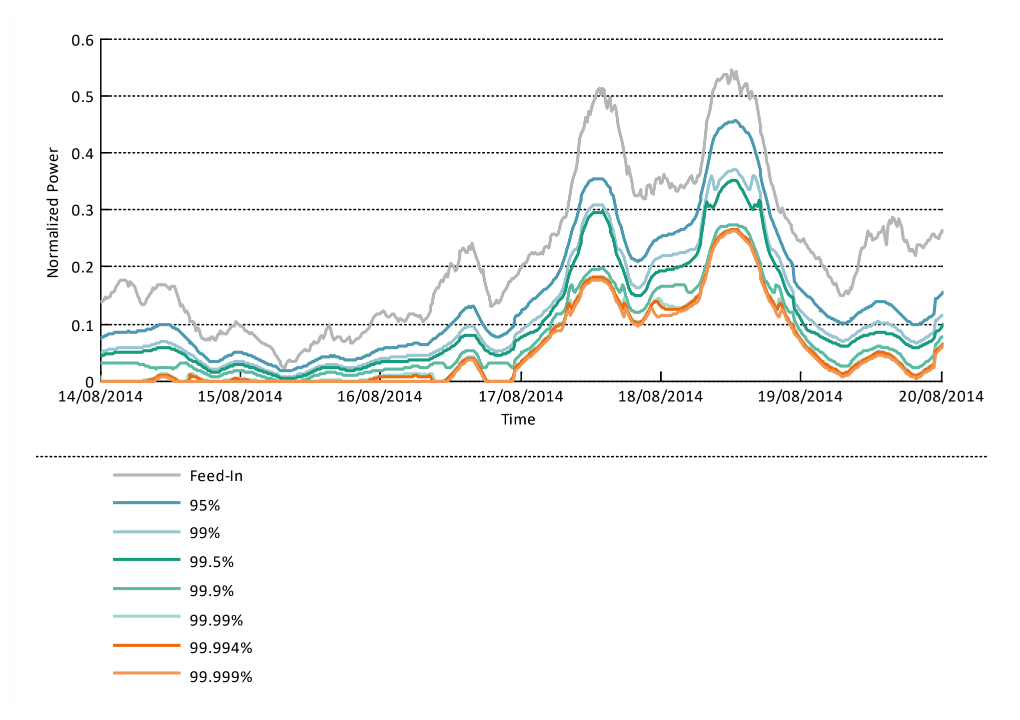
7. The **influence of the proof mechanism** on the bidding behaviour is investigated and resulting effects on the spot market quantified, which will reveal the interdependency between spot markets and control reserve markets.

8. The **welfare gains** to the system through the participation of fluctuating RES are quantified using a welfare economic approach.

9. **Welfare gains for the future are forecasted** for the years 2020 and 2030.

1.3 Results

The introduction of probabilistic forecasting allows fluctuating RES generators to provide control reserve as reliable as conventional generators. This thesis uses a kernel density estimator (KDE) to calculate the probabilistic forecasts. The results from this methodology for a 30 GW pool of wind farms, representing all German wind turbines, between the 14th of August 2014 and the 20th of August 2014 can be seen in the figure below, based on the day-ahead forecast. The graph depicts the different quantiles of a probabilistic forecast from 95 % reliability to 99.999 % where the increase in forecast reliability leads to decreasing potentials. So called point forecasts are commonly used throughout the industry. They have only one value, which is the value with the highest probability.



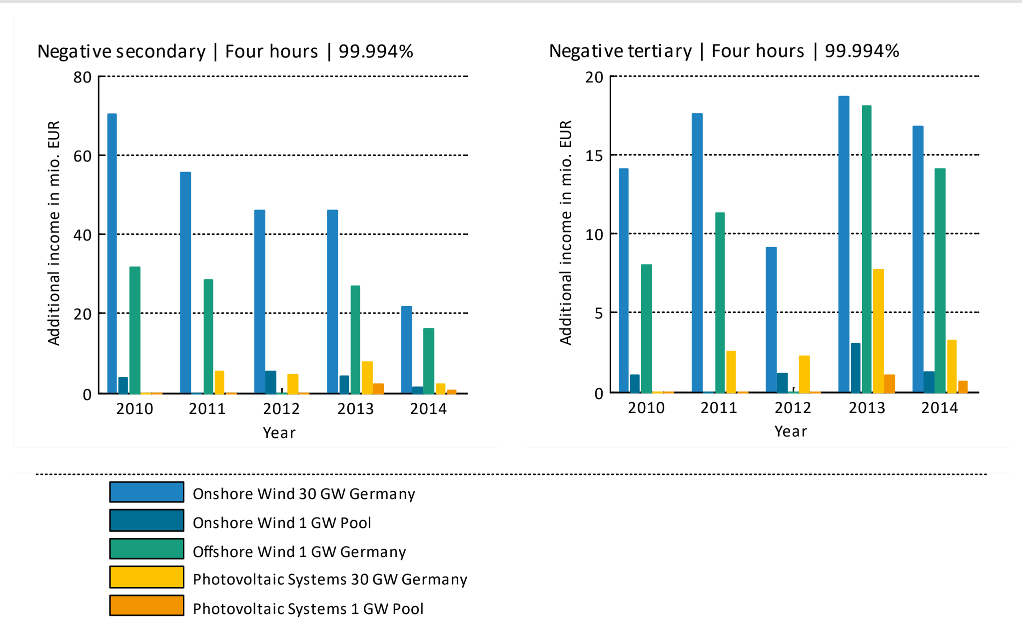
Source: Own analysis

Figure 1-2: Probabilistic day-ahead forecast of a 30 GW onshore wind farm pool, representing all German wind turbines, for different levels of reliability

Regardless of the generator type, the probabilistic forecasts generated are significantly lower than what has been forecasted with the point forecast. With a forecast reliability of 99.994 % it is guaranteed that the control reserve is as reliable as from conventional units. While the KDE can deliver reliable forecasts, other forecasting methods might deliver more suitable results that in turn would enhance the economic potential.

Using the probabilistic forecasts, bids for the market are created, with each one containing a capacity price, an energy price and a quantity. Two fundamentally different sets of bids are generated. The first set of bids is based on an opportunity cost approach, whereas the second set has a market-based approach that maximizes the possible additional income in the market. For the fluctuating RES generators the difference between both approaches results in additional income that could be earned through the market participation. The REBal model performs a full cost calculation of the capacity and dispatch costs of the control reserve market, comparing the costs of the participation of fluctuating RES with the base case.

The figure below illustrates the possible additional income for a 30 GW pool of wind farms, a 1 GW pool of wind farms, a 1 GW pool of offshore wind turbines, a 30 GW pool of PV systems and a 1 GW pool of PV systems; all based on different forecasts. The assessment period is from 2010 to 2014, with missing data for some of the generators in individual years. The figure shows the results for the negative secondary and the negative tertiary control reserve markets, as these are the markets with the highest market potential, whereas the tertiary market is the most likely option for the initial market entry. The results for a product length of four hours with a reliability level of 99.994 % would be the market setup that is equivalent to the real negative tertiary control reserve, and to the negative secondary control reserve in the future (Bundesnetzagentur, 2015). Positive control reserve market segments are practically irrelevant in the current market structure.

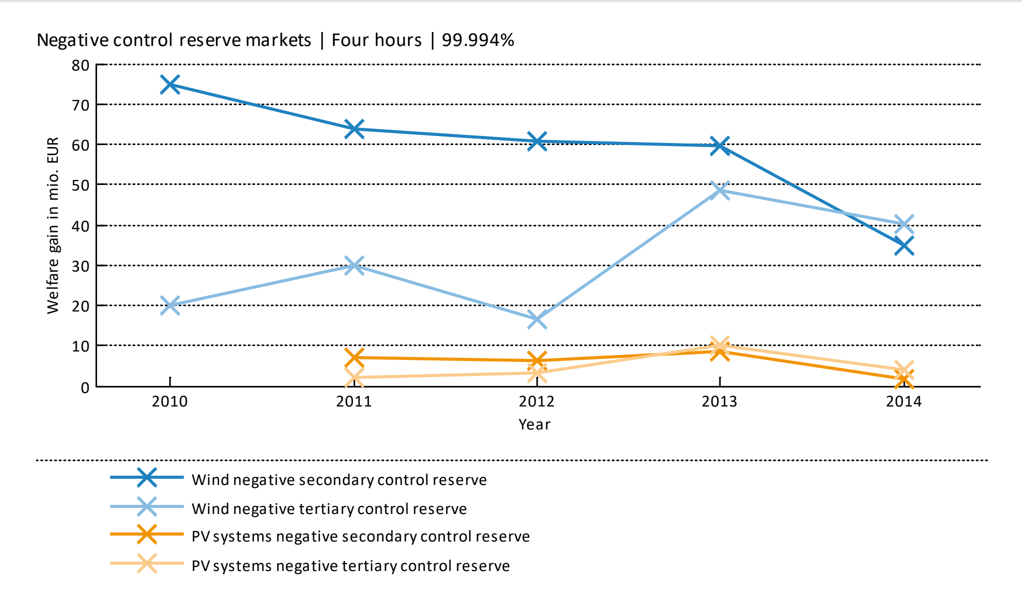


Source: Own analysis

Figure 1-3: Additional possible income for different fluctuating RES generators in the negative secondary and negative tertiary control reserve with realistic market conditions

The results show that the fluctuating RES generators could generate substantial revenue in both market segments. In all market segments, apart from the negative tertiary control reserve, a decreasing market potential is observed. A clear trend between the years 2010 and 2014 is visible for the secondary control reserve markets. Revenues in the negative tertiary market for the 30 GW pool of wind farms would have reached between 9.1 million EUR (2012) and 18.7 million EUR (2013), whereas the 1 GW pool of wind farms would have yielded between 1.1 million EUR (2010/2012) and 3.0 million EUR (2013). It can be concluded that the fluctuating RES generators will be able to access the markets' potential in an increasingly competitive environment.

The REBal model is also able to calculate the welfare gain that is created by to the participation of fluctuating RES generators in the control reserve market. The welfare gain can either be allocated to the control reserve providers as additional income, or as cost saving potentials for the systems. The welfare gain by the wind farms are shown in blue in the figure below, whereas the PV systems are shown in orange. The darker lines apply to the negative secondary market and the lighter lines to the negative tertiary market.



Source: Own analysis

Figure 1-4: Welfare gain for the capacity component induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of four hours and a level of reliability of 99.994 %.

The results show the welfare gain for the capacity costs only, since the dispatch costs might increase the costs for the system, in some cases. The participation of fluctuating RES generators in the control reserve market is beneficial for the power system, if potential dispatch cost increases are addressed by improved market regulations. The welfare gain of the dispatch component in the negative control reserve markets is positive for all years, market segments and generator types. However, the total value decreases over the years, due to a decreasing total market volume. The correlation between the market volume and the welfare gain allows the forecast of the welfare gain in the future.

1.4 Conclusion

The study was set up to explore the economics of a control reserve provision by fluctuating RES generators. The very specific feed-in characteristics require additional steps to bring these generators to a market that requires reliable delivery. The research results show that the research question can be answered.

Being able to replace large amounts of conventional generators in the control reserve market fosters the transformation of the power system. In a system with increasingly dynamic residual load requirements, conventional generators often do not operate at their maximum capacity. Each conventional generator in the power system that provides control reserve is therefore a potential must-run unit and causes uneconomic dispatch.

Fluctuating RES generators should be admitted to the control reserve market since they can deliver added value to the market. The ability to provide all necessary ancillary services from fluctuating RES generators is paramount for a power system with high shares of renewables. This implicitly demands fair competition, with a regulatory framework that facilitates the market participation of as many units as possible. Given fair market conditions, wind farms and PV systems are a part of the solution for a secure and stable energy system in the future.

2 Introduction

2.1 Motivation and Problem Statement

Climate change has been identified as a threat to humankind by the Intergovernmental Panel on Climate Change. In its synthesis report of the fifth assessment report the IPPC states (Pachauri & Mayer, 2014, p. 13):

Climate change

> *“Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed […] [amongst] countries at all levels of development.”*

The IPCC further concludes that climate change is induced mostly by the energy related emissions of CO_2 into the atmosphere of the earth. Limiting global warming requires the reduction of CO_2 emissions to pre-industrialization levels and thus an adaptation of the way energy is generated and used. One of several pathways to mitigate CO_2 emission is the use of renewable energies.

In the year 2009, the European Union agreed upon the EU 20/20/20 targets. These targets oblige its member states to source 20 % of its energy consumption from renewable sources by 2020. Subsequently this decision was transferred into the national action plans that were published in 2010 (Directive 2009/28/EC of the European Parliament and of the Council, 2009). In the same year, Germany decided on its targets for Renewable Energies for the year 2020 and beyond. The share of electricity from renewable energy sources (RES) will reach 35 % by 2020 (Bundesregierung, 2010). The German Renewable Energies Act (EEG) defines the target of 80 % of renewable electricity in the year 2050 (Erneuerbare-Energien-Gesetz, 2014). These changes will lead to a decreasing share of conventional generation in the future. A possible path towards meeting these targets can be seen at the EE-Langfristszenarien (RES long term scenarios) (Nitsch J. et al., 2012, p. 185).

Targets and scenarios for the on the use of renewable energy sources in the future

High shares of renewables requires the delivery of ancillary services by renewables

In these scenarios, we are more likely to observe situations in which the electricity demand is satisfied solely by RES. This means that conventional generation units will have very small shares in the overall power supply, especially in times of very high instantaneous penetration levels of fluctuating RES. As of today, ancillary services are provided mainly through conventional generation units, as they still supply large amounts of the electric energy in the power system. Ancillary services are those services in the power system that ensure the security of supply, such as control reserve, voltage control or black start capability, amongst others.

Ancillary services are sourced inefficiently by using units that are not used in the spot market

With the introduction of fluctuating RES generators, the electricity generation pattern has changed significantly in the last decade. This leads to times when a large amount of conventional generation is disconnected from the grid, since the energy is supplied by RES. This stands contrary to the fact that currently ancillary services are mainly provided by conventional generation units. Alternative generation technologies in the power system will have the responsibility for maintaining the security of supply. Ancillary services always should be supplied by those units, which are providing power to the system.

Ensuring grid parameters when RES feed-in is high

The transmission system operators (TSO) in Europe use control reserve for the confinement of frequency deviations from 50 Hz within operational limits of ±200 mHz (UCTE, 2009). Currently these frequency control services are mainly provided by conventional generation units. In a future power system, it will be necessary that this reserve is also provided by fluctuating RES when their power feed-in is high.

Legislation for RES generators

In accordance with the energy economics act ("Energiewirtschaftsgesetz") the energy system should be affordable, ecological and reliable. This triangle of competing objectives needs to be balanced and optimised appropriately under changing framework conditions. One has to take these conditions into consideration in deciding when wind turbines should offer control reserve (Energiewirtschaftsgesetz, 2011). The 2012 revision of the German Renewable Energies Act (EEG) enables RES to deliver energy to the markets and provide ancillary services at the same time (Erneuerbare-Energien-Gesetz, 2014). With the RES support scheme "optional market premium" a successful integration of wind farms and photovoltaic systems (PV systems) into the energy markets was observed (Lange et al., 2014, p. 16). The share of wind turbines being sold under this RES support scheme was more than 80 % by the end of February 2014 (Köpke, 2014). Biomass is already integrated into the control reserve markets (Lange et al., 2014, p. 14).

Previous assessments were only able to capture single effects

Apart from legislative changes, the regulatory framework has not been adapted for a possible control reserve provision of fluctuating RES. Earlier assessments by Brauns et al. (2014) have proven the feasibility of the delivery of control reserve from wind turbines, assessing how wind turbines could fulfil the requirements of the current market design. The economics of a control reserve delivery were discussed in Brauns et al. and a computer model for the economic impact assessment was developed. Despite the results, further research in this field is necessary in order to understand the influence of the market design on economic aspects. This thesis investigates the economic aspects of the control reserve provision from fluctuating RES.

Solving the inefficient dispatch problem through market control reserve market changes

The increasing share of renewable energies leads to times when fluctuating RES have a very large share in the production at a given hour. This could lead to a situation where conventional generators are only delivering energy to the system because they have committed to deliver control reserve on a larger time horizon, e.g. a week in advance. However, depending on the share of fluctuating RES it would not be necessary to keep those generators connected to the grid for the supply of electricity. They are solely connected for delivering control reserve to the system and therefore distort the market as a whole. This ultimately leads to the point where fluctuating RES are curtailed for that reason.

2.2 Objectives and research hypothesis

Lack of knowledge on the economics of fluctuating RES in control reserve markets

Available literature does not provide information detailed enough to assess the potentials for the delivery of control reserve from fluctuating renewable generation in a realistic scenario. Many publications refer to a situation without any markets or regulations. They do, however, provide useful information on the technological and economic strengths and weaknesses of wind farms providing control reserve. Photovoltaic systems so far have not been examined as thoroughly as wind farms. This is mainly because wind farms are widely built throughout the world and the technology has a higher degree of maturity.

Developing a methodology for economic impact assessment for the provision of control reserve

During the literature research, the most advanced methodology considering the assessment of control reserve in real markets was found in several papers by Kirby, Ela, Tuohy, Milligan et al. (2011; 2010; 2012) . However, it does not address the central issues of volatility and forecast errors. The results presented with the given scenario do not allow the transfer of the results to the European power system. The economic revenues from the system's point of view are not presented. Due to the nature of different regulatory philosophies in the power system, the assessment needs to be adapted specifically to the target region. Results cannot be transferred to Europe without considering the framework conditions. The proposed thesis presents a methodology to offer control reserve and quantify the economic impact in a close-to-reality scenario.

Identifying ideal framework conditions

This thesis presents the economic potentials of a control reserve provision from fluctuating RES as well as the influence of the regulatory framework on these potentials. Recommendations for changes in this framework are given, in order to enable the provision of control reserve by fluctuating RES. The delivery of control reserve to the markets with different bidding strategies under varying framework conditions has an impact on the economic viability. One superior policy goal is to reduce the amount of must-run capacity of conventional generation that is required for the delivery of ancillary services under the current framework conditions. The assessment is carried out for the German market and its regulations.

Requirements for regulatory changes

The underlying economics are an essential part of a successful delivery of such services by any unit to the power system. If fluctuating RES generators are to have an increasing responsibility for system balancing, regulations will require changes in order to guarantee the system reliability. It is only possible to achieve positive changes in the energy system if market rules are non-discriminatory for all market participants. Therefore, it is necessary to investigate the market rules in reserve markets and the interdependencies with other electricity markets.

Based on the current state of the research the hypothesis for the thesis is as following:

Main research hypothesis

> **Stochastic units, such as wind farms and PV systems, can provide control reserve to the power system competitively without altering the level of reliability whilst decreasing system costs.**

The aspects that have to be investigated in order to be able to acknowledge or to reject the main hypothesis of the thesis are the following subordinated hypotheses:

Subordinated research hypotheses

- It is possible to provide control reserve with fluctuating RES generators reliably.
- The provision of fluctuating RES generators can temporarily substitute services that are currently provided by conventional generation.
- The impact of the regulatory framework is important for the delivery of control reserve by fluctuating RES and other stochastic units with regard to economic incentives.
- The economic benefits are greater than the costs when fluctuating RES provide control reserve.

Based on the aforementioned aspects the hypothesis will either be acknowledged or rejected. Additionally one could formulate research questions out of these hypotheses, which will be answered throughout this work. Conclusive results shall ensure that fluctuating RES deliver control reserve when they can and at the same time, the delivery is carried out with other units when they cannot. This would follow the principle that energy and ancillary services are dispatched from different units most efficiently.

Improving power system efficiency through better dispatch

The novelty will be the presentation of a scalable methodology to assess the economic value of fluctuating RES delivering control reserve from the

Expected novelty and results

system's point of view as well as from the sellers' point of view. The conclusion identifies the need for change of individual market rules and regulations that hinder the integration of fluctuating RES into control reserve. The effect on the potentials, as well as the loss or gain in social welfare is also quantified.

2.3 Thesis outline

Chapter 3 – State of the discussion in energy economics

Firstly, the fundamentals of the relevant energy-economic and physical backgrounds are laid out in chapter 3. This includes a general description of energy markets, ancillary services and the relevant regulatory framework. All relevant information in relation to the presented methodology is shown. A description of the wholesale power market prices and the prices in the control reserve markets is included. The regulations and mechanisms for the delivery of control reserve in Germany are presented in detail. The current situation for the delivery of control reserve by both non-fluctuating and fluctuating RES is presented. This chapter also presents available literature on the topic of control reserve provision of fluctuating RES and approaches to perform the economic impact assessments. Derived from this, the study setting is described and the research question is located in the context of the available literature. Based on the given literature different approaches for the economic impact assessment are presented as well as an alternative approach, which is presented in this thesis. All approaches are evaluated according to quality criteria.

Chapter 4 - Modelling the economics of control reserve provision by fluctuating RES

The methodology, which is developed in chapter 4, is derived from the findings in the previous chapter. The modelling for answering the research question is developed here, starting with modelling a market participation of fluctuating RES generators in the control reserve market. Subsequently the methodology for measuring the economic potential is presented. Different influencing factors are captured and included in the methodology. The data used are shown here, with limitations and potential problems arising from the data sets clearly communicated. The modelling assumptions and limitations of the chosen approach are also presented in this chapter.

The results from the first part of the methodology chapter are presented in chapter 5, which contains the economic assessment from the fluctuating RES generators' point of view. It presents the probabilistic forecasts and the technical potentials. Based on this the bids for the market are presented following the methodology on bid creation. Lastly, in this chapter the possible additional income for the RES generators is presented and compared between different pools of RES generators.

Chapter 5 - Economics of fluctuating RES in the control reserve market

The economic impact from the system's point of view is presented in chapter 6. Firstly, the cost changes under different bidding approaches are analysed. Secondly, the micro-economic impact of the proof method for the delivery of control reserve is quantified, showing how regulations affect more than just the control reserve markets. Thirdly, based on the cost saving potentials and the possible additional income from the previous chapter the welfare gain is explained and the added value for the system quantified. A forecast of the welfare gain in 2020 and 2030 is shown at the end of this chapter.

Chapter 6 - Economic impact of fluctuating RES on the power system level

Chapter 7 summarizes and concludes the research results from this work, drawing on the initial research question. The hypothesis is tested and accepted or rejected. The implications for the regulatory framework are laid out and further research is identified. The chapter closes with a presentation of the advancement in the research through this thesis.

Chapter 7 - Final assessment of the hypothesis and conclusions

3 State of the discussion in energy economics

3.1 Energy-economic foundations

Markets access for fluctuating RES generation

This doctoral thesis assesses the technical and economic potentials of wind farms and photovoltaic systems to provide control reserve. Since the liberalization of the power markets in Europe (Directive 96/92/EC of the European Parliament and the Council, 1996) energy and selected ancillary services are traded on markets. Currently control reserve is the only ancillary services in Germany that is procured in a standardized market environment. Since markets will determine the value of wind farms and photovoltaic systems in the power system, the fundamentals of the relevant market segments in Germany and the underlying regulatory framework are explained in this chapter.

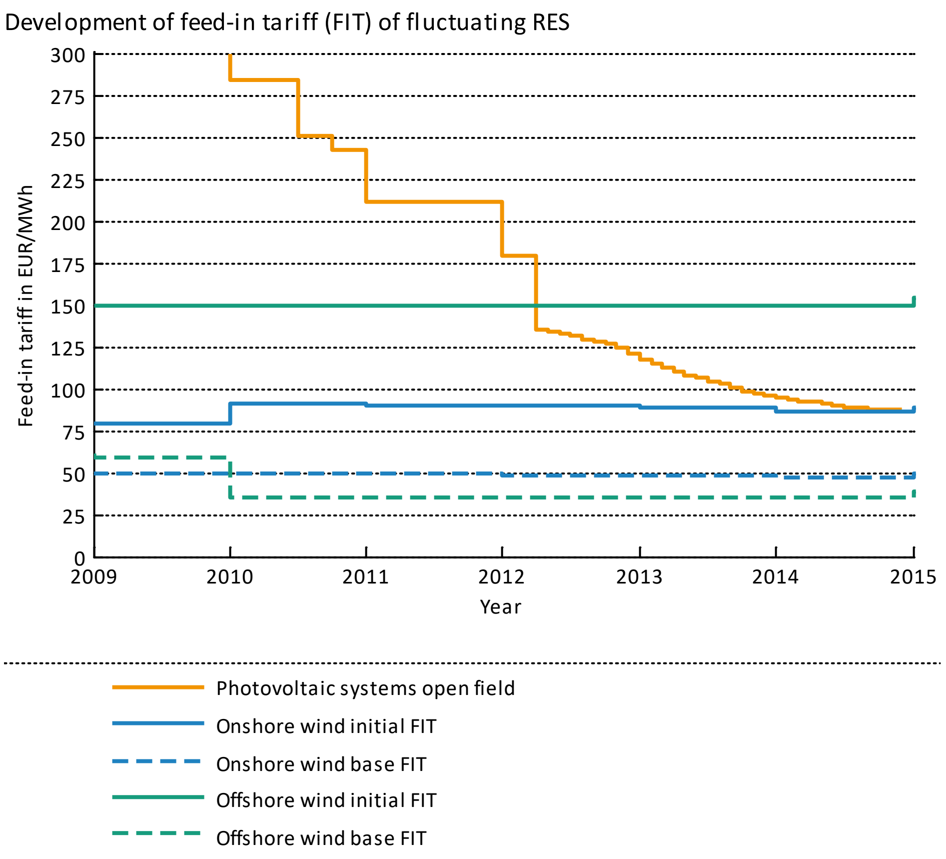
3.1.1 Regulatory Framework for Power Markets

EU internal market directive, German Energy Act and the regulator BNetzA

The introduction of the EU internal market in electricity directive 96/92/EC on 19th December 1996 (Directive 96/92/EC of the European Parliament and the Council, 1996) has led to the liberalization of electricity markets. The directive was implemented on the 24th of April 1998 into the Energiewirtschaftsgesetz (EnWG) (English: German Energy Act) (Energiewirtschaftsgesetz, 2011). The entire electricity market has been opened for competition, which led to the possibility for electricity customers to choose their own supplier freely. Additionally the non-discriminatory network access had to be granted, and integrated energy utilities had to be unbundled. The Bundesnetzagentur (BNetzA) (English: Federal Network Agency) was set up in 2005 as an independent regulatory body to regulate power market rules (Konstantin, 2009, p. 46). Rights and privileges of the regulator are organized in Stromnetzzugangsverordnung (StromNZV) (English: regulation on electricity feed-in to and consumption from electricity supply grids) (Stromnetzzugangsverordnung, 2014).

RES support scheme

The framework under which Renewable Energy Sources (RES) are supported is the German Erneuerbare-Energien-Gesetz (EEG) (English: German Renewables Act) (Erneuerbare-Energien-Gesetz, 2014). This regulates the payments for electricity from RES generators. The law grants RES generator payments for each kilowatt-hour (kWh) that is fed into the grid. Since 2012, the generator can opt between a fixed feed-in tariff (FIT) model and a direct marketing model with market premium payments. With the market premium model applied, the income from the power market is supplemented by market premium payments, which are aligned with the height of the FIT as a reference. (Erneuerbare-Energien-Gesetz, 2014)



Source: own analysis based on data (Erneuerbare-Energien-Gesetz, 2014; Fraunhofer IWES, 2015; Quaschning, 2015; www.solaranlagen-portal.com)

Figure 3-1: Development of the EEG based initial and base feed-in tariffs for onshore and offshore wind farms and the feed-in tariff for photovoltaic systems

Historic feed-in-tariff and chosen FIT for simulations

Figure 3-1 shows the development of the FIT in the past for on- and offshore wind farms and open field photovoltaic systems. On- and offshore wind farms initially receive a higher FIT, indicated as initial FIT (blue and green line).

After a pre-defined period of time and based on the location of the wind farm, the FIT is reduced to a base tariff (dashed line) until the end of the support time span. For all calculations in this thesis, the FIT is based on the initial FIT for the 31st of December 2014, providing a consistent FIT through all years.

Balancing responsibility and allocation of electricity to balancing groups

Balancing responsibility for electrical energy consumption and production in Germany is commercially allocated to balancing groups. A balancing group is responsible for the balancing of all contracted generation and consumption units for every quarter of an hour. Every grid connection point has to be allocated to a balancing group within a transmission system operator's (TSO's) control area, according to the grid access regulation StromNZV §4 (3) (Stromnetzzugangsverordnung, 2014). Balancing groups pool the power trades, electricity generation and electricity consumption of one or more market participants. All power trades between different balancing groups have to be carried out by means of schedules (StromNZV §5 (1)) which announce the exchanged energy between those balancing groups.

Balancing group contract

The balancing group contract is a standard contract containing formal definitions from the Federal Network Agency (Bundesnetzagentur, 2013)[1] and is made between the Balance Responsible Party (BRP) and the operator of the control area (TSO). It coordinates the rights and obligations of BRPs in each control area. A list of balancing groups is published regularly[2]. The balancing group contract allows the exchange of electrical energy with the grid, i.e. consumption, production or trading of electricity. One of the key duties of a BRP is balancing the feed-in and purchase trades of electricity with consumption and sale trades of energy in every quarter of an hour. Every exchange of electricity has to be reported by the BRP to the TSO through schedules prior to consumption one day in advance. (Bundesnetzagentur, 2011a)

Scheduling of energy exchange

For planning purposes, schedules have to be sent to the TSO as well as the scheduled consumption and generation forecast. All schedules for balance

1 An English version of this contract can be found here:
http://www.amprion.net/sites/default/files/pdf/Standard%20Bilanzkreisvertrag_DE_EN.pdf
2 http://www.bdew.de/internet.nsf/id/DE_EIC-Codes-und-VNB-Bilanzkreise

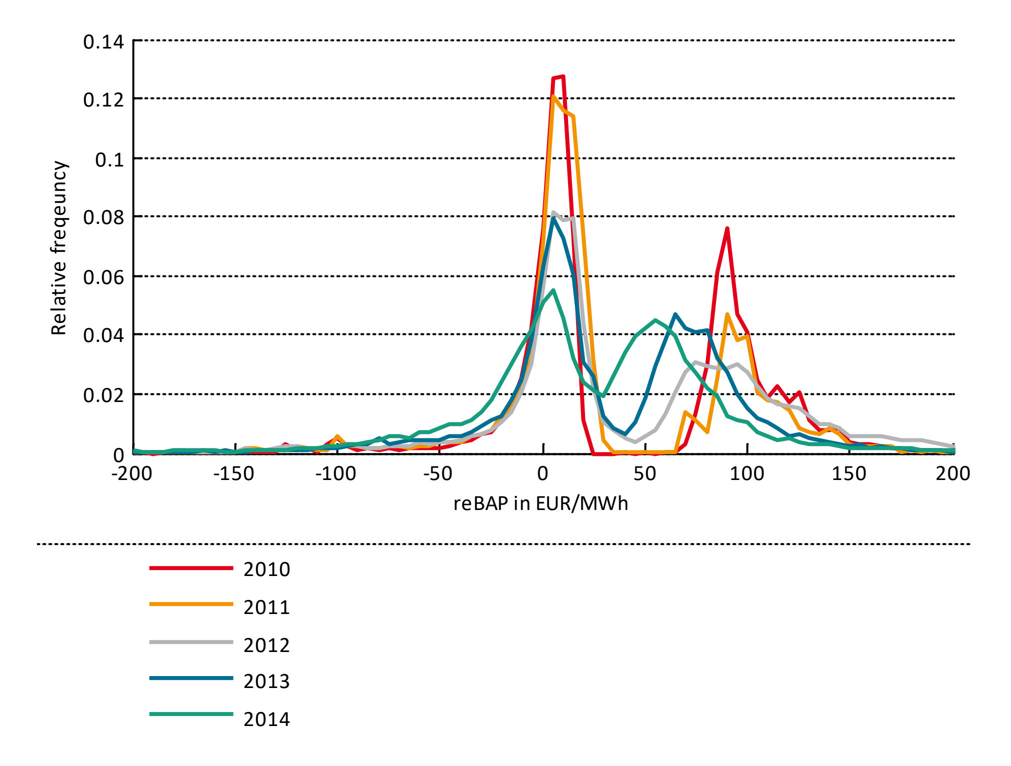
responsible parties have to be balanced for each 15-minute imbalance settlement period. The exact processing of data and billing is stated in the Market rules for balancing group billing in the area of electricity (MaBiS) (Bundesnetzagentur, 2009a, 2009b, 2009c, 2011b). Schedules from the BRP have to be transmitted before 14:30 on the previous day (day-ahead). Amendments to the schedules within the German control areas may be changed no later than 15 minutes prior to the delivery period. Verification of grid safety requires an individual schedule of every unit (e.g. power plants) with a physical electrical capacity of more than 100 MW before 14:30 at the previous day (day-ahead).

Balancing energy price

According to the balancing group contract, imbalances that occur during operation will result in the allocation of balancing energy from the TSO to the balancing group. The exchange of balancing energy is subsequently priced at the balancing energy price. The balancing energy price for each quarter hour is multiplied by the quarter hour balancing energy price. Depending on the balancing group's imbalance and the balancing energy price, this may result in financial obligations or reimbursements. Balancing energy prices are calculated for every quarter of an hour based on the dispatch costs of control reserve. Balancing energy prices are a uniform common balancing energy price (German: regelzonenübergreifender einheitlicher Bilanzausgleichsenergiepreis (reBAP)) which is applied symmetrically to the balancing energy delivered (50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH, 2012b). 'Symmetrically' means that received balancing energy will be charged while supplied balancing energy will be reimbursed with the balancing energy price. Balancing energy cost obligations can be transferred from one balancing group to another. (50Hertz Transmission GmbH et al., 2012b)

Publication of balancing energy price

The TSO will publish the reBAP no later than on the 20th working day after the end of the delivery month and will determine the balancing deviations of the balancing groups from the 30th working day after the end of the delivery month based on the billing data available at the end of the 29th working day. The settlement of balancing energy is made on a monthly basis, 42 working days after the end of the delivery month, at the latest. The following histogram shows the annual frequency of the balancing energy price with a bin width of 5 EUR/MWh. (50Hertz Transmission GmbH, 2015)



Source: Own analysis based on data from (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH, & TenneT TSO GmbH, 2013)

Figure 3-2: Annual frequency of balancing energy price reBAP

3.1.2 Wholesale Power Markets

Trading the commodity electricity

The basic principles of electricity trading on spot markets and derivative markets are similar to other commodity markets. Commodity trading is typically applied for different commodities such as metals, coal, agricultural products, crude oil and natural gas. The purpose of the long-term derivative markets is to hedge risks against unforeseen price developments in the shorter-term spot markets. The nature of a commodity contract is that the seller agrees upfront to pay a price for specified goods at a specified delivery date whereas the seller agrees to deliver the goods at the specified time. These contracts can be concluded at exchanges or bilaterally between the buyer and the seller, the so-called over-the-counter trade (OTC). (Liebau, 2012, pp. 42–43)

Exchange market for electricity trading

The European Energy Exchange (EEX) operates the power derivative market for the market area of Germany. Daily operation and matching of supply and demand for the German market area is facilitated though the short-term spot markets, which are operated by EPEX SPOT. Spot markets determine equilibrium power prices for every hour and for every quarter of an hour. Trading on spot markets is one way of balancing a balancing group as described in chapter 3.1.1. Trading does not affect the balancing responsibilities. (Liebau, 2012, pp. 43–45)

Procurement of ancillary services

Alongside electricity trading it is necessary for the TSOs to procure ancillary services in order to guarantee the stable operation of the system. Ancillary services are procured by the TSO either bilaterally or through a market scheme (50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH, 2012a). Currently control reserve is the only ancillary service that is procured through a market scheme. The assessment of the economics of a control reserve provision by fluctuating RES is based on this market. Its rules and conditions are essential to the outcome of the assessment. Details for the control reserve market are shown in chapter 3.2. The following graph shows an overview of possible ways to trade power on wholesale markets.

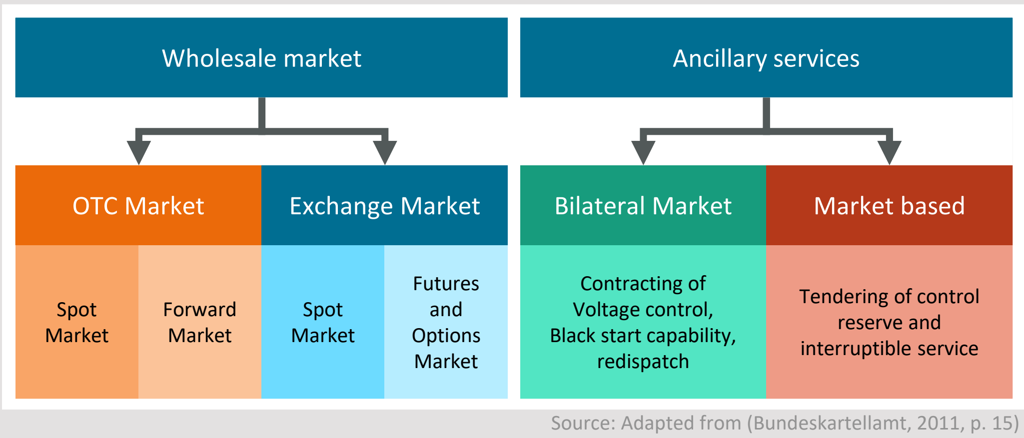
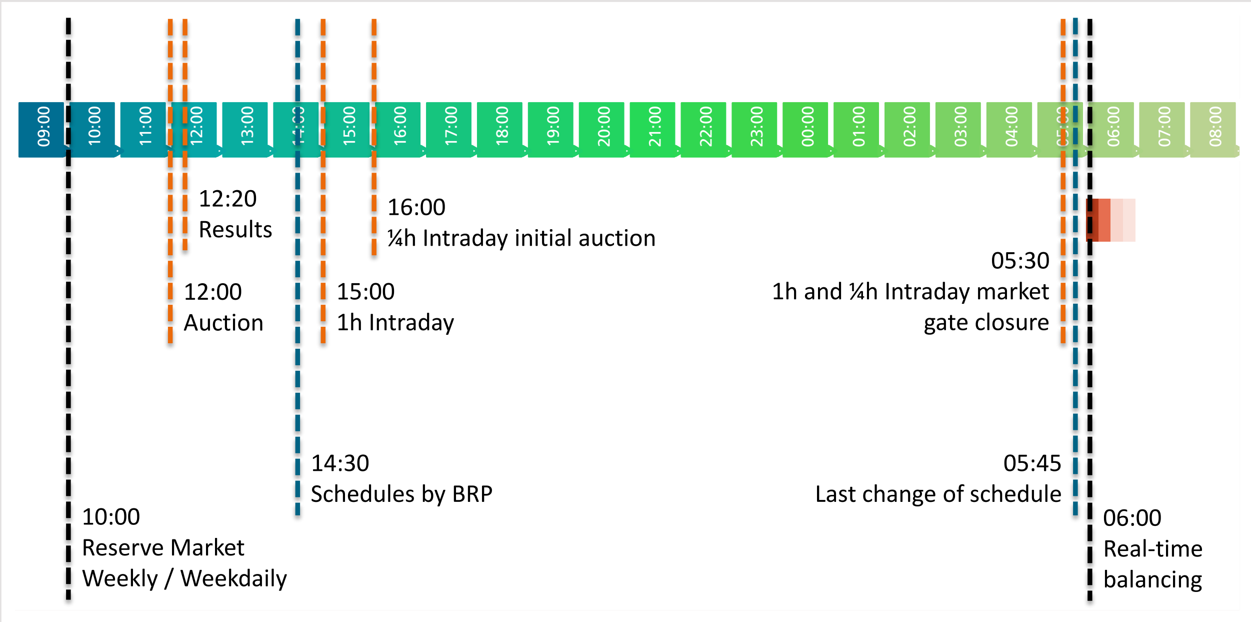


Figure 3-3: Overview of trading on wholesale and ancillary service markets

Market participants' actions

The different trading options and the actions by single market participants are shown in Figure 3-4. The spot market actions are marked in orange, the actions as balance responsible party in blue, and the actions on the control reserve market in black.



Source: Own analysis based on (Consentec, 2014; EPEX SPOT SE, 2016; Liebau, 2012, p. 41)

Figure 3-4: Schematic overview of the procedures covering the participation in spot energy and control reserve markets

OTC trading

As an alternative, energy can be trade over-the-counter (OTC). OTC transactions can take place without further formal framework conditions. The OTC contract conditions such as time of delivery and volume are not standardized and are negotiated between the trading parties involved. Both counterparties need to be associated with a balancing group to account for the traded electricity. Different OTC trading platforms provide an organizational setup to facilitate OTC trading. One example of such a solution is the internet platform IntradayS (Power2Energy, 2013) where trades are performed as OTC. (Michetti, 2012, p. 5)

3.1.3 Spot market at the European Power Exchange

Purpose of exchange trading and share of traded wholesale electricity

Trading on the spot market enables market participants to sell and buy electricity in a non-discriminatory and anonymous environment and ensures the maximization of the social welfare through merit-order dispatch (Jiang Wu, Xiaohong Guan, Feng Gao, & Guoji Sun, 2008). The exchange prices (spot and derivatives) serve as a reference for all market participants, even for the OTC traded contracts (Kalantzis & Milonas, 2013, p. 460; Michetti, 2012, p. 4). Electricity can be traded in standardized contracts on a day-ahead auction and continuous intraday trading at the European Power Exchange EPEX SPOT. The Energy traded in the power exchange markets accounted for more than 40 % (EPEX SPOT SE, 2015a) of the national gross electricity consumption in the year 2013. An increasing trend can be seen which is driven by the increase of generation from renewable energy sources and their need for day-ahead settlement as well as by the participants desire to optimize unit commitment (EPEX SPOT SE, 2014b).

Alternative ways of trading

Any other shares of national gross electricity consumption are marketed through the intraday exchange, forward markets (energy derivatives) or the OTC market. The number emphasizes the importance of the market and its relevance as a price reference for all the other markets. (EPEX SPOT SE, 2014b)

Rules of market operation

The EPEX SPOT exchange is run applying exchange regulations. These regulations consist of the so-called the code of conduct, the market rules and the operational rules. These rules are applied uniformly to all market participants and govern the operation of the exchange (EPEX SPOT SE, 2014c).

Admission to the spot markets

The participation at the EPEX SPOT markets consists of two parts. This includes the admission by the market operator and the admission by a so-called clearing house. For the admission by the market operator, no technical qualification is necessary. Trading on EPEX SPOT does not require any physical units to be delivering or consuming power. Admission to the market enables trading on all market segments. By the end of February 2016 231 companies were admitted to trade in the market.

3.1.3.1 Day-ahead auction

Placing orders on the market

Bids by market participants, also called orders, are submitted via an electronic trading system client to the order book of the exchange. The orders placed in the trading system need to fulfil specified conditions (also see Table 3-1). All orders and transactions are anonymous. The order book is closed each day at 12:00, from which time orders cannot be changed and are binding (EPEX SPOT SE, 2016). In addition to the hourly day-ahead auction, trading has been possible for 15-minute-intervals since December 2014 (EPEX SPOT SE, 2014d).

Forming the market participants individual order curve

Single contract orders are placed as a monotonous individual demand curve with up to 256 price-quantity combinations that limit the volume to a specific price. The curve is interpolated linearly between the entered price-quantity combinations. The entered prices must lie in-between the minimum and the maximum price of the exchange market. (EPEX SPOT SE, 2016)

Specification	**Product detail - 1 hour day-ahead auction**
Trading procedure / days	Daily Auction / Year-round
Tradable Contracts	1 hour of the day Hour 01: the period between midnight and 1:00, Hour 02: the period between 1:00 and 2:00, and so on and so forth
Order Book opening / Trading session opens	45 days before Delivery Day
Order Book closes / Trading closes	Daily at 12:00 for the next day
Publication time	As soon as possible from 12:42 for preliminary results; Binding final results will be published between 12:55 and 13:50[3]
Minimum and maximum prices	-500.00 EUR/ 3000.0 EUR
Minimum price increment	0.1 EUR/MWh
Minimum Volume Increment	0.1MW
Order quantity	One order with at least 2 and no more than 256 price/quantity combinations

Source: (EPEX SPOT SE, 2016)

Table 3-1: EPEX SPOT day-ahead auction contracts specifications

Determining the market clearing price

The orders are auctioned daily after the closure of the order book. The price is determined through matching of the exchange members' aggregated supply and demand curves[4] for each time interval. The price determined by

[3] Time between order book closure the publishing of the results is needed for the calculation. The calculation of the market settlement requires computing-intense processes that differ with the amount on bids entered into the trading system.

[4] Aggregated curves are the sum of all individual curves (demand or supply). Each one of them can consist of up 256 price-quantity combinations

the trading system is the price at which the highest volume will be executed, the so-called market clearing price with the equilibrium quantity. With the marginal pricing principle applied, also called pay-as-clear pricing, every market participant receives the same price. The entire process of price determination is called market clearing (EPEX SPOT SE, 2016). If the matching algorithm does not generate a valid market price (e.g. insufficient liquidity) a second auction is performed. This should give the exchange members the chance to change their orders to improve the situation. (EPEX SPOT SE, 2016)

Post trading period, notification of market participants and scheduling of the market participants

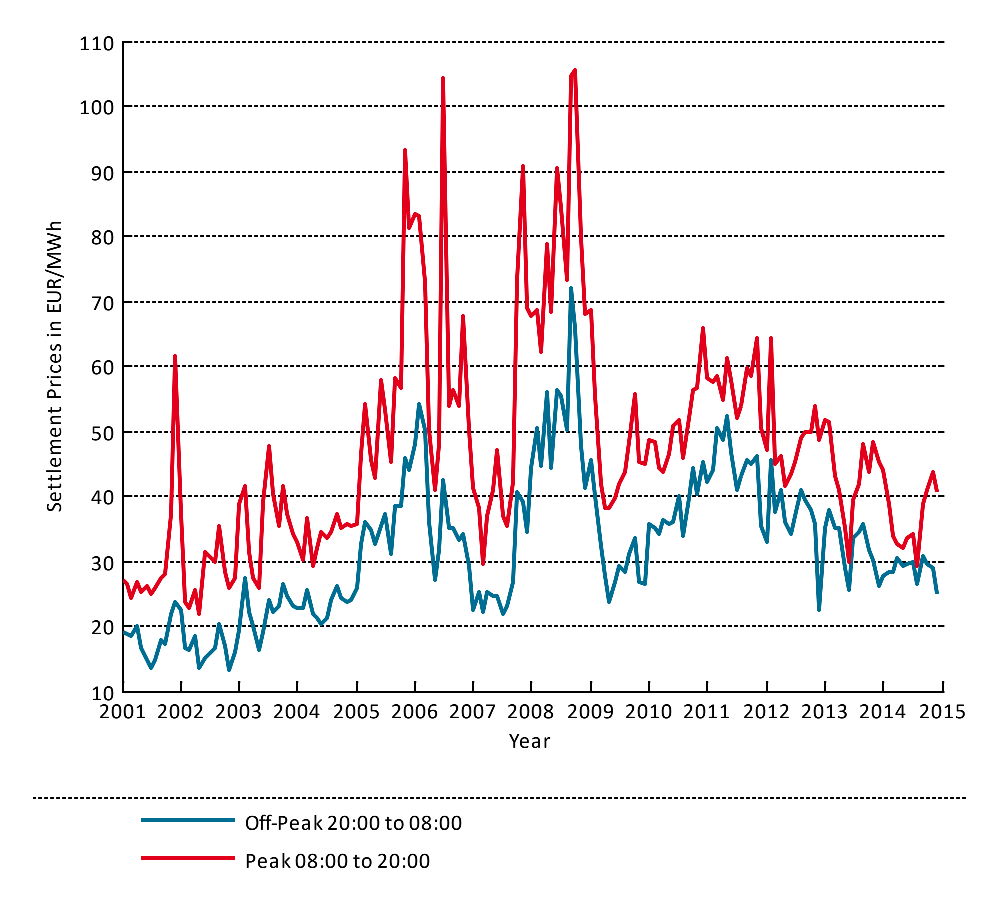
In the post-trading period, the market participants receive notice from the exchange operator about the traded amounts. The exchange members are responsible for transferring the market results into schedules for the TSO. The exchange members forward the results to the corresponding balance responsible party for the creation of schedules. Balance responsible parties have to fill in the form for the schedule using the exchange operator as a counterpart to balance positions. The energy exchange operator provides a balancing group for that purpose. The traded amount on the exchange has to match the amounts in the exchange schedule of the balance responsible party. The BRP equilibrium of physical production, consumption and trading is covered under the regulations of the balancing group contract and the MaBiS processes (see also chapter 3.1.1). Trading on the exchanges is a separate process from the obligations of the balancing group contract. (EPEX SPOT SE, 2016)

Market coupling

Due to grid constraints and other barriers, markets are locally segmented. These segmented markets can be brought together by means of market coupling. Market coupling has the effect of harmonization of market prices and encourages the most efficient unit commitment (den Ouden & Jean Verseille, 2011, p. 47), resulting in a social welfare gain (EPEX SPOT SE, 2014a).

Price and quantity development

Figure 3-5 shows the price and volume development of the day-ahead auction market at EPEX SPOT. The price curves present the monthly average off-peak price (average price from 20:00 to 08:00) and the monthly average peak price (average price from 08:00 to 20:00).



Source: Own analysis based on data from (EPEX SPOT SE, 2015a, 2015e)

Figure 3-5: Monthly averaged Base and Peak prices and Highest Twelve Prices of the day-ahead auction at EPEX SPOT

3.1.3.2 Intraday trading

Intraday trading at the EPEX SPOT

Intraday trading on EPEX SPOT intraday markets includes the trading of one-hour products as well as quarter-of-an-hour products. The basic principles of both markets are identical except for the product length. As opposed to the day-ahead auction, intraday market contracts are traded continuously, starting the day before physical settlement at 15:00 for the hourly products. The quarter-of-an hour contracts have an initial auction at 15:00, followed by continuous intraday trading of the contract from 16:00. The last trading opportunity under continuous trading is 30 minutes before physical settlement, after which the order book is closed. (EPEX SPOT SE, 2016)

Purpose of intraday markets and the relation to trading volume

The traded volume on the intraday market is much smaller when compared to the day-ahead spot market. This can be explained by the nature of the day-ahead spot market, where the largest share of electricity is traded in order to ensure the most economic dispatch. Intraday markets are most commonly used for balancing unexpected events, such as power plants failures and forecast updates of fluctuating RES, throughout the day prior to operation. Fluctuating RES have more reliable forecasts the closer the forecast is to the actual time of production, hence trading on the intraday markets close to real time decreases the need for balancing fluctuating RES forecast errors. (Liebau, 2012, pp. 45,98–99)

Order execution

Since the intraday market has continuous trading, liquidity and prices for each contract might vary over time. Depending on the order's price limit, quantity, and order book configuration, single contracts may not be executed due to the lack of a matching counter position in the order book by that time. After the submission of the orders to the trading system, they are immediately matched with other orders in the order book. If a match is found the orders are executed at the best price available in the system. (EPEX SPOT SE, 2016)

The following table shows the contract specification for intraday trading at the EPEX SPOT:

Intraday contact specifications

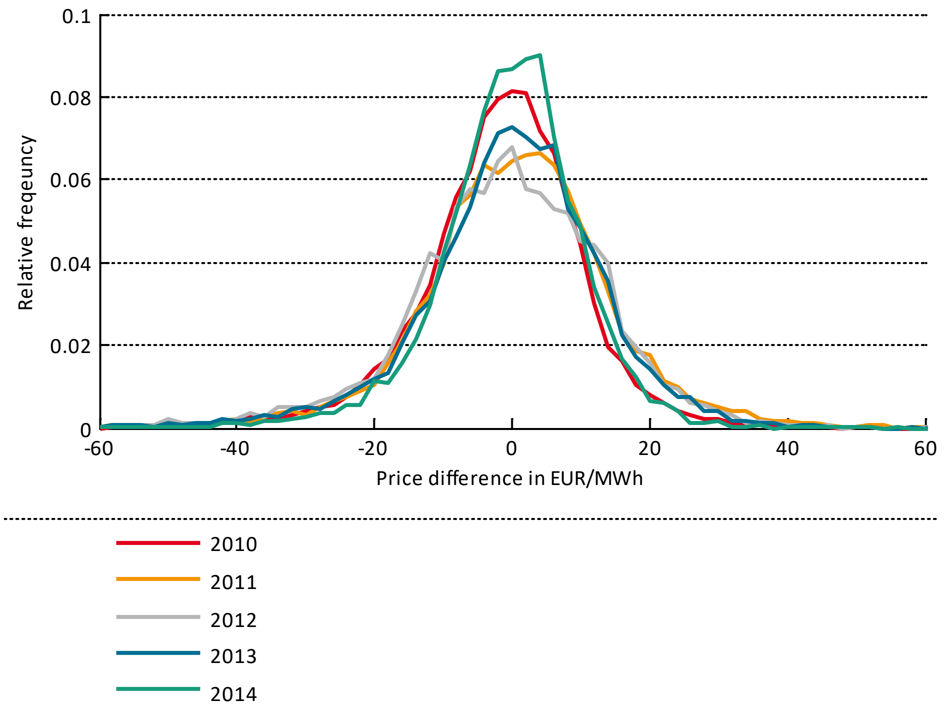
Specification	Product detail - 1 hour continuous trading	Product detail - Quarter hour continuous trading	Product detail - Quarter hour intraday auction
Trading procedure / days	Continuous / Year-round	Continuous / Year-round	Daily Auction / Year-round
Tradable Contracts	1 hour of the day Hour 01: the period between midnight and 1:00 Hour 02: the period between 1:00 and 2:00, and so on and so forth	Quarter hour (15 min.) Four 15-minute contracts open per corresponding underlying hour e.g.; For Hour 01, the following 15-minute contracts will open: 00:00-00:15 00:15-00:30 00:30-00:45 00:45-01:00	Quarter hour (15 minutes) Four 15-minute contracts open per corresponding underlying hour e.g.; For Hour 01, the following 15-minute contracts will open: 00:00-00:15 00:15-00:30 00:30-00:45 00:45-01:00
Order Book opening / Trading session opens	24 hours a day Hourly contracts for the next day open at 3:00	24 hours a day 15-minute contracts for the next day open at 16:00	24 hours a day 15-minute contracts for the next day open at 15:00
Order Book closes / Trading closes	30 minutes before delivery	30 minutes before delivery	Daily at 15:00 for the next day
Publication time	No publication time in continuous trading possible. Prices are publicized continuously	No publication time in continuous trading possible. Prices are publicized continuously	As soon as possible from 15:10 pm
Minimum and maximum prices	-9999.99 EUR / 9999.99 EUR	-9999.99 EUR / 9999.99 EUR	-3000.00 EUR/ 3000.00 EUR
Minimum price increment	0.01 EUR/MWh	0.01 EUR/MWh	0.01 EUR/MWh
Minimum Volume Increment	0.1MW	0.1MW	0.1MW
Order quantity	Unlimited (with limit in daily monetary value stated by clearing house)	Unlimited (with limit in daily monetary value stated by clearing house)	One order with at least 2 and not more than256 price/quantity combinations

Source: (EPEX SPOT SE, 2016)

Table 3-2: EPEX SPOT intraday trading contracts specifications

Price and quantity development

The traded volume on the intraday market is less than a tenth of the day-ahead traded volume. This amount does also include several trades from one party that acquired electricity at one time and has sold it at later point. The frequency of price differences between day-ahead prices and the average intraday prices of each contract is given in Figure 3-6 for several years. The majority of price differences of contracts for one hour between both of these markets are smaller than 20 EUR. (EPEX SPOT SE, 2015a, 2015e)



Source: Own analysis based on data from (EPEX SPOT SE, 2015a, 2015e)

Figure 3-6: Annual frequency of price differences (day-ahead minus intraday) between the last intraday price (ID) and the day-ahead price (DA) of contracts traded for the same hour

3.2 Control Reserve

3.2.1 Types of Ancillary Services and their costs

Types of ancillary services

TSOs are responsible for secure grid operation at all times, which may require the use of ancillary services to address different system stability issues. The ancillary services used by the TSOs in Germany are as follows. In other countries, especially outside Europe, this may vary significantly: (Bundesnetzagentur & Bundeskartellamt, 2014)

- Compensation of grid losses: Energy transmission causes grid losses, which have to be accounted for. The TSOs are responsible for the compensation of these losses. The predictable long-term losses have to be procured through a tendering procedure. Short-term losses can be procured through a third party who has to be selected through a tendering process. In both cases energy can also be procured on the market at EPEX SPOT (Bundesnetzagentur, 2008a).

- Black start capability: This service is used in the case of a grid failure that has led to outages. Power generators that are providing black start services are able to reinitiate the supply infrastructure after a blackout without external help. This service is procured by the TSOs from the generators through bilateral contracts.

- Reactive power for voltage control: For the operation of most electrical devices, the voltage has to be kept within specific limits. The grid operator has to ensure that the voltages in the grid are within certain levels at all points along the line. The transport of reactive power can lead to a deviation of the voltage that is not desirable. To compensate these deviations counteractive reactive power is used to increase the ratio between active and reactive power. This service is contracted bilaterally or is originated from controllable grid components.

- Countertrading: This service is used to resolve congestion issues in the grid. Countertrading is performed in anticipation of a congested grid. The energy is usually traded on the energy exchange.

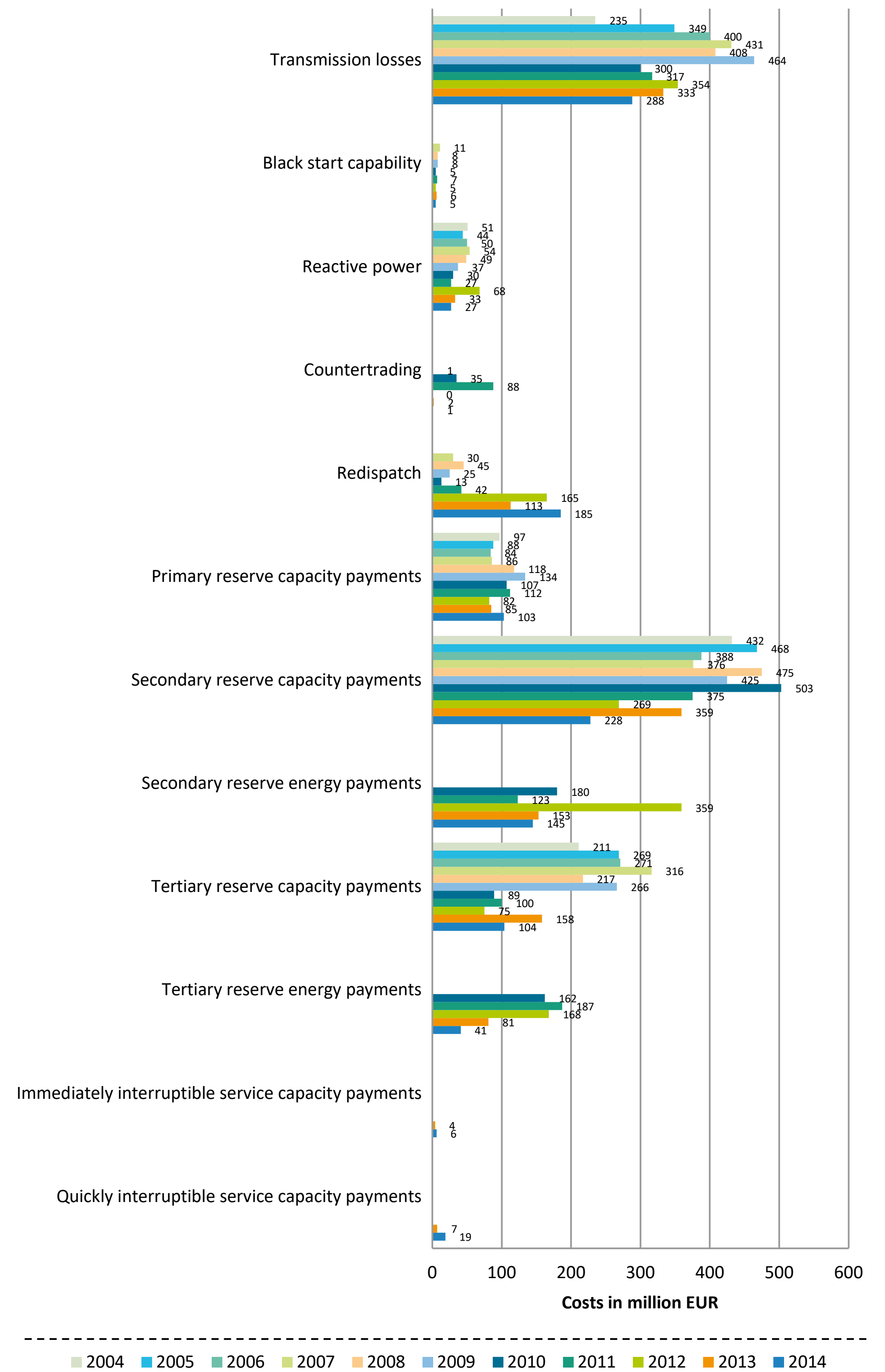
- Redispatch: Physical congestions in the grid may occur due to the energy flow or voltage issues. Either could be resolved by a change of the production from numerous generators and consumers according to §13(1) and §13(2) EnWG (Energiewirtschaftsgesetz, 2011). The generators and consumption units are reimbursed for their financial damage.

- Control reserve for frequency control: For grid operation, it is necessary that the frequency of the grid does not deviate from its set point of 50 Hz. This occurs when the power that is fed into the grid is not equal to the power drawn off. The grid operator compensates this difference between feed-in and consumption with the help of fast responding reserves. The procurement of control reserve in Germany is carried out at the dedicated market regelleistung.net.

- Interruptible service: Since the end of 2012, immediately and quickly interruptible loads are procured by the TSOs. An interruptible load is a unit in the power system that is consuming large volumes of electricity in a continuous manner. It is also capable of reducing or interrupting its electricity consumption on short notice for a certain time span. It therefore acts similarly to the control reserve. The procurement is organized as for control reserve markets and is governed by the AbLaV (interruptible loads regulation) (Verordnung zu abschaltbaren Lasten, 2012). The costs are shifted through a dedicated levy.

Cost monitoring by the regulator

The TSOs are financially reimbursed for the costs of procurement and dispatch of ancillary services. The costs of these ancillary services are monitored and published annually in a summary by the Federal Network Agency (BNetzA) (Bundesnetzagentur, 2010, p. 201, 2012b, p. 109; Bundesnetzagentur, 2014, p. 74; Bundesnetzagentur & Bundeskartellamt, 2013, p. 80, 2014, p. 87). The costs for each ancillary service can be seen in Figure 3-7. By the end of 2015 only data until the end of 2014 were available from official sources. The costs of interruptible services and control reserve have been recalculated, based on data from regelleistung.net (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH, & TenneT TSO GmbH, 2015).



Source: (Bundesnetzagentur, 2006, 2007, 2008b, 2009d, 2010; Bundesnetzagentur & Bundeskartellamt, 2014, 2015)
Control reserve costs and interruptible service costs are own calculation based on:
(50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

Figure 3-7: Costs for the different ancillary services for the years 2004 to 2014

Costs of ancillary services – Grid losses, black start, reactive power, countertrading, redispatch and interruptible loads

The last available monitoring report is from the year 2015 and provides data for the year 2014. According to this the report the costs for transmission losses in 2014 were 288 million EUR. The German TSOs spent 5 million EUR in 2014 for the provision of black start capability and 27 million EUR for the procurement of reactive power. This is similar to the years 2010, 2011 and 2013 – in 2012 there were special expenditures that had to be considered. The costs for countertrading measures in the year 2014 were 1 million EUR. Redispatch costs are constantly rising: they multiplied more than tenfold from 2010 to 185 million EUR in 2014. This accounts for 2686 changes in production of generators in that period. The increase in renewable energies and the lack of additional transmission capacity has led to more congestion in the grid. The costs for the interruptible loads accounted for 11 million EUR in 2013 and 25 million EUR in 2014. The costs for 2013 however are not representative since the regulation came into force in the end of 2012 and the market participants did not have time to engage fully in 2013. (Bundesnetzagentur, 2010, p. 201, 2012b, p. 109; Bundesnetzagentur, 2014, p. 87; Bundesnetzagentur & Bundeskartellamt, 2013, p. 80, 2014, p. 87)

Costs of ancillary services – Control reserve

The costs for secondary and tertiary control reserve capacity and energy payments accounted for 878 million EUR in the year 2014, having been 751 million EUR in 2013 and 871 million EUR in 2012. The German TSOs procure three different types of control reserve (see chapter 3.2.2). In the year 2014, primary control reserve accounted for 103 million EUR of the costs, secondary control for 249 million EUR and tertiary control for 506 million EUR. The capacity payments are socialized through the grid utilisation fees whereas the energy payments are covered through the payments of the imbalance settlement price by the balance responsible parties. The entire costs can also be considered the market size of the control reserve market. Comparing the costs of all ancillary services it can be concluded that the costs of all types of control reserve together are the biggest single position. Besides the countertrading, it is also the only ancillary service that is procured in a market environment. (Bundesnetzagentur, 2010, p. 201, 2012b, p. 109; Bundesnetzagentur, 2014, p. 87; Bundesnetzagentur & Bundeskartellamt, 2013, p. 80, 2014, p. 87)

3.2.2 Types of control reserve

Balancing responsibilities

For the stable operation of the power system, it is necessary that the frequency and voltage in the grid is kept within specified operational limits. To ensure a constant frequency in the power system, generation and consumption always have to be in balance. This is part of the daily operational planning implemented by the MaBiS processes. It accounts for any deviations that occur between the planning until 15 minutes prior to consumption. Until then the balancing responsible party (BRP) manages the deviations of its own balancing group through trading or changes in the schedule. In the case of an unforeseen event beyond the BRP's time horizon, which leads to an imbalance between generation and consumption units, the TSOs have a responsibility to balance the system at short notice. Each individual TSO in Europe is solely responsible for the balancing in its own so-called control area. The TSO is responsible for the minimization of the area control error (ACE) and the energy exchange over the cross-border interconnectors. Required reserves are usually therefore procured for each TSO's own control area. (UCTE, 2009)

Cooperation between the TSOs - Grid Control Cooperation in Germany and Europe

Despite the obligation to balance each control area in itself, cooperation between TSOs is possible. Since 2010 the German TSOs cooperate within a Grid Control Cooperation (Netzreglerverbund) (GCC), resulting in the operation of four control areas[5] as a single control area. The joint operation prevents opposite control reserve dispatch in single control areas. It also allows the common dimensioning of control reserve, common procurement of control reserve and cost-optimised activation of control reserve (merit-order principle) (50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH, 2011b; Müller, 2011).

International grid control cooperation IGCC

As a result of the cooperation, barriers for the procurement and activation of control reserves in Germany have been lifted. Different aspects of the GCC have been extended to the neighbouring countries, forming an International GCC (IGCC). Denmark, the Netherlands, Switzerland, the Czech Republic,

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[5] In Germany all four TSOs are grouped as a control block

Belgium and Austria prevent the opposite control reserve activation, if no transmission contingencies are present (50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH, 2011a). Additionally Switzerland and the Netherlands procure a part of their primary control reserves (25 MW respectively 35 MW) via a common auction with the German TSOs (50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH, 2012). This auction is open for all prequalified providers of primary control reserve from these three countries. (Weidhas, 2012)

Acer framework guidelines, network code electricity balancing and pan-European balancing energy market

The Agency for the Cooperation of Energy Regulators (ACER) has suggested creating a fully integrated balancing energy market for Europe. This would improve the economic efficiency of control reserve procurement and utilization. Existing barriers to a closer collaboration between the TSOs are e.g. the diversity of balancing products and pricing mechanisms. ACER has published its Framework Guidelines on Electricity Balancing in 2012 to address the incompatibility issues. Core elements of the Framework Guidelines are models for cross-border exchanges of balancing energy[6] that should result in one European platform for the procurement of control reserves (ACER, 2012). Based on these Framework Guidelines ENTSO-E has improved the Network Code on Electricity Balancing (NC EB) (ENTSO-E, 2013b).

Frequency restoration through control reserve

TSOs procure ancillary services to fulfil their balancing responsibilities. For the frequency control, the TSOs procure the so-called control reserve. Control reserve is used for the restoration of frequency deviations from the set point of 50 Hz within the operational limits of ±200 mHz (UCTE, 2009, p. 5). This is carried out by control reserve units that are either generation or consumption units and which can increase or decrease their generation or consumption depending on frequency, or through dispatch by the TSO. The German TSOs procure three different types of control reserves. They are

[6] At this point balancing energy describes only the energy that is dispatched, not the reservation of capacity

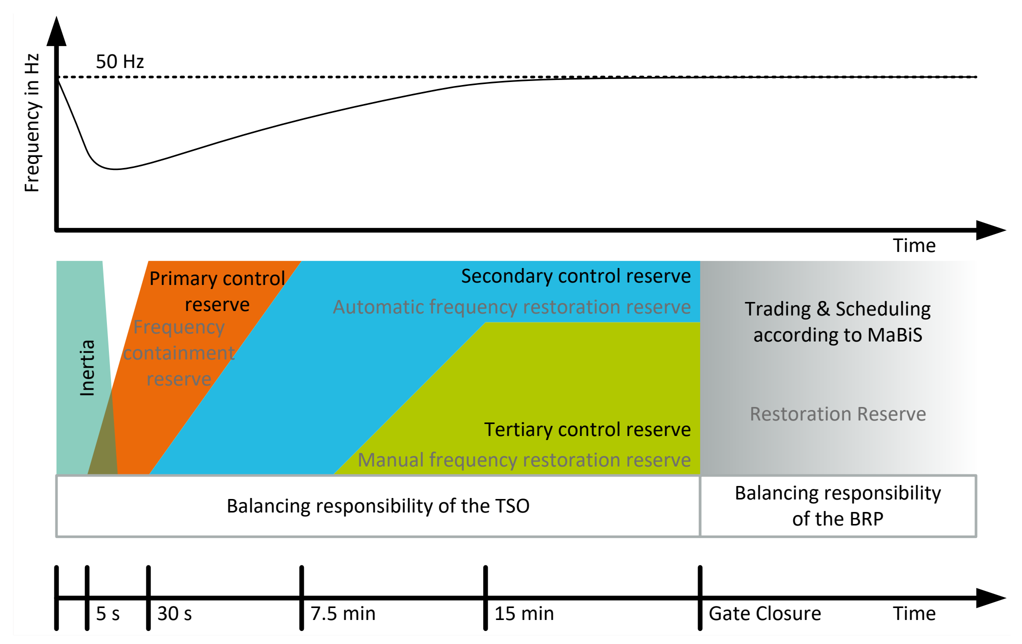
called primary control (reserve), secondary control (reserve) and tertiary control (reserve), in Germany called minute reserve. (UCTE, 2009)

Nomenclature differences in the ENTSO-E

The described ancillary service of frequency control in the power system will be called control reserve throughout the thesis; however, it is lacking a consistent naming scheme. Different names are used for the same or similar services throughout Europe as well as outside of it. The European Network of Transmission System Operators for Electricity (ENTSO-E) has performed the task of harmonizing the European nomenclature of control reserve for its different synchronous grid areas, also called regional groups (RG) (ENTSO-E, 2012). Each regional group has defined a set of frequency control services that fulfil the same purpose, i.e. balancing the power system. The individual characteristics of each individual service are different from one RG to another one. The services are defined in (ENTSO-E, 2013b). The RG that is considered in this thesis is the continental Europe RG (ENTSO-E RG CE).

Nomenclature differences in the ENTSO-E

The ENTSO-E nomenclature is divided into frequency containment reserves (FCR), frequency restoration reserves (FRR) and replacement reserves (RR). FRR are further divided into automatic frequency restoration reserves (aFRR) and manual frequency restoration reserves (mFRR). FCR is equivalent to primary control reserve, with aFRR provided by secondary control reserve and mFRR delivered by tertiary control reserve. RRs are allocated to the balancing responsibility of the BRPs in Germany. Figure 3-8 below shows the different control reserve names used in this thesis with their equivalent ENTSO-E name. Secondary control reserve is often referred to as automated generation control (AGC). (ENTSO-E, 2013b)



Source: adapted from (UCTE, 2009, p. 3)

Figure 3-8: Idealized dispatch cascade of positive control reserve after the occurrence of a system event in the ENTSO-E RG Continental Europe with nomenclature according to this thesis and its ENTSO-E equivalents

Idealized control reserve dispatch cascade

Figure 3-8 shows the idealized dispatch of all three control reserve types for an event resulting in a frequency drop. This could be caused by the unplanned outage of a power plant or the addition of a large consumer. The figure shows the dispatch of reserves in a cascade where one control reserve replaces the previous one. This is idealized since this would only be applicable to a single system event. In reality, different events and their effects overlap with each other. Table 3-3 summarizes the three different control reserve types in Germany.

	Primary control reserve	Secondary control reserve	Tertiary control reserve
Purpose	Stabilise grid frequency after a disturbance	Balance control areas, bring grid frequency back to nominal value, replace primary control	Complement and replace secondary control
Time until complete activation	30 sec	5 min	15 min
Reaction time	Immediately, no longer than 5 sec	30 sec until first change of power for pooled reserve providers[7]	No more than 7.5 min
Activation	Local, static relation to the frequency	Automatically by grid control centre with MOL; activation through MOLS	Manually by grid control centre using MOL; activation through MOLS

Source: Own analysis based on (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

Table 3-3: Control reserve specifications

Principles of primary control reserve

Primary control reserve is a fast responding reserve available for the fast stabilisation of the grid frequency after an event. The first response has to be visible after five seconds and has to be fully activated within 30 seconds, following a linear ramp between its initial activation and full activation. It is activated uniformly by all contracted providers of primary control reserve throughout the synchronous area of the ENTSO-E RG CE, disregarding the origin of the imbalance (principle of solidarity). It is activated on a decentralized basis, depending on the locally measured grid frequency. (UCTE, 2009, pp. 4–11)

Dispatch mechanism of primary control reserve

Every generator providing primary control reserve is controlled through a decentralized control at each individual unit tracking the grid frequency[8]. The dispatch of control reserve is proportional to the frequency deviation in the grid. No reaction within a dead band of ±20 mHz is required. Deviations between ±20 mHz and ±200 mHz trigger a dispatch of control reserve along a

[7] Pools providing secondary control reserve have to show a first reaction to the secondary control activation signal of the TSO within 30 seconds, at the latest.

[8] Disregarding simultaneity effects it can be assumed that the frequency is identical at every point of a synchronous grid

linear ramp. This follows a static relation to the frequency with ±20 mHz meaning no activation at all and ±200 mHz a full activation of the contracted control reserve at each individual unit. (UCTE, 2009, pp. 4–11)

Principles of secondary control reserve

Secondary control reserve is used to balance the power system within each TSO's control area, counteract the area control error, replace primary control and restore scheduled interconnector flows. Secondary frequency control is activated centrally and automatically by the TSOs through a load-frequency control. In Germany, this is performed jointly through the GCC. Activation signals are sent to the units from the TSOs using the merit-order principle and a merit-order list server (MOLS). Activated units have to respond within 30 seconds and have to be fully activated within five minutes. The dimensioning of secondary control reserve is carried out for secondary control reserve and tertiary control and will be explained in chapter 3.2.3. (UCTE, 2009, pp. 5–24)

Principles of tertiary control reserve

Tertiary control, also called minute reserve in Germany, initially complements secondary control reserve and ultimately replaces it. After the dispatch signal, tertiary control reserve has to be fully activated in 7.5 to 15 minutes, depending on the time of activation. The decision for dispatch is made manually at the TSOs grid control centre. Although this decision is made by the person in charge at the control centre, it is recommended by the TSOs own operational rules whenever more than 60 % of the secondary control is activated (M. Stobrawe, personal communication, 2012). Since 2012, the activation signal is transmitted to the units electronically using the merit-order principle and a merit-order list server (MOLS). (UCTE, 2009, pp. 25–28)

3.2.3 Demand for control reserve

Dimensioning of primary control reserve – Dimensioning with the Graf-Haubrich-methodology

In the ENTSO-E RG CE synchronous area 3000 MW of primary control reserves are procured in total. This provides enough capacity for the outage of the two largest generators in the power system (n-2). The required capacity is split between all TSOs according to their annual peak load. The German TSOs for example had to procure 568 MW in 2014 (50Hertz

Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH, 2015a). The necessary amount for the German TSOs is procured on regelleistung.net (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015). (UCTE, 2009)

Principles of dimensioning of secondary and tertiary control reserve

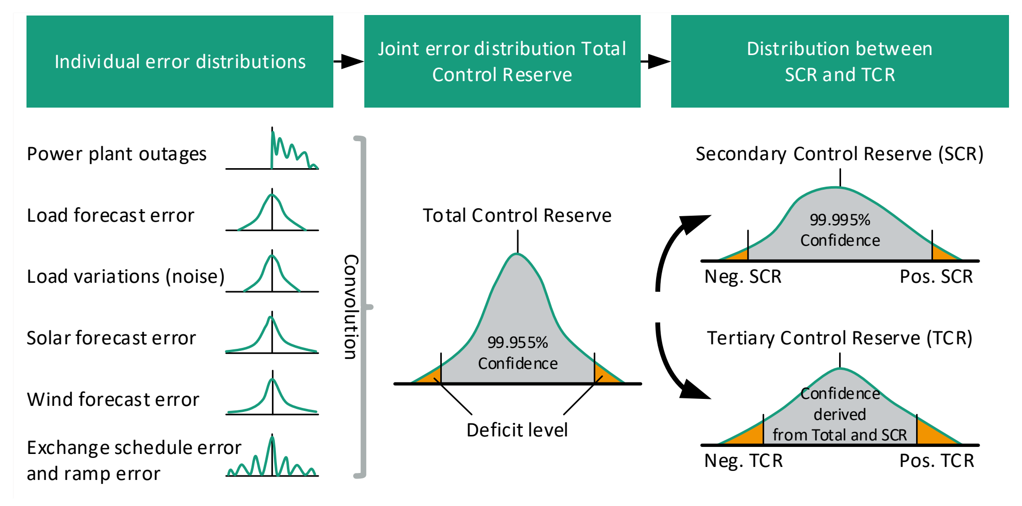
Germany has a probabilistic approach for the dimensioning of the secondary and tertiary control reserve demand, which is named the Graf-Haubrich-method. The principle of this method is the calculation of control reserve demand based on previous imbalances. The calculation is carried out every three months (in March, June, September and December) for the next three months using data from the last four years. The same quarter of each of the past years is selected for the dimensioning of the upcoming quarter[9]. Based on this data a joint probability density functions for different imbalances is generated. In the Graf-Haubrich-method different sources of imbalances (load forecast error, power plant outages, etc.) are convoluted to a probability density function that represents the probabilities for the occurrence of all different imbalances. The method assumes stochastic independency of the different imbalances, allowing the application of the mathematical operation of convolution to generate a joint probability density function. The principles are depicted in Figure 3-9. (Maurer, Krahl, & Weber, 2009)

Defining the level of significance and distribution between secondary and tertiary control reserve

When deficit and surplus probabilities are defined, they can be applied to the probability density function as levels of significance. These levels of accepted deficit for both negative and positive control reserve allow the calculation of the required amounts of control reserve. The chosen deficit levels are 0.0225 % (Consentec, 2010, p. 21) for secondary and tertiary control reserve together. This deficit level is distributed into deficit levels for secondary and tertiary control reserve individually. The deficit levels for the tertiary control reserve are derived from the total deficit level and the deficit level of secondary control reserve. Currently the deficit level for secondary control reserve is 0.0025 % (Consentec, 2010, p. 21). Due to this level of significance,

[9] This means that the dimension for the second quarter of 2015 includes data from the second quarter of 2011, 2012, 2013 and 2014

deficits may occur where the available control reserve is insufficient to meet needs. A deficit may also occur if there is sufficient total control reserve but it can only be activated with a time delay (Maurer et al., 2009, p. 5). Figure 3-9 shows the principles of this dimensioning process. (Consentec, 2008, 2010)



Source: adapted from (Consentec, 2008, 2010; Jost, Braun, & Fritz, 2015)

Figure 3-9: Classification of different sources of imbalances, calculation of total control reserve demand and separation into secondary and tertiary control reserve and their required confidence levels

Individual imbalances

In order to create a joint probability density function all occurring imbalances will have to be accounted for. Deviations may occur on different time horizons, as some will have a noise characteristic and fluctuate within the balancing period of fifteen minutes. According to (Maurer et al., 2009), the influencing factors for the dispatch of control reserves can be classified as following:

- Power plant outages: Unplanned outages of thermal power plants can be characterized by power plant availability statistics. Unplanned outages usually require the activation of secondary reserve after the event. They only contribute to the positive reserve demand.

- Load variations and load forecast error: The stochastic behaviour of consumers is the deviation of the sum of consumers from the standard load profiles (SLP). It requires the dispatch of secondary control reserve for its noise characteristics and tertiary reserves for consistent deviations, such as temperature induced behaviour that is not represented in the SLP. Data availability is an issue

- Forecast error of fluctuating RES generation: Similar to load variations due to the stochastic behaviour of wind and solar forecast errors. Deviations that have not been forecasted before gate closure have to be counteracted by activation of control reserve.

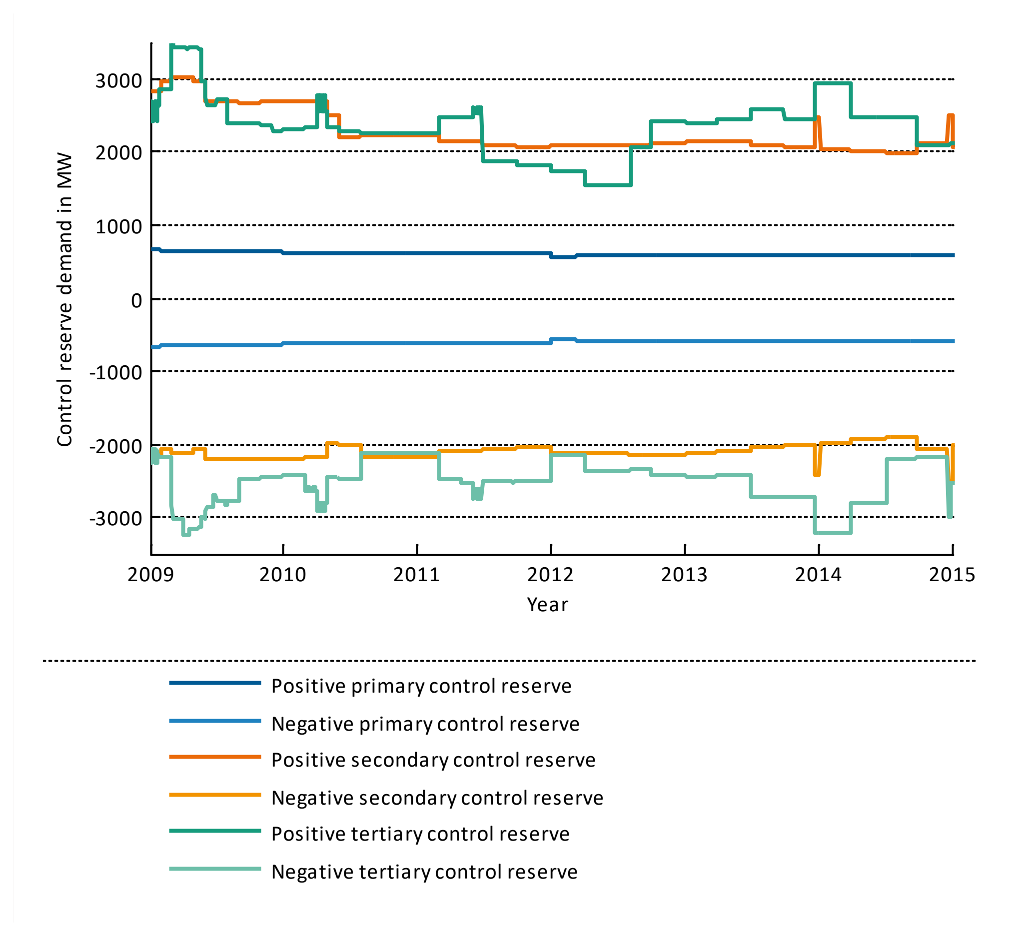
- Exchange schedule error and ramp error (also called schedule step error): Forecasting errors of cross-border trading could result due to physical reasons as infeed in lines are ramped over a longer period of time. This applies for the ramping characteristics of power plants. Secondary control reserve is needed to balance these deviations.

Developments of the control reserve demand

Depending on the development of these imbalances, the entire demand for control reserve might change. With an increasing share of fluctuation RES in the power system challenges may arise as discussed in (Dany, 2001; Hamon & Söder, 2011; Holttinen et al., 2009; Jónsson, Morales Gonzalez, Zogno, Madsen, & Otterson, 2011; Matos & Bessa, 2011). Dobschinski et al. (2010) have investigated the influence of the wind power forecast error. They conclude that one of the best ways to reduce the control reserve demand is to increase the quality of the wind power forecast. This can be generalized to all the aforementioned sources of imbalances. The doctoral thesis of Weißbach (2009, pp. 77–94) proposes the necessary changes to decrease the schedule step errors.

Development of control reserve volumes

Figure 3-10 shows the results from dimensioning of control reserve for all three control reserve types since 2009. The procured volumes have changed over time. The decline in the procured amounts is mainly due to smaller errors in the different imbalance types and the introduction of the GCC in 2010 (50Hertz Transmission GmbH et al., 2011b). The different errors have declined due to better RES forecasts, shorter gate closure times for trading and increased incentives through the imbalance mechanism.



Source: Own analysis based on (50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH, 2014)

Figure 3-10: Tendered amount of primary, secondary and tertiary control reserve

3.2.4 Procurement and price development

Control reserve market access for capable units

This chapter provides information on the current market design. Complying with these rules would enable generators and consumers to participate in the market. Usually large thermal and hydro power plants, pumped hydro storages and loads provide control reserves. Recently smaller biomass power plants have also gained in importance (Consentec, 2014, p. 12).

Procurement procedure

The German TSOs, partially in cooperation with neighbouring countries, procure control reserve on a joint internet platform www.regelleistung.net. An invitation to tender is published for the required amounts of each control reserve individually. The specific call characteristics are presented in chapter 3.2.4.1. Market participants have to complete a nonrecurring prequalification process and sign framework contracts before they are allowed to participate in the auction of each market segment. The conditions to successfully complete the prequalification are presented in chapter 3.2.4.2. The list of all prequalified providers for each type of control reserve can be accessed on www.regelleistung.net[10]. The auction results are published anonymously on www.regelleistung.net. (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

3.2.4.1 Product specifications

Control reserve product types

In total five different control reserve products are tendered. Primary control reserve is procured symmetrically, which means that positive and negative reserves are procured together. Each bid in the auction will have to be able to deliver the same amount of positive and negative control reserve. Primary control reserve is tendered for a whole week (product length is one week (Monday to Sunday)). Secondary and tertiary control reserve is procured separately where the supplier of control reserve bids delivers either negative or positive control reserve. Additionally it is differentiated between negative and positive secondary control and peak and off-peak time, similar to the energy exchange. The product length for secondary control reserve is one week. Negative and positive tertiary control reserve is tendered in blocks of four hours each (product length) on weekdays. This means that on Fridays, it is procured for Sunday and Monday. The same principle applies to public holidays. (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

[10] https://www.regelleistung.net/ip/action/static/provider

	Primary control reserve	Secondary control reserve	Tertiary control reserve
Auction time	Weekly (10:00 on Tuesdays for the next week)	Weekly (10:00 on Wednesdays for the next week)	Daily, only on weekdays (10:00 for next day and following weekend or holidays)
Product delivery time period	One calendar week (Monday to Sunday)	Peak (Monday to Friday from 8:00 till 20:00) or off-peak(Monday to Friday from 0:00 till 8:00 and 20:00 till 24:00 as well as weekends and national holidays from 0:00 till 24:00) of one calendar week	4 h blocks (6 time slices per day, 00:00-04:00, 04:00-08:00, 08:00-12:00, 12:00-16:00, 16:00-20:00, 20:00-00:00)
Product type	Positive and negative reserve in one product	Positive and negative reserve separated	Positive and negative reserve separated
Minimum bid size	≥ 1 MW symmetrical positive and negative reserve	≥ 5 MW	≥ 5 MW
Minimum bid increment	1 MW	1 MW	1 MW
Payment scheme	Capacity price (Pay-as-Bid)	Capacity and energy price (Pay-as-Bid)	Capacity and energy price (Pay-as-Bid)
Number of prequalified providers (by November 2015)[11]	19	33	44

Source: Own analysis based on (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

Table 3-4: Control reserve product specifications and tender conditions

Pooling and Payment scheme

Providers of all three types of control reserve have to be able to deliver control reserve according to the offered capacity over the entire product length. Pooling is allowed within the control area between different prequalified units. Units can be changed freely for every 15-minute interval (FNN, 2009, pp. 13–14). The bids placed by the market participants have to contain the amount of control reserve, the capacity price and the energy price. The TSOs accept the bids with increasing capacity prices until the required amount is reached (the award criterion). The capacity price is paid

[11] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, and TransnetBW GmbH (2015)

if the participant is awarded with the capacity. Control reserve units are dispatched in increasing order of the energy price. Upon activation, the energy price is paid to the market participant. Energy prices are only paid for secondary and tertiary control reserve. All payments on the control reserve market have the pay-as-bid principle applied, while the energy exchange markets have the marginal price principles applied. Differences between the two pricing methods can be seen in (Cramton, 2009; Guerci & Rastegar, 2013). (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

3.2.4.2 Requirements for market participation

Prequalification process

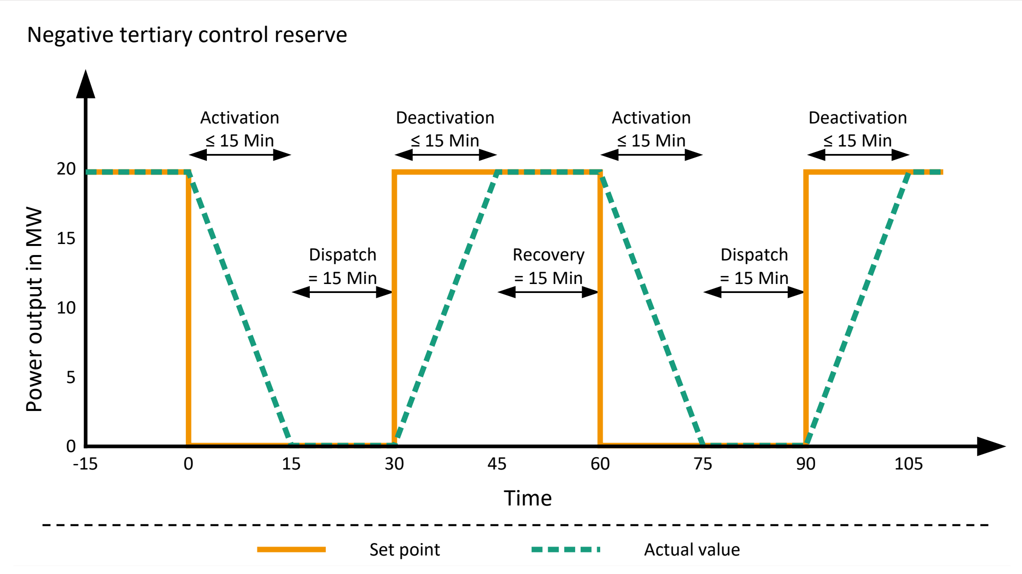
The main requirement to access the control reserve market is the successful completion of a prequalification process. The prequalification process allows potential providers of control reserve to demonstrate their ability to operate in the market and comply with all technical, financial and operational requirements. This process usually takes no less than two months since it involves the submission and review of all required prequalification documents[12]. One important organisational requirement is the constant availability of a contact person for the TSO during the provision of control reserves. (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

Model protocol

For each technical unit (i.e. the individual units providing control reserve) the potential provider of control reserve has to demonstrate technical capabilities where the unit is tested using a model protocol which resembles the dispatch of control reserve. Figure 3-11 shows the protocol adapted for the negative tertiary control reserve. Model protocols for the other market segments can be accessed on regelleistung.net (50Hertz Transmission GmbH et al., 2014). This model protocol also explains how the market participant

[12] All important documents regarding the prequalification process can be found regelleistung.net: https://www.regelleistung.net/ext/static/prequalification

can prove the delivery of control reserve to the system for the TSO. (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)



Source: translated from (50Hertz Transmission GmbH et al., 2014)

Figure 3-11: Model protocol for the prequalification of a technical unit for negative tertiary control eserve

Operational issues

All three types of control reserve can also be provided by pools of several units. Pooling is permitted within one control area. Pooling outside the control area is only permitted for secondary and tertiary control reserve if the minimum bid size could not be reached otherwise. The providers have to ensure that their offer is delivered when needed by the TSO. A very high degree of availability is required for the entire product length. The framework contracts require 100 % availability (50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH, 2015a, 2015b, 2015c) although this will not be possible with a technical system. The market participant has to provide backup capacity. This capacity backs up either 20 % of the tendered capacity or the loss of the two largest units in the pool (n-2 backup). (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

Procedure in the case on non-fulfilment

In the case that the provider is not able to fulfil this requirement the TSO is allowed to cancel payments for missing capacity (lack of availability) or energy (lack of energy during dispatch). The market participant is held liable for any additional costs for appropriate substitution caused by its action.

Continuous breaches of contract within one year will allow the TSO to charge the market participant a contractual penalty (50Hertz Transmission GmbH et al., 2015a, 2015b, 2015c). Continuous non-compliance may result in the withdrawal of the prequalification. (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2015)

Communication prerequisites

Providers of primary and tertiary control reserve have to submit online data and additional information to the TSO about the status of units providing control reserve. Providers of secondary control reserve have additional and more demanding requirements. The communication infrastructure needs to feature e.g. redundant communication channels and quick control cycles (maximum four seconds). Detailed requirements are available at regelleistung.net (50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH).

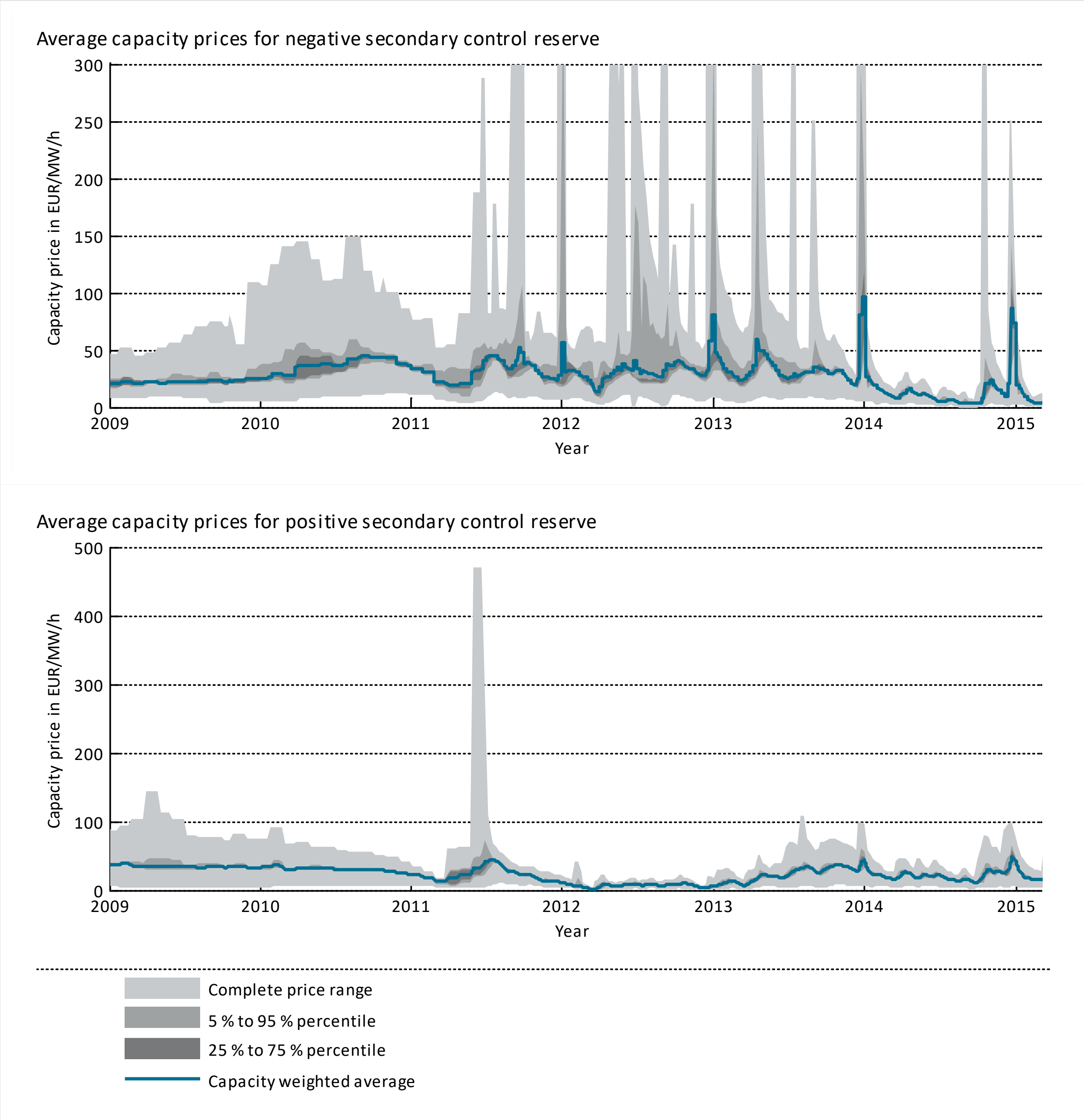
3.2.4.3 Development of control reserve prices

Control reserve market prices

The prices of all primary, secondary and tertiary control reserve products are presented in the following graphs using a common price unit. For the capacity prices, EUR/MW/h is used. For the energy prices, EUR/MWh is used. Prices vary significantly between the different control reserve types and product delivery time periods. Since the primary control reserve market will not be focussed on in the thesis, market prices are only displayed for secondary and tertiary control reserve markets.

Capacity prices in the secondary control reserve market

The capacity prices of the secondary control reserve market are shown in Figure 3-12. The top half illustrates the capacity prices for the negative secondary market whereas the lower half is for the positive reserve market. The figure shows the capacity-weighted average capacity prices (blue line) and the complete price range of accepted bids (shades of grey). This is necessary to account for the bay-as-bid pricing mechanism. The lighter grey shows the entire price range, the medium grey area gives the price range between the 5 % and 95 % percentile, and the darkest area is for the 25 % to 75 % percentile. For better readability, the graphs only display a limited range of data. The highest capacity price observed in the negative secondary control reserve market was 1969 EUR/MW/h during Christmas 2012. The highest capacity price observed in the positive secondary market was 470 EUR/MW/h in spring 2011. The presented prices are one-week moving average prices for peak and off-peak products simultaneously.

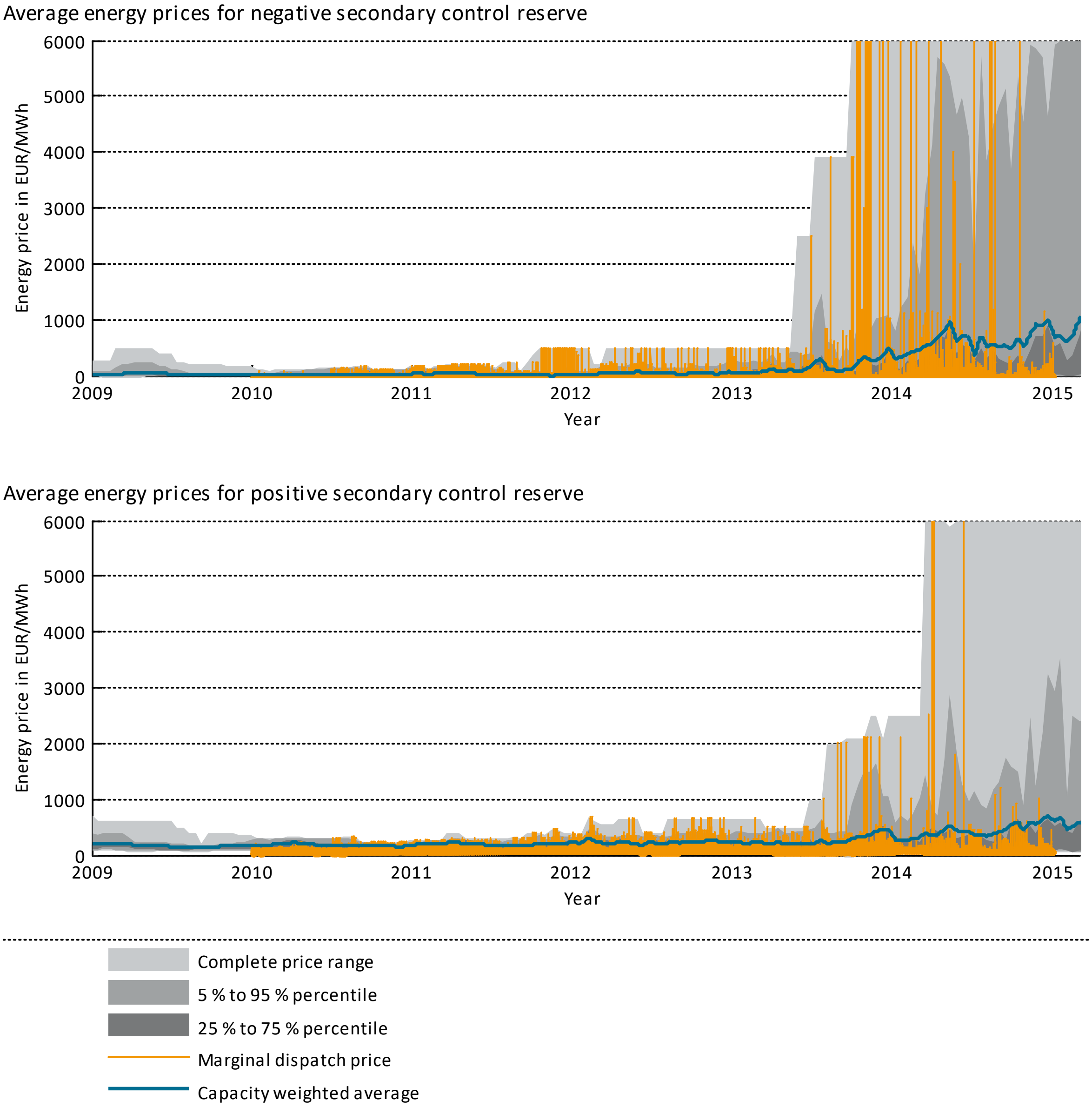


Source: Own analysis based on (50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH, 2015d)

Figure 3-12: Weekly average capacity prices of the secondary control reserve market

Energy prices in the secondary control reserve market

The energy prices are shown in a similar fashion, extended by the marginal price of the dispatch as an orange line. The prices are displayed for a seven-day average. The dispatch prices are based on a 15-minute average dispatch of secondary control reserve, rather than the four-second data. Higher resolution data would lead to higher marginal prices, even though they would only be reached for a short time and thus would not cause high costs due to the low energy contents. Maximum energy prices reached 6666 EUR/MWh in the negative and 7995 EUR/MWh in the positive secondary market.

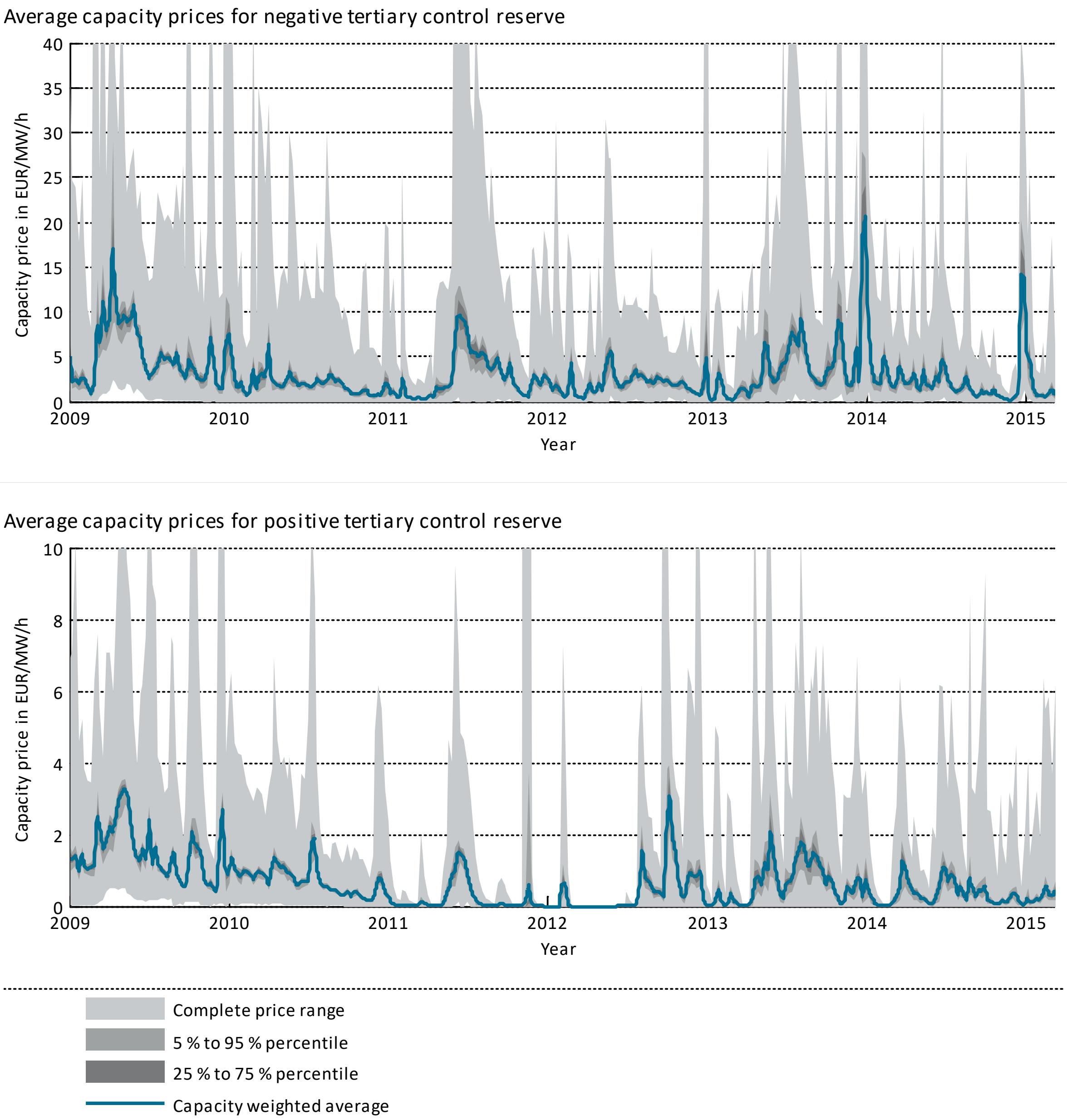


Source: Own analysis based on (50Hertz Transmission GmbH et al., 2015d)

Figure 3-13: Weekly average energy prices of the secondary control reserve market and marginal price of dispatch

Capacity prices in the secondary control reserve market

The capacity prices of the tertiary control reserve market are illustrated in Figure 3-14, although the capacity price does reach higher prices than shown. The highest capacity price in the tertiary control reserve was 124 EUR/MW/h reached in December 2010. In the positive market prices reached 158 EUR/MW/h. This seemed to be a one-off event since the next highest price was 20 EUR/MW/h.

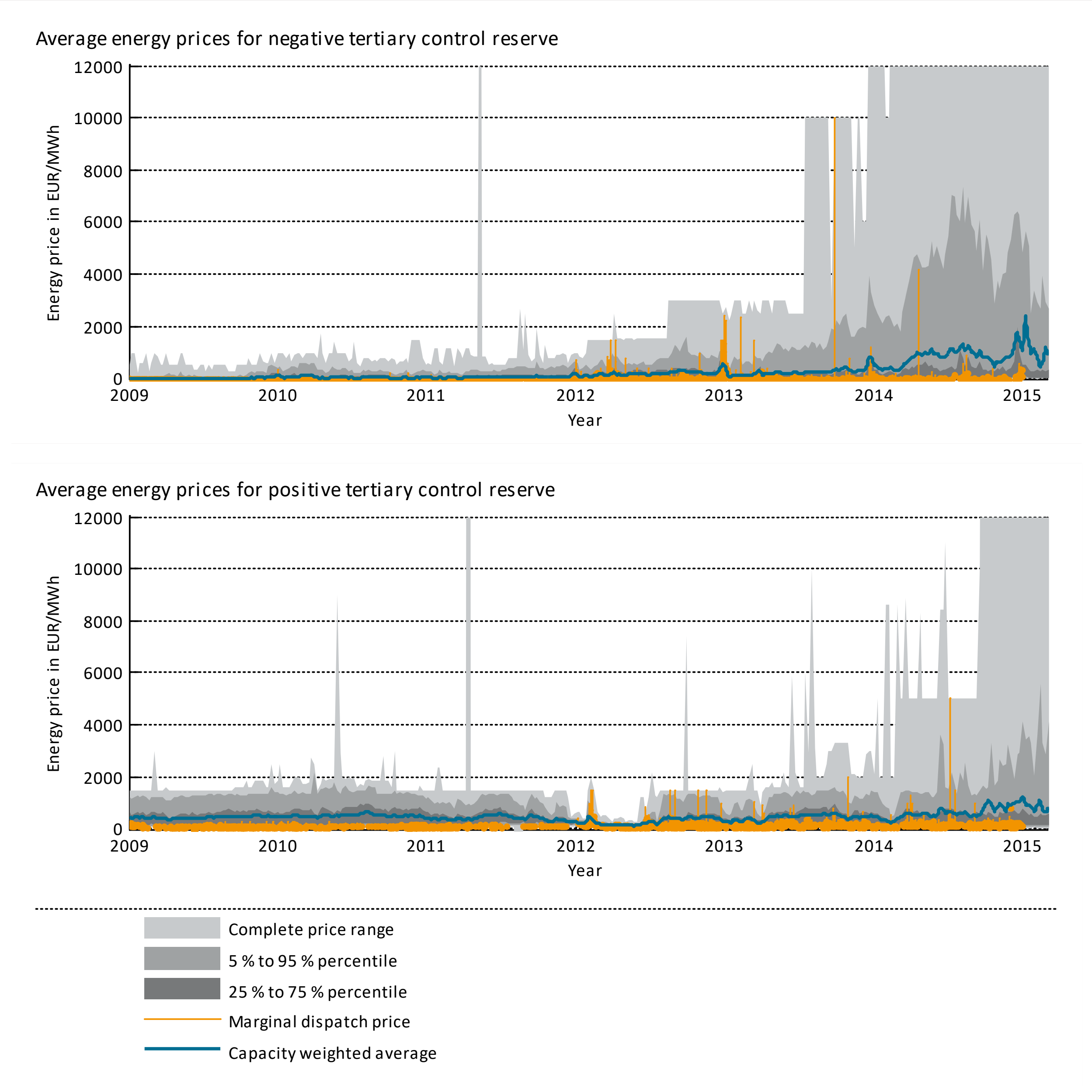


Source: Own analysis based on (50Hertz Transmission GmbH et al., 2015d)

Figure 3-14: Weekly average capacity prices of the tertiary control reserve market

The energy prices in the tertiary control reserve market are shown in Figure 3-15. The prices are displayed for a seven-day average. Maximum energy prices soared up to 202,000 EUR/MWh several times in the negative control reserve market, while in the positive tertiary market 93,882 EUR/MWh was reached in a single event. By the end of 2014 a maximum price of 40,000 EUR/MWh was reached continuously as maximum price.

Energy prices in the tertiary control reserve market



Source: Own analysis based on (50Hertz Transmission GmbH et al., 2015d)

Figure 3-15: Weekly average energy prices of the tertiary control reserve market and marginal price of dispatch

Conclusion on market prices

The previous figures depicting the capacity and energy prices in the secondary and tertiary control reserve market revealed a high volatility in prices. If price patterns were explicable with fundamental analysis tools, they would follow developments on the spot markets. The sudden and high price peaks that slowly fade out imply that the market participants perform strategic bidding. The competition in the market has led to decreasing capacity prices in all market segments whilst very high increases in the energy prices can be observed. This increase in the spread of the complete price range in 2013 as well as the increase of the average price can be observed in the negative secondary and tertiary markets. This is mainly due to the opening of the control reserve market in 2011 by the regulator (Bundesnetzagentur, 2011e) and the subsequent introduction of market participants with different bidding strategies. Since the energy prices are not part of the award criterion, they can be set to any price, which could encourage strategic bidding.

3.2.5 Renewables in the control reserve markets

Changing market environment and transformation process for the integration of fluctuating RES

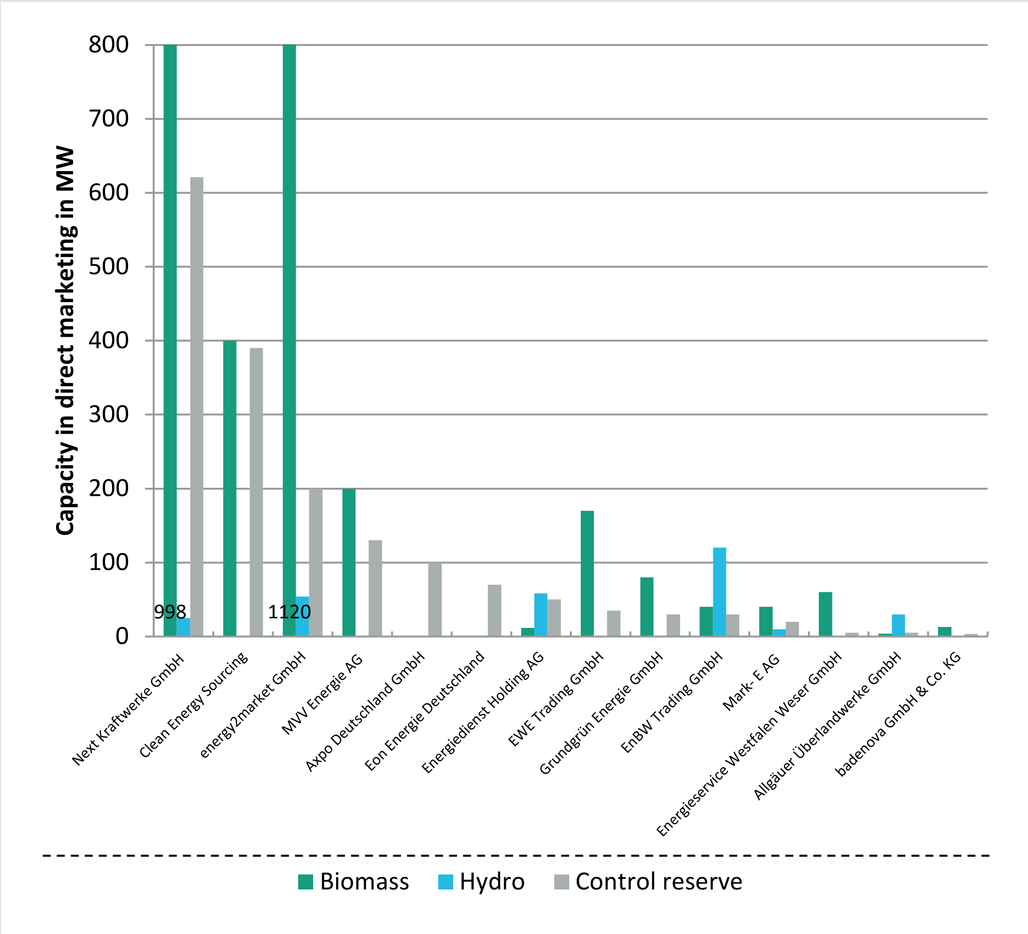
Market prices in the control reserve are highly influenced by its framework conditions. The price development is highly volatile as it can be seen in chapter 3.2.4.2. The pooling of virtual power plants (VPP) as well as the 2012 amendment of the EEG introduced the market premium model for RES generators. Through this direct marketing scheme, the market was opened for RES generators, including the control reserve markets. This has led to decreasing prices and increased competition, especially in the negative tertiary reserve market. Additionally the Federal Network Agency facilitated easier market participation by reducing tender periods and product lengths (Jansen, 2014; Jansen, Schneider, Siefert, & Widdel, 2014; Jansen & Speckmann, 2013a; Jansen, Speckmann, & Baier, 2012, Jansen, Speckmann, Harpe, & Hahler, 2013, 2013; Jansen, Speckmann, Schneider, & Siefert, 2013; Jansen, Speckmann, & Schwinn, 2012; Rohrig et al., 2013).

The regulator is determined to decrease the necessary must-run capacities due to control reserve market design issues which currently account for up to 25 GW of must-run capacity, as stated in FGH, Consentec & IAEW (2012, p. 1) or 19.9 GW as shown in Grünwald, Ragwitz, Sensfuß and Winkler (2015, p. 107). Much more recently the Federal Ministry of Economic Affairs and Energy (BMWi) has issued the Green Paper "An Electricity Market for Germany's Energy Transition" in October 2014 (Bundesministerium für Wirtschaft und Energie, 2014) to change the market for electricity. This will most likely lead to changes in the electricity market design demanding more flexibility from the market participants. Control reserve markets are one of many aspects in the subsequent white paper published in July 2015 (Bundesministerium für Wirtschaft und Energie, 2015b). In this context, it is necessary that fluctuating RES can provide ancillary services.

Reducing must-run capacity

According to a survey by the industry magazine Energie&Management (English: Energy and management) (Energie&Management, 2015b) more than 45 direct marketers are active in bringing RES to the energy markets under the market premium model in the EEG. In January 2015 more than 45,000 MW were marketed in this scheme, including wind farms, photovoltaic systems, biomass plants and hydro power plants. All data provided is by the companies and may show inconsistencies when added up. Contracted capacities are particularly likely to be exaggerated. In total approximately 1,690 MW of control reserve from renewable energy sources is available. Due to the lack of prequalified units of fluctuating RES, the capacities are provided by biomass plants and hydro power plants only. Figure 3-16 shows the portfolios of those direct marketers that have biomass and/or hydro power plants and that participate in the control reserve market. (Energie&Management, 2015a)

Current situation of controllable RES in the control reserve market



Source: Own analysis based on (Energie&Management, 2015a)

Figure 3-16: Selection of portfolios with direct marketing of RES and prequalified units for the provision of control reserve

Distribution of units to different technologies and markets

A previous study (Lange et al., 2014, p. 13) claims that approximately 1,050 MW of RES are prequalified for participation in the control reserve market. Furthermore, the authors state that 230 MW of this capacity is from hydro power plants. This is in line with the numbers from (Energie&Management, 2015a) where 298 MW of hydro power plants were in direct marketing. It can be safely assumed that most of the capacity is able to provide control reserve. Taking this into account and using the updated data from (Energie&Management, 2015a) the total number of biomass plants delivering control reserve is approximately 1460 MW. This would account for 36 % of all directly marketed biomass plants. Lange et al. assume that 20-30 % of the capacity is prequalified as secondary control reserve; the rest is prequalified as tertiary control reserve only. This finding can be confirmed by looking at Schäfer-Stradowsky et al. (Schäfer-Stradowsky et al., 2014, pp. 19–20). From the authors' findings, one can conclude that the ratio of positive to negative prequalification is 5 % whereas the ratio of secondary to tertiary control reserve is 42 %.

Market structure cannot be analysed precisely

Schäfer-Stradowsky et al. (Schäfer-Stradowsky et al., 2014) have surveyed the participation of controllable RES in the control reserve market. Based on the responses to the questionnaire the authors state that 378 MW (960 units) of Biomass plants are prequalified. The author states that due to a lack of responses to the questionnaire the actual number is likely to be higher, although the returned questionnaires have led the author to state that additional capacity will be prequalified in the near future. This would increase the prequalified capacity to 1,150 MW. The sources in Lange et al. (2014), Schäfer-Stradowsky et al. (2014) and Energie&Management (2015a) state different numbers for the capacity. It is apparent that the market is dynamic and has seen continual significant growth over the past. It is also not easily identifiable which contribution can be allocated to individual market players.

LichtBlick delivers control reserve with a pool of micro-CHP

The German green energy provider LichtBlick SE has developed a system to deliver secondary control reserve with a large number of micro-CHPs, called "Schwarmstrom" (English: swarm electricity). In this concept, more than 400 home-installed CHPs are connected through an ICT solution (information and communications technology). The first delivery of control reserve was performed in April 2015. For prequalification LichtBlick did not follow the standard procedure of prequalifying each individual technical unit. (LichtBlick SE, 2014)

Type base prequalification

Together with the TSOs new approaches were developed. Prequalification was granted based on the type of the technical unit, also called type prequalification. Previously, technical units were admitted to the market individually, since they were different each time. In order to achieve high levels of reliability the pool concept is examined and tested thoroughly. Communication links to the individual micro-CHPs are realized using GSM connections (GPRS) (LichtBlick SE, 2014, p. 20). This is also a novelty in the area of secondary control reserve provision. (LichtBlick SE, 2014, 2015)

Statkraft delivers negative tertiary control reserve with wind farms

Statkraft Markets GmbH delivered negative tertiary control reserve with the German wind farm Dornum in January 2015 after accomplishing prequalification. The prequalified capacity is 5 MW, the minimum bid size. The proof method for the delivery was the same as for any other unit in the market, generating energy losses for the wind farms. Statements on the level of reliability have not been issued. (Statkraft Markets GmbH, 2015)

Upcoming market changes

Towards the end of 2015 the German TSOs announced the allowance of prequalification of wind turbines in the negative tertiary control reserve market within a pilot project (50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH, 2015b). Wind farms will be prequalified using the available active power proof mechanism (see chapter 3.3.3.1). In addition to this, the BNetzA has started a consultation process on possible market changes in the secondary and tertiary control reserve markets (Bundesnetzagentur, 2015). The proposed changes envision the introduction of "energy-only" short-term balancing markets with a gate closure time of 25 minutes before physical delivery. The secondary control reserve market will have a product length of four hours or less and daily tendering, according to the discussed changes. For the tertiary control reserve market, daily tendering is also proposed.

3.3 Current state of research

Introduction

This chapter will give an overview of the current state of the research. This mainly includes the delivery of control reserve and the market design as well the creation of probabilistic forecast for wind power plants and photovoltaic systems.

3.3.1 Relevant literature on the provision of control reserve to the control reserve markets by RES generators

Thesis Gesino on control reserve from wind farms

The doctoral thesis of **Gesino** (2011) explains the fundamentals of control reserve provision by wind farms. Gesino describes a methodology to calculate wind power forecasts at different levels of reliability. This approach takes into account the forecast errors of wind power forecasts in order to deduct a defined amount from the forecast (Gesino, 2011, pp. 78–80). This increases the level of reliability of a given forecast. Gesino proves in his thesis that wind farms can be regulated in a controlled manner, following a given set point (Gesino, 2011, pp. 99–119).

Thesis Speckmann on potentials for the delivery of control reserve by wind farms

The doctoral thesis of **Speckmann** (2016) deals with the potentials for the provision of control reserve from wind farms. In this thesis, potentials for the delivery of control reserve have been presented. The results on potentials were created by Malte Jansen in a joint research project with the REBal model, presented in this doctoral thesis. The thesis describes how Malte Jansen calculated the potentials for the delivery of control reserve with the help of a kernel density estimator. The kernel density estimator proves to be a more precise tool to create probabilistic forecasts for fluctuating RES than the methodology presented by Gesino (Speckmann, 2016, pp. 65–66). A probabilistic forecast has at least a set of two values. One value is the predicted power and the other one is the probability that which the predicted power will be reached. Speckmann also presents a new method to prove the delivery of control reserve using the available active signal of a wind farm rather than the announced schedule (Speckmann, 2016, pp. 67–75).

Doctoral thesis of Braun, Papers by Frunt et al and Kapetanovic et al. on technical and economic potentials for the delivery of ancillary services by controllable RES generators

The doctoral thesis of **Braun** (2009) investigated the technical and economic potentials of controllable distributed generators under a FIT scheme delivering control reserve. Braun has focussed on frequency control (i.e. control reserve) and voltage control. For this thesis, the economic potentials are of interest. Using a cost-benefit analysis, he concludes on the issues of profitability that controllable distributed generators are most likely to operate in negative secondary and negative tertiary control reserve markets (Braun, 2009, p. 61). In the paper of **Frunt, Kechroud, Kling and Myrzik** (2009) the potential of different decentralized generators (DG) in the control reserve market is investigated. They state that participation is unprofitable for generators receiving a FIT. They conclude with suggestions for regulatory changes to open the market for DG (Frunt et al., 2009, p. 6). **Kapetanovic, Buchholz, Buchholz and Buehner** (2008) come to the same finding and emphasize the effects that the European market integration will have an influence on the potentials of DG (Kapetanovic et al., 2008, p. 458).

Paper Pinson et al. on probabilistic wind power forecasting

In **Pinson** (2006) a methodology is presented to generate accurate forecasts of wind generation. It is shown that forecasts can be accompanied with information on their uncertainty. The methodologies laid out in this thesis allow the application to ancillary services (Pinson, 2006, p. 154). In Pinson, Chevallier and Kariniotakis (2007) short term wind power forecasts are used for trading in the Dutch electricity spot market using probabilistic forecasts, with confidence intervals ranging from 10 % to 90 % (Pinson et al., 2007, p. 6).

Paper Papaefthymiou on additional income for offshore wind in negative tertiary control reserve market

A research paper by **Papaefthymiou et al.** (2015) presents the potential income of offshore wind farms in the German control reserve markets. The authors implement a methodology that is similar to the methodology in this thesis. They conclude that offshore wind farms are able to generate additional income in the negative control reserve market and will be able to do so in the future (Papaefthymiou et al., 2015, p. 5).

Paper Kirby et al. on economics of control reserve provision in Texas

In **Kirby, Milligan and Ela** (2010) the economics of the provision of control reserve from wind farms were assessed for different control areas in the United States. Following the market structure, the authors use an opportunity cost approach for market participation. As a consequence of this approach the wind turbines compete in the market with conventional generators. The authors state that the provision from wind is an economical option for some hours of the year and that market rules are a barrier to the provision (Kirby et al., 2010, p. 1). They also state that wind power forecasts have to be developed further (Kirby et al., 2010, p. 8), which is a challenge for researchers according to **Yuen, Oudalov and Timbus** (2011).

Paper Andersen et al. on control reserve provision from wind farms in Eastern Denmark

In **Andersen, Strom, Tang, Davidsen and Dupont** (2012) the participation in the eastern Denmark (Market DK2) negative manual activation reserve market is described for a 21 MW wind farm. For the offer calculation, deterministic forecasts were used. The Danish manual activation reserve market has a lead-time of one hour and, unlike the German reserve market, is an energy only market. It was shown that under the Danish conditions wind farms could provide balancing energy reliably and economically (Andersen et al., 2012, p. 26).

Saiz-Marin, Garcia-Gonzalez, Barquin and Lobato (2012) and **Saiz-Marin, Lobato and Linares** (2012) describe the creation of offers where a fixed share of the forecast is subtracted, determined by risk assessment. The offered amount is set to 10 % of the wind power forecast (Saiz-Marin, Garcia-Gonzalez et al., 2012, p. 870). The participation in the control reserve market is also assessed. The concept presented for the provision matches the concept used for the Spanish demonstration in the project TWENTIES.

Paper Saiz-Marin et al. on the use of wind farms for ancillary services in the TWENTIES project

A dispatch simulation by **Tuohy, Brooks, Ela and Kirby** (2012) shows the opportunities for the provision of control reserve by wind farms in a 2020 scenario. The authors state that wind farms should not provide more than 20 % of the procured reserve, as the economic gain at this value appears optimal (Tuohy et al., 2012, p. 5).

Paper Tuohy et al. on reserve provision in a 2020 scenario

In a study by **Consentec, r2b and FGH** (2011) it is shown that fluctuating RES have a high potential for the provision of control reserve, especially at times when conventional generation has a very low production (Consentec et al., 2011, pp. 105–106). The participation of fluctuating RES however is hindered by current market regulations in Germany. Consentec et al. also state that for the provision of control reserve conventional generation that otherwise would be disconnected has to stay connected to the grid (Consentec et al., 2011, p. 105). The capacity of these must-run power plants is estimated to be between 8 GW and 25 GW (FGH et al., 2012, p. 1).

Policy study on the future of control reserve and identification of must-run capacity through inefficient market design

A different study by **Consentec** (2011) showed an approach to calculate the impact of dispatchable renewable energies on the control reserve market (Consentec, 2011, p. 21). This approach uses a hindcasting approach to calculate the effects on the market.

Policy study on controllable RES in the market

Zhang, Sun and Cheng (2013) have investigated the possible participation of wind farms in regulation markets in California. Regulation markets are ancillary services markets similar to control reserve markets in Germany.

Paper Zhang et al. on the selection of the right market

Zhang et al. incorporate a stochastic approach for the wind power forecast and the expected market prices. The wind forecast errors were generated using an auto-regressive moving average (ARMA) model for wind speeds and a power curve. It was concluded that participation in down-regulation is more beneficial than up-regulation (Zhang et al., 2013, p. 886). The authors also state that power markets and ancillary service markets are different in Europe to the ones in the United States and propose to use different bidding strategies for these markets (Zhang et al., 2013, p. 894).

Papers Morales et al. and Zugno et al. on minimizing price risks for producers

Morales, Conejo and Perez-Ruiz (2010) have developed methodology to bid wind energy to the MIBEL spot market and reduce the risk of price volatilities through an auto-regressive model. **Zugno, Pinson and Jónsson** (2010) presented a bidding strategy for wind energy in the NordPool spot market. Both author teams used probabilistic forecasts of wind farms for their optimisation strategies.

Previous publications of the same author of this doctoral thesis

Previous publications on the provision of control reserve were made by the author of this doctoral thesis on several occasions (e.g. (Brauns et al., 2014; Hennig et al., 2014; Jansen, 2014, Jansen & Speckmann, 2013a, 2013b; Jansen, Speckmann, Harpe et al., 2013; Rohrig et al., 2013)). These publications include the participation of wind farms and PV systems in the negative control reserve markets. The modelling approach in this thesis was developed in those papers. The model has also been used to assess the impact of controllable generation. A description of the publications can be found at the end of this thesis.

Classification of approaches in the literature

The following table classifies the aforementioned approaches according to their topics. It can be seen whether a source covers wind energy or not, whether it is addressing control reserve, market participation, stochastic bidding, possible income for the generators and the impact on the market.

Author / Highlights	Wind / PV /Others	Control reserve	Market participation	Stochastic	Income potentials	Cost saving potentials
Gesino (2011): Calculation of wind power forecasts at different levels of reliability. Wind farms can be regulated, following a set point	Wind	Yes	No	Yes	Yes	No
Speckmann (2016): Potentials for the provision of control reserve from wind farms. New method to prove the delivery of control reserve using the available power signal	Wind	Yes	No	Yes	Yes	No
Braun (2009): Technical and economical potentials of controllable distributed generators	Wind, PV & others	Yes	Yes	No	Yes	No
Frunt, Kechroud, Kling, and Myrzik (2009): Potentials of different decentralized generators in the control reserve market, participation unprofitable with FIT	Wind, PV & others	Yes	Yes	No	Yes	No
Kapetanovic, Buchholz, Buchholz, and Buehner (2008): Participation unprofitable for generators receiving a FIT; European market integration will have an influence on the potentials of DG	Others	Yes	Yes	No	Yes	No
Pinson (2006): Generate accurate forecasts of wind	Wind	No	No	Yes	No	No
Pinson, Chevallier, and Kariniotakis (2007): Short term probabilistic wind power forecasts are used for trading in the Dutch electricity spot market	Wind	No	Yes	Yes	No	No
Papaefthymiou et al. (2015): Offshore wind farms in the German control reserve markets are able to generate additional income in the negative control reserve market	Wind	Yes	Yes	Yes	Yes	Yes
Kirby, Milligan, and Ela (2010): Economics of the of control reserve provision from wind farms in the US show that provision is economic in some hours	Wind	Yes	Yes	Yes	Yes	Yes
Andersen, Strom, Tang, Davidsen, and Dupont (2012): Participation of wind in the eastern Denmark negative manual activation reserve market is economically viable in the Danish market	Wind	Yes	Yes	No	Yes	No
Saiz-Marin, Garcia-Gonzalez, Barquin, and Lobato (2012): Participation on the control reserve market is assessed with offers that have a fixed share subtracted from the forecast	Wind	Yes	Yes	No	Yes	No
Tuohy, Brooks, Ela, and Kirby (2012): Opportunities for the provision of control reserve by wind farms in a 2020 scenario	Wind	Yes	Yes	No	Yes	Yes
Consentec, r2b, and FGH (2011): Fluctuating RES have a high potential for the provision of control reserve	Other	Yes	No	No	No	No
Consentec (2011): Impact of dispatchable renewable energies on the control reserve market with hindcasting approach	Other	Yes	Yes	No	No	No
Zhang, Sun, and Cheng (2013): Participation of wind farms in regulation markets in California, using a stochastic approach, is more beneficial for down-regulation	Wind	Yes	Yes	Yes	Yes	Yes
Morales, Conejo, and Perez-Ruiz (2010): Stochastic methodology to bid wind energy to the MIBEL spot market	Wind	Yes	Yes	Yes	Yes	Yes
Zugno, Pinson, and Jónsson (2010): Bidding strategy for wind energy in NordPool spot market Use probabilistic forecasts of wind farms for their optimisation strategies	Wind	No	Yes	Yes	Yes	No

Source: Own analysis based on (Andersen et al., 2012; Braun, 2009; Consentec, 2011; Consentec et al., 2011; Frunt et al., 2009; Gesino, 2011; Kapetanovic et al., 2008; Kirby et al., 2010; Morales et al., 2010; Papaefthymiou et al., 2015; Pinson, 2006; Pinson et al., 2007; Saiz-Marin, Garcia-Gonzalez et al., 2012; Speckmann, 2016; Tuohy et al., 2012; Zhang et al., 2013; Zugno et al., 2010)

Table 3-5: Classification of the different approaches by their addressed topics

3.3.2 Identification of the challenges of bringing generators to the control reserve market

Control reserve by hydro power plants

Spitalny, Unger and Myrzik (2012) show how control reserve can be delivered from run-off hydro power plants in the German control reserve market. The authors show how the available reserve could be brought to the market and how run-off hydro could be supplemented with wind farms and PV systems. They state that the forecast quality of fluctuating RES is insufficient to serve the entire product length (Spitalny et al., 2012, p. 5). It was also concluded that the delivery of positive control reserve (primary, secondary and tertiary) is economically and ecologically inefficient, also due to the FIT paid to these units (Spitalny et al., 2012, p. 5). The current price structure would prohibit beneficial market participation. In a study by Sterner et al. (2010) the relevance of pumped hydro and other storages are investigated. The impact on the balancing demand is shown. Pumped hydro power plants already provide control reserve to the market (Sterner et al., 2010, pp. 104–105).

Increasing balancing needs and impact of wind farms

The study dena II (dena et al., 2010) investigated the impact of increasing RES on the power system in detail. The study identified an increasing demand of control reserve for 2020 (dena et al., 2010, p. 19) and also assessed how wind farms could provide control reserve. These results agree with e.g. Dany (2001, p. 6). In the overview paper of Hamon and Söder (2011) the impact of wind farms on balancing needs is investigated (Hamon & Söder, 2011, pp. 898–899). The paper shows how they can contribute and provide primary and secondary control reserve (Hamon & Söder, 2011, pp. 899–900).

Risk management and co-optimizing for control reserve markets

Ehsani, Ranjbar and Fotuhi-Firuzabad (2009) introduce the concept of risk management for the provision of control reserve and spot market energy using co-optimization. They compare deterministic risk management (n-1 criterion) with probabilistic approaches (risk indexing). The authors have shown how the social welfare can be maximized using a market model (Ehsani et al., 2009, p. 106). The paper also mentions the application of game theory to bidding behaviour (Ehsani et al., 2009, p. 105).

Impact of fluctuating RES on the electricity market

Ketterer (2014, p. 279) investigated the relationship between wind power generation and electricity price behaviour in Germany. She concludes that the introduction of wind power decreases prices due to the merit-order effect (Ketterer, 2014). The merit-order effect was described by Sensfuß, Ragwitz and Genoese (2007). Impacts on the technical parameters of conventional power plants is given in Gottelt (2009). Gottelt concludes that retrofit of power plants is necessary (Gottelt et al., 2009, pp. 198–199). Ketterer shows that regulatory changes can have a significant impact on the electricity price by incentivizing a desired behaviour of the market participants (Ketterer, 2014, p. 279). The findings are confirmed by Forrest et al. (Forrest & MacGill, 2013, p. 130) for the Australian electricity market. Wassermann, Reeg and Nienhaus (2015) summarize the current development in Germany and indicate regulatory changes. Nicolosi (2010) has indicated that the increase in fluctuating RES requires more flexibility in the market. It is assumed that this could be provided partially by fluctuating RES with an adequate change in market design (Nicolosi, 2010, p. 7267).

Comparison of different market design for reserve provision

Two papers by Rebours, Kirschen, Trotignon and Rossignol (2007a; 2007b) investigate the technical and economic features of control reserve provision in eleven different countries worldwide, including their costs. In Rivero, Barquin and Rouco (2011) different European reserve markets are compared. A systematic overview of the different schemes presented in Rivero et al. (2011) concludes that secondary control reserve is handled similarly throughout Europe whereas tertiary control reserve is interpreted and used differently in each country (Rivero et al., 2011, p. 338). This can be confirmed with (ENTSO-E, 2013a). Market design is one key factor for a successful market integration of fluctuating RES. This is one of the reasons why results for one country cannot be applied to another country without further work.

Dependency between spot market and control reserve market

The doctoral thesis of Waver (Waver, 2007) investigates the German market design. The dependency between the spot market and the control reserve market is assessed. Growitsch, Rammerstorfer and Weber have investigated the dependencies between the spot market and tertiary control reserve market. The authors were able to show that the impact of spot prices on positive tertiary control reserves is higher than on the negative tertiary control reserve. They conclude that the market for positive tertiary control reserves serves as an alternative market for the spot market, which was not directly observable for the negative control reserve market (Growitsch et al., p. 5). Weber (2010) investigates the dependencies between intraday markets, control reserve markets and the balancing settlement mechanism, concluding that additional research is necessary to formulate the most efficient market design (Weber, 2010, p. 3163).

Stochastic dispatch probability

The thesis of Kurscheid (Kurscheid, 2009) has investigated the possibilities of positive tertiary control reserve through decentralized micro-CHPs. The author investigated the technical and economic potentials and used a stochastic approach to determine the dispatch probability.

Economics of electric vehicles providing control reserve

A comprehensive study by Schuller and Rieger (2013) shows the economic potential of electric vehicles participating in the control reserve market based on a methodology by Kempton and Tomić (2005). Schuller and Rieger apply their opportunity cost model to the different control reserve markets. They conclude that it is most beneficial to participate in the markets for negative control reserve (secondary and tertiary) (Schuller & Rieger, 2013, p. 192). With a number of adaptations, the approach can be used for wind farms and PV systems.

Importance of wind farms in the reserve market

In their overview paper Aho et al. (2012) emphasize the importance of wind turbine control that enables the wind farms to deliver frequency support services and operate reliably at a given power set-point. The authors also state the importance of establishing an ancillary market for services from wind farms.

Economic impact of wind farms in the control reserve market is positive

The doctoral thesis of Al-Awaad (2009) investigates the delivery of ancillary services by wind farms. This publication includes a short economic evaluation from the wind farm’s as well as from the TSOs point of view. Al-Awaad states that the participation of wind turbines will not increase the costs for the TSO since wind farms will only provide reserves if they are cheaper than the existing units in the market (Al-Awaad, 2009, p. 81). The approach does not include the uncertainty of the wind power forecast.

Proven technical capabilities of wind farms and PV systems to provide frequency control

Almeida and Lopes (2007) have also investigated the delivery of control reserve by wind turbines. They focused on the double-fed induction generator (DFIG) technology of wind turbines. The authors describe how a wind turbine can provide a symmetrical reserve band which is controlled by the grid frequency. Anaya-Lara, Hughes, Jenkins and Strbac (2006) have presented a methodology to use the rotors kinetic energy to provide frequency support in the form of virtual inertia (inertial response). This finding is supported in the paper of Morren, Haan, Kling and Ferreira (2006, p. 434), Bevrani, Ghosh and Ledwich (2010, p. 453) and Bhatt, Roy and Ghoshal (2011). Chowdhury and Ma (2008) show that inertial response and pitch control can be used to provide frequency control services. The same approach is used by Erlich and Wilch (2010), expanding it by adding the possibility to increase the rotor speed first and let it discharge later. All the methods are tested in simulations. Ping-Kwan Keung, Pei Li, Banakar and Boon Teck Ooi (2009, p. 286) assess the performance of inertial response on the system level. They conclude that wind turbines can potentially fully replace the inertia provided by conventional generation today. Margaris, Papathanassiou, Hatziargyriou, Hansen and Sørensen (2012, p. 198) show that wind farms are technically capable of providing inertia (see also Figure 3-8) and primary control reserve. The authors quantified the expected benefits and costs for both options for different wind turbine technologies. Okou, Akhri, Beguenane and Tarbouchi (2012) have developed a control algorithm for a PV system that is able to provide frequency (i.e. primary control reserve) and voltage control. Their findings show that the PV system is technically capable of behaving like a synchronous generator for the investigated time frame (Okou et al., 2012, p. 5).

Provision of negative tertiary control reserve using probabilistic forecasts

In a diploma thesis by Schaich (2010) the provision of negative tertiary control reserve is investigated using stochastic approaches. For the forecast creation Schaich follows the methodology from Pinson (2006). Schaich also calculates the possible additional income for the wind farms using a 300 MW wind farm as an example. For the calculation, he uses the average weighted capacity price. The diploma thesis by Schwinn (2011) uses probabilistic forecasts to calculate possible contributions from wind farms and PV systems. The forecast method used is called quantile regression. Schwinn used lower intervals for confidence intervals of up to 99.9 % (Schwinn, 2011, p. 53).

Impacts of the balancing settlement mechanism

In Ravnaas, Farahmand and Doorman (2010) the incentives for strategic bidding of wind farms within different balancing settlement pricing mechanisms are investigated. Ravnaas et al. conclude that a one-price system (as implemented in Germany) allows the creation of additional revenue by willingly deviating from the schedule when the bids for the market are created (Ravnaas et al., 2010, p. 35). With a two-price system (as in Norway and Denmark) no additional revenue could be generated. These results concur with the findings in the master thesis of Jansen (2011, pp. 78–79).

Determination of the available active power signal wind for the new proof method

A methodology to proof the delivery of control reserve is presented in Speckmann and Baier (2011, p. 2) and further developed in Brauns et al. (2014, pp. 75–81). The implementation of the new proof method requires obtaining the value for the available active power of the wind farm, which is the maximum possible feed-in under current meteorological conditions. In Eisen, Sørensen, Donovan and Hansen (2007) a wake model of a wind farm was used to correct the errors that were previously observed during curtailment. Ramakrishnan Kirshna (USA 2012/0078518 A1, 2009) has applied to patent the estimation of the available active power in the US using the power output of the turbine, the current rotor speed and the blade pitch angle. Schneider, Kaminski, Siefert and Speckmann (2013) presented a method using high resolution three-second data for the delivery of secondary frequency control. The approach with the least error is the one where the turbines' anemometers are used (Schneider, Kaminski et al., 2013).

Determination of the active power signal of PV systems for the new proof method

In the doctoral thesis of Glotzbach (2010) existing approaches for the creation of the available active power signal for PV systems are presented, including the robust approach presented in Beyer, Heilscher and Bofinger (2004). Glotzbach also presents a new approach using artificial neural networks (ANN) (Glotzbach, 2010, pp. 74–95). The approach of Beyer et al. has also been used by Bündgen (2012) in his diploma thesis.

Reliable forecasts are subject to further research

Since the delivery of control reserve has to be reliable, the offer has to be based on reliable forecasts. Ernst, Reyer and Vanzetta (2009) have presented a methodology to use short-term ensemble and meta forecasts for balancing renewables. The authors state that forecasts can be used to calculate the necessary amount of control reserve for balancing (Ernst et al., 2009, p. 1). The necessity for further research is postulated in Hodge et al. (2012, p. 6). They state that forecast errors cannot be estimated by the standard distribution appropriately[13], as there are far more values at the tails of the distributions than the standard distribution would allow (Hodge et al., 2012, pp. 5–6). For probabilistic forecasts, this can be very important. A hyperbolic distribution could achieve a better fit. In Lange et al. (2011, pp. 95–96) the forecast qualities for wind are given. The forecast quality is usually given with the value for the normalised root mean square error (nRMSE). For the one hour-ahead forecast the nRMSE is approximately 1.5 % (Lange et al., 2011, p. 95), while for the day-ahead forecast it is approximately 5 % (Lange et al., 2011, p. 96). It can be assumed that the forecast quality has increased in the meantime.

Possible approaches to generate probabilistic forecasts

Probabilistic forecasts can be created in several ways. One way is to use a kernel density estimator (KDE) (Bowman & Azzalini, 1997). Based on this approach Bessa, Miranda, Botterud, Zhou and Wang (2012) further develop the method to use a time-adaptive quantile-copula estimator for kernel density forecasts. Bessa et al. also elaborate on the difficulties of selecting appropriate kernels for the modelled problem. In their approach they used a conditional kernel (Bessa et al., 2012, pp. 30–32). They also compare their results with a second state-of-the-art approach, called quantile regression (QR). The authors conclude that their approach is superior to the quantile regression approach (Bessa et al., 2012, p. 38). Foley, Leahy, Marvuglia and McKeogh (2012) show an in-depth analysis of stochastic

[13] Which does not mean that the KDE cannot use Gaussian kernels

(KDE and QR) and machine learning approaches (ANN) to create probabilistic forecasts. Juban, Fugon and Kariniotakis (2007) and Juban, Siebert and Kariniotakis, (2007) also used a KDE to generate probabilistic wind power forecasts. Both author teams conclude that the KDE is a suitable approach to match the state-of-the-art forecasting techniques (Juban, Fugon et al., 2007, p. 8; Juban, Siebert et al., 2007, p. 1). They point out that kernel density forecasts have the tendency to be computational intensive. The bachelor thesis of Wingenbach (2011) presents a methodology to calculate probabilistic wind power forecasts using quantiles.

Short product lengths lead to economic use of units

Just (2011) raises the question of the optimal market design by assessing the impact of contract durations in the primary and secondary control markets on efficiency. This extends and builds on an analysis of the dependency of spot market prices on control reserve market prices in Just and Weber (2008). Just concludes that shorter product lengths lead to an economic dispatch of units, and thus to lower prices on the spot market and the control reserve market (Just, 2011, p. 19). Long product lengths favour holders of large portfolios of units whereas smaller market participants have a disadvantage (Just, 2011, p. 19). Together with the discriminatory pay-as-bid pricing mechanism and the market power exercised (see also (Growitsch et al.; Heim & Goetz, 2013)) by large portfolios this will lead to market distortions. Just concludes that daily four-hour or hourly auctions would be preferable to achieve economic dispatch (Just, 2011, p. 19).

Market reforms increase competition in the tertiary control reserve market, whereas other markets are less competitive

Haucap, Heimeshoff and Jovanovic (2012) have investigated the effects of the reforms in the control reserve market. The authors found evidence that the introduction of the common internet platform for the tendering of primary, secondary and tertiary control reserve (regelleistung.net) has had an impact on the tertiary control reserve prices (Haucap et al., 2012, p. 8,28). This was not the case for the secondary and primary control reserve market. This would imply that the tertiary control reserve market is much more competitive than the secondary and primary control reserve markets. This is also evident when looking at the numbers of participants in the market (50Hertz Transmission GmbH et al., 2015a). Competitive markets decrease the incentives to bid strategically, even in pay-as-bid markets.

Cramton and Stoft (2007) have investigated the difference between bay-as-bid pricing and marginal pricing in spot markets for electricity. The authors conclude that it is favourable to implement marginal pricing rather than pay-as-bid (Cramton & Stoft, 2007, pp. 36–37). Oren (2004) discusses situations when it is favourable to implement pay-as-bid pricing and when marginal pricing is preferable. Although in theory, both schemes should generate the same revenue, Oren states that pay-as-bid pricing has the effect of flattening the supply function of the merit-order curve (Oren, 2004, p. 713). Oren argues that pay-as-bid pricing is more suitable for highly fragmented markets, such as the reserve markets (Oren, 2004, p. 714).

Difference between pay-as-bid markets and marginal pricing markets

Swider and Weber (2007) have developed a methodology for bidding on several markets with price uncertainty using strategic bidding behaviour. They conclude that strategic bidding behaviour is needed. This supports the modelling approach of determining the range of possible solutions and identifying the best and the worst outcome for the bidder, as described in chapter 4.4.3. Heim and Goetz (2013) examine the use of market power in their discussion paper and present the relevant literature. The authors investigate the behaviour of market participants in the secondary control reserve market. They conclude that market power is exercised by the largest companies on the market due to the applied pay-as-bid pricing mechanism (Heim & Goetz, 2013, p. 1). They also examine the problems introduced by the “guess-the-clearing-price” phenomenon (Heim & Goetz, 2013, p. 17). In comparison, the authors state that the tertiary control reserve market is the most competitive control reserve market. Even for this market high concentration and insufficient competition has been identified by Growitsch, Höffler and Wissner (2010, p. 30). It was proven by Son, Baldick, Lee and Siddiqi (2004, p. 1997) that pay-as-bid markets lead to less efficient dispatch and lower total revenue.

Strategic bidding in the control reserve market is necessary to maximize income

Elberg, Growitsch, Höffler, Richter and Wambach (2012) have considered a unit commitment with the spot market positive control reserve market only, assuming that negative reserves will be provided by RES. The authors claim that there is a link of spot market and control reserve market prices. Prices in control reserve markets depend on the spot market price and the volumes in

Coupling of spot market and control reserve market with possible contributions from CCGT the control reserve market. Prices in the spot market and the control reserve market influence each other and are driven both ways by their opportunity costs (Elberg et al., 2012, p. 93). The authors assess income possibilities for gas turbines (GT) and combined cycle gas turbines (CCGT). They also state that the results are very much dependent on the initial assumptions (Elberg et al., 2012, pp. 26–28).

Strategic behaviour in electricity markets

The issues with bidding in markets for control reserve have been discussed by David and Fushuan Wen (2000), who show the existence of strategic behaviour by the market participants. This leads to the finding that the market participants base their decision on additional factors other than pure economic incentives (David & Fushuan Wen, 2000, p. 2172). Richter (2012, p. 1) showed that the outcome on the control reserve market is determined by the expectations of the outcome from the market participants. The spot market followed the decisions taken on the control reserve market. If outcomes are influenced by expectations, fundamental analysis will no longer yield valid results. This will then be in the field of game theory as discussed by Shahidehpour, Yamin and Li (2002), and would also imply that costs are no longer the driver for the economic activity rather than the (expected) prices, as discussed in Ferrero, Shahidehpour and Ramesh (1997).

3.3.3 Research projects and international development

3.3.3.1 Research projects

European research project TWENTIES on the delivery of ancillary services by wind turbines in Spain and Germany

In the EU Framework 7 funded research project **TWENTIES** (European Commission, 2009) the delivery of ancillary services was demonstrated with wind farm clusters in Spain. These tests were conducted for the provision of control reserve and reactive power. Both tests were completed successfully. The determination of offers in the reserve markets were performed by subtracting a security margin from the wind power forecast (Azpiri et al., 2013). In addition to this an independent economic evaluation for the delivery of control reserve was performed by the author of this doctoral thesis for the German markets (Jansen, Hochloff, Schreiber, Oehsen, & Peñaloza, 2013).

Another EU Framework 7 funded project is **REserviceS** (European Commission, 2010). The project consortium consisted of different partners in research, the renewables trade bodies and the industry. The aim is to provide recommendations for the design of a European ancillary services market. Results from earlier iterations of the methodology shown in this doctoral thesis have been presented in the project reports (Faiella, Hennig, Cutululis, & van Hulle, 2013, pp. 47–52), although no direct contribution to the project was made.

European research project REserviceS concludes on the necessary market changes for control reserve

In the German research project **Kombikraftwerk2** (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2014) the delivery of ancillary services in a 100 % RES scenario has been investigated. The project concludes that it is possible to provide all necessary ancillary services in a carbon-free electricity system (Knorr et al., 2014, p. 209).

German research project Kombikraftwerk2 is providing answers to AS provision in a 100 % RES scenario

The project **Dynamische Bestimmung des Regelleistungsbedarfs im Stromnetz** (English: dynamic dimensioning of control reserve demand) addresses the issues with the calculation of the demand for control reserve. Results of this project can be seen in Jost, Braun and Fritz (2014; 2015). Today in Germany, the control reserve demand is calculated every three months, taking into account the errors in the power system from the corresponding quarters of the last four years. For details, see chapter 3.2.3. In a system with high RES penetration levels, it is important to calculate the reserve demand more frequently, e.g. on a daily basis, taking into account the day-ahead forecasts of wind farms and PV systems. This flexibility would allow wind farms and PV systems to offset potentially high forecast errors through a flexible provision of control reserve, since the hours with a high demand can be identified (Jost, Braun, Fritz, Drusenbaum, & Rohrig, p. 41). Comparative papers have been published e.g. by Ela et al. (2010) and Holttinen et al. (2011).

German research project to develop RES sensitive control reserve dimensioning

European research project ANEMOS.plus on probabilistic forecasts and control reserve offering

The principles of market participation in spot and control reserve markets using probabilistic forecasts have been shown in a study by the Fraunhofer IWES for **Westkapital** (Speckmann & Baier, 2011) and in the European project **ANEMOS.plus** project (Focken & Schaller, 2011). It was concluded that the proof method for the delivery of control reserve has to be adapted for wind farms (Fraunhofer IWES, 2011, p. 31). The principles to calculate probabilistic forecasts presented in this thesis build upon these findings, although no direct connection was established.

German Research project PV Regel researches the delivery of control reserve from PV systems

PV Regel is a research project by SMA, the Technical University of Braunschweig and GEWI AG that is targeted at the provision of control reserve from photovoltaic systems. The project develops a concept for the delivery of control reserve and plans to test this with a field test. The project also considers the black start capabilities of photovoltaic systems. (SMA, TU Braunschweig, & GEWI AG, 2015)

German research project to create solutions how wind farms could deliver control reserve

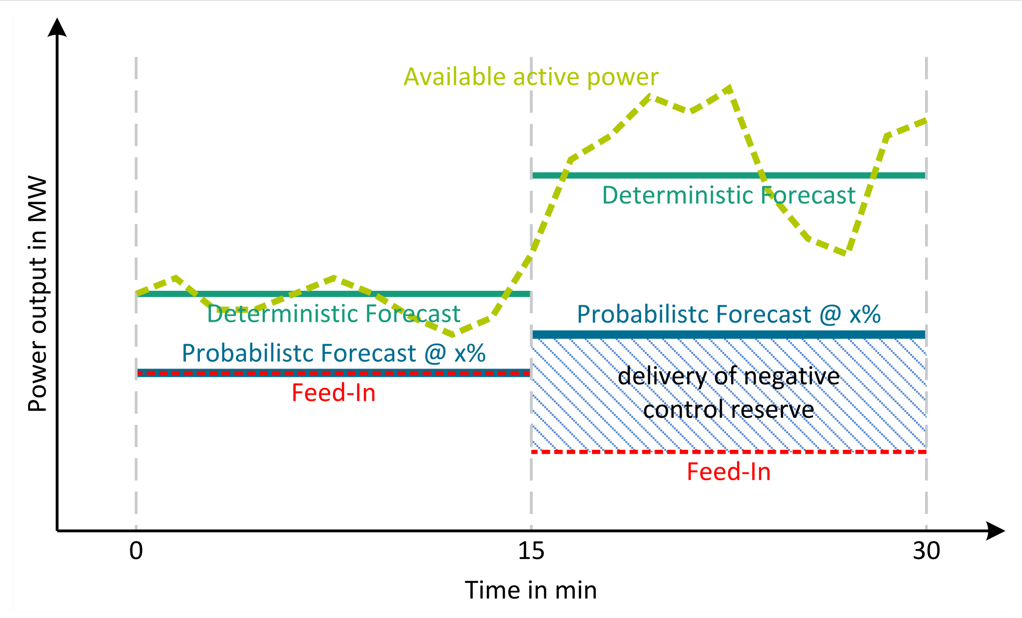
In the research project **Regelenergie durch Windkraftanlagen** (English: Control reserve from wind farms) Fraunhofer IWES together with partners from the industry and two TSOs developed concepts for the delivery of control reserve from wind farms (Brauns et al., 2014). The project included the development of a proof mechanism that would allow wind turbines to deliver control reserve without previous curtailment to their schedule. The project also developed a method to offer control reserve in the market that has the same level of reliability as conventional generation. Some aspects of this thesis were presented in (Brauns et al., 2014). The results were also used in (Speckmann, 2016). Finally, all theoretical concepts were tested in a field test. The concepts have also been applied to offshore wind farms (Rohrig et al., 2013).

Proof method investigated in Regelenergie durch Windkraftanlagen

Two **different proof methods for the delivery of control** have been assessed in Regelenergie durch Windkraftanlagen (Brauns et al., 2014). A detailed analysis of the proof methods is also presented in the doctoral thesis of Speckmann (2016).

The first proof method is derived from the proof method for conventional generation, called **balance control (BC)**. The proof of the delivery from the unit to the system is carried out through the comparison of the planned schedule of the power plant with the actual feed-in. It is assumed that the generator would have produced according to the schedule, since it is controllable. When the generator changes production for the delivery of control reserve a delta occurs between the schedule and the actual feed-in. This is then interpreted as the proof of delivery of the contracted amount of control reserve. The delta has to match the contracted amount of control reserve. However, this leads to the circumstance that the wind farm (or PV system) is curtailed when the capacity is contracted but not dispatched. This not only influences the economic feasibility but also generates energy losses that have to be compensated by other generators. Figure 3-17 shows the principles of this proof method. The wind farm is curtailed to a reliable schedule that is then used for reference. During dispatch the wind farm is curtailed based on this schedule. (Brauns et al., 2014, pp. 75–76)

Current proof method requires the curtailment of fluctuating RES generators

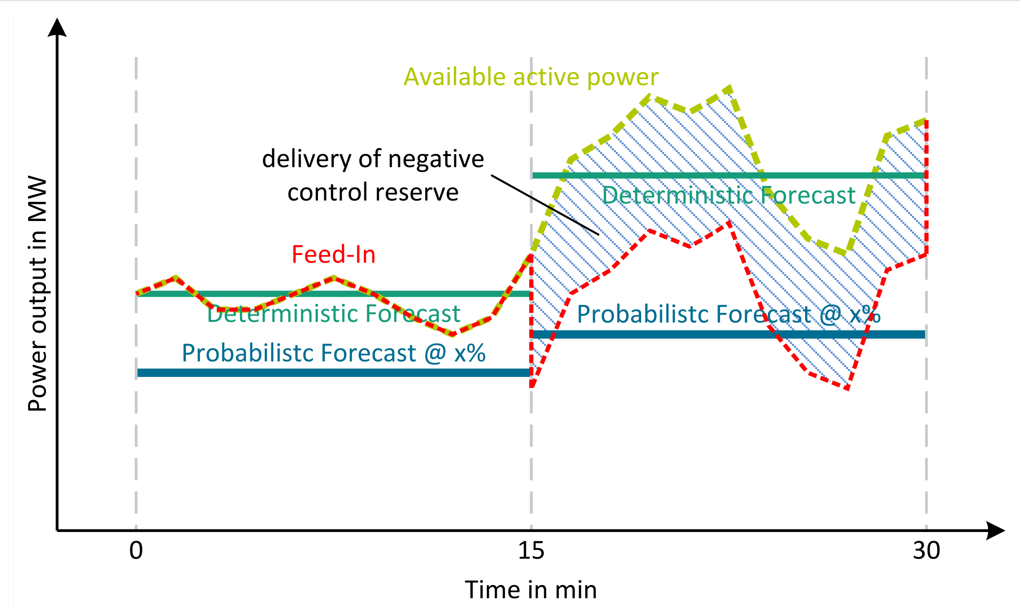


Source: adapted from (Brauns et al., 2014, p. 75)

Figure 3-17: Balance control (BC) proof method for the delivery of negative control reserve

Alternative proof method does not require curtailment when reserve is ready for dispatch

The second proof method investigated in "Regelenergie durch Wind und PV" is called **available active power control (AAP)**, or delta control. For this proof method the active power signal of a wind farm has to be calculated. The available active power signal is the power that would have been produced if the wind farm had not been curtailed. The proof of the delivery is achieved by comparing the available active power signal with the actual feed-in. Assuming that the available active power signal is accurate the difference between the signal and the feed-in is equal to the contracted amount of control reserve. The calculation however is challenging, according Schneider, Tietz, Siefert, & Speckmann (2013, p. 5). The graph below shows the principles of operation. If the wind farm is not dispatched for control reserve, it operates as it currently would under the market premium model. (Brauns et al., 2014, pp. 76–77)



Source: adapted from (Brauns et al., 2014, p. 76)

Figure 3-18: Available active power (AAP) proof method for the delivery of negative control reserve

Danish research project PossPow determines the best way to calculate the available active power signal

The Danish research project **PossPow** (Possible Power) (DTU, 2012) at the Technical University of Denmark, together with Vattenfall, Vestas and Siemens wind power, investigates the question of the calculation of the available active power signal for offshore wind farms. From the Danish perspective offshore wind is the obvious choice since it will most likely contribute the most when the RES share is increased in Denmark. With adaptations it might be possible to scale the results to onshore wind turbines. The concepts in this research were developed in parallel to the concepts at Fraunhofer IWES.

To follow up on these ideas the research project **Regelenergie durch Wind und PV** (English: Control reserve from wind farms) (Fraunhofer IWES et al., 2014) is currently being carried out. It adapts the concepts developed for the wind turbines to photovoltaic systems and investigates possible benefits for the combination of both technologies. It also investigates the central question of determining the available active power for PV systems.

German research project Regelenergie durch Wind und PV

The research project **INEES** by Fraunhofer IWES, Volkswagen, SMA and LichtBlick (Fraunhofer IWES, LichtBlick SE, & Volkswagen AG, 2012) investigates the possibility of control reserve delivery by electric vehicles. The field test took place in a test phase with several cars in greater Berlin. The problem for electric vehicles is similar to wind farms and PV systems as their availability can only be predicted with a certain degree of reliability. The forecast of the availability however is influenced by user pattern rather than weather forecasts. Additionally the communication solutions are very challenging. The business model is still subject to ongoing research. In general, this concept is adaptable to any sort of demand side management (DSM) application for the delivery of control reserve. Possible solutions will be more diverse than for wind farms or PV systems. The research in the project was influenced by the finding of the project “Regelenergie durch Windkraftanlagen“ through communication and joint project work.

German research project INEES combines pools electric vehicles for the delivery of control reserve

The following table briefly summarizes the project results from the previous sections. It provides a non-exhaustive list of topics that are relevant in this doctoral thesis. Each project might have additional project results that are relevant in a different context.

Summarizing table on relevant projects

Project	Results
TWENTIES	• Provision of control reserve and reactive power with wind farm clusters in Spain • Testing was completed successfully • Offers in the reserve markets were created by subtracting a security margin from the wind power forecast • Reserve provision economically not viable in the Spanish control reserve market
REserviceS	• Provides recommendations for the design of a European ancillary services market, based mostly on literature review • Required changes in the market structure to include more decentralized generators were identified
Kombikraftwerk2	• Energy system with 100% renewables is technically feasible • All ancillary services can be provided in a 100 % RES scenario
Dynamische Bestimmung des Regelleistungsbe-darfs im Stromnetz	• In a system with high RES penetration levels, it is possible to calculate the reserve demand on a short term to include forecast errors of wind farms and PV systems
Westkapital	• Concept for market participation in control reserve markets using probabilistic forecasts are shown
PV Regel	• Development of concept for the delivery of control reserve with PV systems • Plans for field testing • Investigation on black start capabilities of PV systems
Regelenergie durch Windkraftanlagen	• Development of a proof mechanism for wind farms that would allow wind turbines to deliver control reserve without previous curtailment using the available active power signal • Development of signal requires further research • Methodology to offer control reserve in the market that has the same level of reliability as conventional generation • Field testing to show the proof of concept
PossPow	• Calculation of the available active power signal for offshore wind farms
Regelenergie durch Wind und PV	• Adapting the concepts developed for the wind turbines to photovoltaic systems • Investigation of possible benefits for the combination of both technologies • Determining the available active power for PV systems
INEES	• Investigation of concepts to provide control reserve with electric vehicles • Field testing with 20 vehicles in Berlin proved technical feasibility • Currently no business model • Communication solutions developed for bi-directional charging

Source: Own analysis based on (Azpiri et al., 2013; Brauns et al., 2014; DTU, 2012; European Commission, 2009, 2010; Fraunhofer IWES, 2011; Fraunhofer IWES et al., 2014; Fraunhofer IWES et al., 2012; Jost et al.; Knorr et al., 2014; Schneider, Tietz et al., 2013; SMA et al., 2015)

Table 3-6: Main results of projects related to the doctoral thesis

3.3.3.2 International development

In **Great Britain** wind farms with an installed capacity of more than 50 MW have to be capable of being controlled in a frequency sensitive droop mode. Two different modes are used. One control mode is always active (Frequency Sensitive Mode) and one is only applicable if the frequency exceeds 50.4 Hz (Limited Frequency Sensitive Mode). Additionally wind farms can participate in the control reserve market if they fulfil the minimal technical requirements which prove to be difficult to match with the fluctuating generation of wind farms. (National Grid Electricity Transmission plc, 2012)

Control reserve provision by fluctuating RES in Great Britain

All wind farms in **Denmark** have to be capable of being frequency controlled in two modes. The first one controls the wind farms in relation to the frequency throughout the entire generation envelope. The second mode ensures a linear progressive curtailment beyond a threshold frequency. This is similar to the British model. The participation of wind turbines on the control reserve market for energy-only-bids is possible and used without capacity payments. Participation in the capacity based secondary and primary control reserve markets is not possible. (Elkraft, 2004; Elkraft & Eltra, 2004)

Control reserve provision by fluctuating RES in Denmark

For **Ireland** (Republic of Ireland), the control reserve provision by wind farms is mandatory for the grid connection. The wind farms are operated in a droop control mode based on the frequency. The droop control is applicable for positive and negative control reserve, which creates energy losses during normal operation. The control reserve would be equivalent to primary control reserve in ENTSO-E RG CE. (EirGrid, 2009)

Control reserve provision by fluctuating RES in Ireland

3.4 Possible methodologies for the validation of the research hypothesis

3.4.1 Conclusion of challenges from the literature

Summary of the critical aspects

From the previous review of the literature different challenges are identified, as discussed in chapter 3.3. In order to answer the research question one has to assess the major challenges that exist due to the given setup of the environment. The critical aspects examined can be summarized as follows:

1. The **technical capabilities** for the delivery of ancillary services are **proven**. Wind farms (Al-Awaad, 2009, p. 81; Almeida & Lopes, 2007, p. 949; Anaya-Lara et al., 2006, p. 169; Andersen et al., 2012, p. 28; Bevrani et al., 2010, p. 453; Chowdhury & Ma, 2008, p. 5; Erlich & Wilch, 2010, p. 7; Gesino, 2011, pp. 99–119; Margaris et al., 2012, p. 198; Morren et al., 2006, p. 434; Ping-Kwan Keung et al., 2009, p. 286) and PV systems (Bhatt & Chowdhury, 2011, p. 6; Kakimoto, Takayama, Satoh, & Nakamura, 2009, p. 548; Okou et al., 2012, p. 6) are technically capable of providing different types of reserves. This ranges from fast responding virtual inertia to all different types of control reserve, as currently used by the TSOs. This allows the conclusion that technical problems are solved, or will be solved in the near future. The technical feasibility does not pose a challenge in itself.

2. Several different **approaches for economic assessments** have been presented. These approaches mostly aim to predict the possible income of the control reserve providers. Different approaches have been selected for different types of units (Consentec, 2011; Elberg et al., 2012; Kirby et al., 2010; Kurscheid, 2009; Schuller & Rieger, 2013; Spitalny et al., 2012; Sterner et al., 2010; Yuen et al., 2011). In the diversity of the models, it can be seen that economic assessment can be performed in different ways. The impact on the system costs has not been investigated with the same level of detail. Literature focusses on the impact of wind on balancing

needs and the costs. Little is known about possible income for wind and even less for PV.

3. The previously presented assessments show **vulnerability to price changes** (Elberg et al., 2012, pp. 27–28). These are partially addressed by using average prices which are mean values over a certain time (Al-Awaad, 2009, pp. 82–86; Schuller & Rieger, 2013, p. 183; Yuen et al., 2011, p. 177) or over all the existing prices in the merit-order list (Kurscheid, 2009, p. 81). Together with the price volatility indicated in 3.2.4.2 one can conclude that it is challenging to investigate the economic effects of a possible reserve provision without investigating the market in detail. A precise picture of the income situation and the impact at the system level can only be achieved by looking at the entire merit-order list.

4. Many approaches in number 3 use a **price oriented** (Consentec, 2011; Khorasani & Rajabi Mashhadi, 2012, p. 86) and/or a **cost-based** (Khorasani & Rajabi Mashhadi, 2012, p. 84; Richter, 2012, p. 7) approach for the economic assessment. Ideally, both approaches should be used to calculate the efficiency gain and the additional benefit that could be distributed between the producer (producer surplus) and the consumer (consumer surplus). The additional benefit is largest for the producer under a price-oriented approach, whereas it is largest under the cost-based approach for the consumer. Current models fail to address this issue. It is **unlikely** that approaches that produce a single result can capture the most likely **outcome** in the market.

5. The **pricing mechanism** in the control reserve market leads to **behaviour of market participants** that cannot be explained with a purely cost-based approach (i.e. fundamental analysis). The behaviour of the market participants is driven by income opportunities rather than their costs. Cost-based approaches are therefore not sufficient (Swider & Weber, 2007, p. 1307). The difficulties arising from the pricing mechanism in the control reserve market

and the influence on the market participants have been acknowledged by many authors (Cramton, 2009; Cramton & Stoft, 2007; Haucap et al., 2012; Heim & Goetz, 2013; Oren, 2004, Swider, 2005a, 2005b). It has been proven that pay-as-bid markets lead to less efficient dispatch and lower total revenue (Son et al., 2004, p. 1997). In order to assess the economic value of wind farms and PV systems in the control reserve market it is necessary to discover the entire range of all possible behaviours (i.e. bidding strategies) of a market participant in relation to the prevailing prices, accepting inefficiencies as a given pre-condition.

6. Introducing wind farms and PV systems to the control reserve market requires the use of **stochastic models** in order to compensate for the forecast errors by the fluctuating RES units. Stochastic modelling and forecasting have been applied in some of presented approaches (Brauns et al., 2014, pp. 33–47; Ernst et al., 2009, p. 7; Kurscheid, 2009, pp. 43–45; Pinson, 2006; Pinson et al., 2007; Pinson & Madsen, 2009; Ruiz, Philbrick, & Sauer, 2009; Schaich, 2010, pp. 36–40; Schwinn, 2011, p. 53; Speckmann, 2016, pp. 32–47). Apart from (Brauns et al., 2014, p. 96) none of the other approaches was used to calculate the impact on the market. Approaches used for controllable generation cannot be used for fluctuating RES without adaptation. One also has to compare the level of reliability with current units in the market.

7. **Prices** in the control reserve market are **volatile**, partly due to the market participants' behaviour, which is induced by the pricing mechanism. On a short-term basis, prices are relatively stable and can be predicted accurately, using the prices from the past bidding period (see chapter 3.2.4.2). In the long term, this leads to large errors when prices for the future are forecasted. This is mainly because the prices cannot be explained accurately with fundamental analysis models. This requires relying on existing prices. **Backcasting** (Robèrt, 2005, p. 843) obtains results which eliminate

uncertainties from flawed price forecasts. Assessments can provide limited information if future markets are considered.

8. In a market with perfect **competition**, with wind farms and PV systems joining the market, we would be able to observe decreasing prices due to the additional capacity on the supply side. Since control reserve markets are **far from being competitive** (Growitsch et al., p. 5; Haucap et al., 2012, p. 28) it is impossible to predict the changes in the prices. Market participants' actions cannot be predicted accurately enough with the addition of these new units. **Market outcomes** will change due to the new units and their unique bidding characteristics. However, it is impossible to evaluate the behaviour of all other market participants since market outcomes (changes in market prices) do not behave according to the standard economic model (Waver, 2007, p. 75). Price changes induced from units other than wind farms and PV systems are therefore omitted in this thesis. A possible approach could be using a game theory approach, calculating the Nash equilibrium (Ferrero et al., 1997, pp. 1341–1343; Shahidehpour et al., 2002, pp. 191–233).

9. All presented models fail to address the **influence of regulatory aspects**. Since social welfare gains in real markets depend on the framework conditions (Just, 2011, p. 19), "wrong" regulation might have a negative effect on the social welfare whereas others would have a positive effect (Forrest & MacGill, 2013, p. 130; Ketterer, 2014, p. 279). It is necessary that different regulatory setups can be investigated (Just & Weber, 2008, p. 3201). For practical reasons this would require keeping all the other variables constant.

10. **Co-optimization** of control reserve markets and spot markets would **increase the complexity** since stochastic optimization would be required. Efficiency gains will be insignificant (Just, 2011, p. 19). This is especially true since the fluctuating RES are driven by their support scheme (Spitalny et al., 2012, p. 5). It is

unlikely that the income from the control reserve market will have a large influence on spot market behaviour.

3.4.2 Requirements for answering the research question through econometric modelling

Rephrasing research question

The research question targets the economic value of fluctuating RES in a future power system. As previously presented, the value of the fluctuating RES in the control reserve market can be determined with different methodologies. The main interest with regard to the research question is the determination of the social welfare gain. This determines the amount of efficiency gain by the introduction of fluctuating RES into the control reserve market environment. Derived from the research hypothesis in chapter 2.2 the research question is formulated as following:

How can stochastic units, such as wind farms and PV systems, provide control reserve to the power system competitively without altering the level of reliability whilst decreasing system costs?

The requirements for answering the research question

Derived from the findings in chapter 3.3 and chapter 3.4.1 the necessary requirements for answering the research question are developed. The requirements towards the model are listed below:

1. The selected model will have to be able to include current **regulations** and be able to assess possible changes in the **regulatory framework**.

2. It will be necessary to show how **wind farms and PV systems perform** in detail under those different regulations. This will determine the **ideal changes** in the current market design.

3. It is **not necessary to determine** how to remove those **inefficiencies** in general. Inefficiencies in the markets are present and accepted in the course of this research. This is due to the finding that the most economic market design has not yet been identified. It is believed that due to the findings in this thesis the market design will evolve from its

current state to a more efficient state. Therefore, this research needs to provide information on how the market should evolve departing from its current state.

4. A **holistic approach** shall unveil the most important effects that are caused by the introduction of wind farms and PV systems to the control reserve market.

5. **Cross-market optimization is not required**, since the control reserve market cannot be the main source of income. Wind farms and PV system shall be driven by their core business model, relying on the spot market and market premium model. In reality these markets are **cleared separately**.

6. The behaviour of the market participants is not predictable and fluctuating RES cannot dominate the market over the entire year. Therefore, wind farms and PV systems will have to be assumed to be **price takers** in the market. Rational expectations will guide the behaviour of wind farms and PV systems in the control reserve market.

7. Price forecasting risks need to be eliminated as they might overshadow or outrun possible errors from the modelling of the participation of wind farms and PV systems in the market. **Perfect price forecast** has to be used since control reserve prices are largely unpredictable, as shown in chapter 3.2.4.2. They follow fundamental events with a large time lag and only to a certain degree. This requirement implies the use of a **hindcasting approach**.

8. The model for the assessment shall provide **detailed knowledge** of the **seller's** point of view as well as the **system's** point of view.

9. It shall provide information on the entire **spectrum of possible outcomes** and therefore identify the possible social welfare gain.

3.4.3 Possible approaches to assess the participation of fluctuating RES in the control reserve market

Comparing three different approaches that have been used before

In this chapter, approaches that have been used for assessing the value of different units delivering control reserve are examined in detail. This includes approaches that were applied to conventional generators and controllable RES as well as wind farms and PV systems. These approaches have all been mentioned in chapter 3.3. The models presented in this chapter are the most commonly used approaches in modelling electricity markets. According to Ventosa et al. (2005, p. 898) the electricity market modelling can be classified into three different categories: equilibrium models, single firm models and simulation models. These three categories, for a shorter time horizon, can be covered with modelling approaches presented further down, called fundamental analysis cost minimizing models (Ventosa et al., 2005, pp. 901–904), profit maximizing unit commitment models (Ventosa et al., 2005, pp. 899-201) and agent-based models (Ventosa et al., 2005, pp. 904–906). However one has to keep in mind that there might be other approaches as depicted in table 2 in (Ventosa et al., 2005, p. 910).

Testing approaches with the previously defined criteria

The purpose of this chapter is to evaluate the approaches and test them with the challenges identified in chapter 3.4.1. The approaches will be tested against the criteria numbered from 1 to 9 in chapter 3.4.2. An assessment will be made as to whether they are suitable for the given task.

3.4.3.1 Option 1 – Fundamental analysis cost minimizing unit commitment models

Unit commitment models provides the a cost efficient solution for power plant dispatch

One approach to determine the value of ancillary services from generators is an analytical approach, using a unit commitment (UC) dispatch model. A UC model optimizes the units in the power system in the most economical way. Either it can be used to minimize the costs for electricity generation from the system's point of view or it can be used to maximize the income for a generation company (GENCO). The latter option will be discussed in 3.4.3.2 (Option 2 – Profit maximizing unit commitment models). Dispatch models are often used for future scenarios since they can provide a roadmap for the development of the power market. Different authors have presented the current state of research, including approaches for chapter 3.4.3.2 (Dentcheva, Gollmer, Möller, Römisch, & Schultz, 1996; Padhy, 2004; Saravanan, Das, Sikri, & Kothari, 2013; Wright, 2013). UC models are also used by companies to support knowledge based strategic decisions (Energy Brainpool, 2015).

Economic dispatch with unit constraints

UC models incorporate constraints of the individual units. Under the given constraints this will lead to the most cost efficient dispatch of units in the power system (Saravanan et al., 2013, p. 223). Usually these are determined by the profit, emissions and/or time constraints of the units. The delivery of control reserve can be added as an additional constraint. Similarly the system's reserve requirements can be included (Chattopadhyay & Baldick, 2002, p. 285). This UC can be performed on the control reserve market or on the spot and control reserve markets simultaneously. Optimization algorithms often used are called exhaustive enumeration, priority listing, dynamic programming, branch and bound, integer and linear programming, simulated annealing, lagrangian relaxation, taboo search, and interior point optimization (Padhy, 2004, pp. 1199–1202; Saravanan et al., 2013, p. 226). Wright (2013, p. 12) states that currently mixed integer programming is the most commonly used. Saravanan lists 28 different UC models using different optimization techniques and purposes.

Unit commitment assumes ideal markets

Ideally functioning markets are necessary in order to realize this economic dispatch. This guarantees that each unit participates in the most efficient manner. It is assumed that the decision for using or withholding a unit is made purely on economic terms (Dentcheva et al., 1996, p. 1). This means that each unit individually has a different optimum of market conditions, e.g. regarding lead-time or product length. In a real market environment, however, the implementation of a market is necessarily a trade-off between the requirements of the different units, also called market participants. This necessarily moves the dispatch solution away from the economic optimum (Saravanan et al., 2013, p. 226).

Computational requirements

UC models are demanding in terms of computation time and memory demand when a large number of different units with many constraints are considered. This was the case in the model presented by Oehsen (2012), which could only be executed on a high-performance cluster (Oehsen, 2012, p. 32). According to Saravanan et al. (2013, p. 223) it is impossible to create an optimization method which is capable of describing the UC problem for the real power system. Therefore, only an approximation will be possible. Hui Wu and Gooi (1999, p. 1489) have presented a method to deal with complex optimization problems by simplifying the problem. They chose to optimize the spinning reserve requirements in a post-processing step and thereby save calculation time. Chattopadhyay and Baldick (2002, p. 285) claim that this step can be integrated into the unit commitment problem at higher computational efficiency by an approximation of the problem.

Suitability in real markets

Since UC models are designed to deliver the economic optimum for unit commitment, the capability to incorporate market constraints is limited. In many cases, the events in the market cannot be approximated sufficiently, using dispatch models. This is the case when the use of units is not solely based on economic decisions (Ventosa et al., 2005, p. 899). The suitability of assessing the market players' behaviour is low in markets where market power is exercised and strategic bidding is used (Kumar David & Fushuan Wen, 2001, p. 357). Therefore, they are not suitable if one wants to assess the quantitative impact of market conditions on the potentials for the delivery of control reserve from fluctuating RES in a highly regulated environment. However, they can provide information on the gap between the economic optimum and the current implementation.

Suitability according to the defined requirements

The approach is tested against the requirements in chapter 3.4.2, numbers 1 to 9. Cost minimizing UC models have a limited capability to address different regulatory framework situations. The influence of such market regulations will have little impact on the fluctuating RES, since they are seen as an input that cannot be adjusted. By definition, cost-minimizing UC does not reflect inefficiencies. These would have to be modelled explicitly, hence increasing the constraints and calculation time. As for the criteria of the holistic approach and separate clearing, the model is suitable. The cost minimizing

UC models do not compute price forecast as an output, although they can be designed to generate price time series. It is not possible to model how the units act as price takers and therefore provide detailed knowledge about the market participants' behaviour. The optimization results in an optimal solution, which will not reveal the range of possible solutions. Overall, cost minimizing UC models have a very limited capability to address the research question.

3.4.3.2 Option 2 – Profit maximizing unit commitment models

Optimizing for a market from the providers point of view

Another approach, which has been used in the literature, is the assessment of the income side from the seller's point of view, to maximize their profits. Similarly to the previous approach it is often carried out with the help of UC software solutions. The goal is to optimize the UC of generation units of different natures for participation in the markets. (Ventosa et al., 2005, pp. 899–900)

Similarities to cost minimizing UC models

Profit maximizing UC, also called price based UC, is a similar approach to the fundamental analysis of cost minimizing UC. While in the cost minimizing approach the main objective is to supply the demand at any given hour at minimal costs, the profit maximizing approach aims at maximizing the income on the market for a market player with a given portfolio. The profit maximizing approach is determined by the expected price. The GENCO has to decide whether it wants to generate electricity to supply its customers or buy the electricity on the market. The GENCO will use its own generation units when they can generate electricity cheaper than the market price. The generation costs are determined by factors such as the fuel price, the generation technology ramp restraints and others. (Hochloff, Baier, Ferner, Lesch, & Schlögl, 2010; Hochloff & Schreiber, 2012)

Optimization techniques

The optimization techniques listed in the previous option can equally be applied to the profit maximizing UC models. However, Li and Shahidehpour (2005) have suggested using mixed integer linear programming. Since all market players are evaluating their UC simultaneously the sum of all results will be traded and then placed on the market (Saravanan et al., 2013, p. 229).

The sum of all UC models will approximate the results obtained from approaches in the previous option. However, the generation of the necessary price forecasts might lead to uncertainties.

Definition of market and price forecast

The participation in the markets for GENCOs requires the previous definition of the market conditions. This includes the calculation of prices as an input. The residual load can be converted into market prices, using the previous approach. Since the (residual) load is information that is not available to the market participants, the price will have to be the leading input that substitutes the (residual) load as the main input. Other market conditions have to be defined prior to optimization (Ventosa et al., 2005, pp. 899–900)

Co-optimization for spot and reserve market

The profit maximizing UC approach would allow assessment of the value of fluctuating RES in the control reserve market for the portfolio operator. The UC would then have to be carried out for the reserve market, with the spot market as a constraint, or be co-optimized for maximized revenue from both markets (Chattopadhyay & Baldick, 2002, p. 285). Together with real market data, the impact of different regulations can be assessed.

Suitability according to the defined requirements

The fulfilment of the requirements in chapter 3.4.2 reveals the suitability of the approach for answering the research question. Profit maximizing UC models can assess the impact of different regulatory framework situations. Through the market prices, the influence of such market regulations will have a large impact on the dispatch of fluctuating RES for control reserve. The inefficiencies in the market can be accounted for through the price forecasts. Inefficient markets will have higher prices than under the most efficient cost minimizing UC approach. A holistic approach is not possible since feedback, induced by the market participants, does not influence the system, i.e. price changes in the market. Clearing is not modelled by profit maximizing UC models, since they are price takers. Price forecasts are a given input, whether they are obtained from a cost minimizing UC model or from other sources. Under the given framework, one can gain detailed knowledge about the dispatch of each unit from the market participants. With the optimization results indicating the optimal solution, one will not be able to assess the entire range of possible solutions. This approach alone will not provide information on the social-welfare gain. Overall profit maximizing UC models are better suited for addressing the research question.

3.4.3.3 Option 3 – Agent-based models

Agent-based modelling

A third option for an approach is the use of a model that emulates the behaviour of several different market participants, called agents. A certain behavioural pattern is predefined (Shafiei et al., 2012, p. 1664) for agents in order to assess the impact on prices and costs. These agents react individually on changing external factors, for example changes in the market price. Based on these input factors the agents implement a certain action from their predefined choice set (Shafiei et al., 2012, p. 1651). Agent-based (AB) modelling can be seen as a more realistic approach to explain the interaction of different market players in the power system (Tesfatsion & Judd, 2006, p. 900).

Characterization of agents in agent-based models

Since the nature of agents is not pre-defined by the modelling approach itself, the specific design of agents is adapted to fit the modelling purposes (Macal & North, 2010, pp. 157–158). Therefore, the specific design of the agents can vary. For example it is possible that agents may have a unit commitment modelling implemented for their decision making or that they may rely on a different set of algorithms such as artificial intelligence (Müller, Sensfuß, & Wietschel, 2007, p. 4285). Agents in AB models are characterized by their ability to make decisions that emulate the behaviour of real market participants (Macal & North, 2010, p. 153). The behaviour is driven by the objectives of an agent, which may be profit maximization for a given portfolio (Ventosa et al., 2005, p. 906). This allows them to interact with other agents and can determine the course of action of an agent (Macal & North, 2010, p. 152). The knowledge communicated between the agents may vary (Conzelmann, Boyd, Koritarov, & Veselka, 2005, p. 1). It would be realistic in the case of the control reserve market to assume little or no communication between the different market players.

Agents as independent decision makers

Agents can be designed as independent entities who make decisions autonomously based on a predefined set of actions. However, they can be set up to learn from their past experiences and adapt their behavioural strategies to achieve their goals (Koritarov, 2004, p. 40). Agents can be assigned to specific tasks. They can take the role of a GENCO, a grid operator, the demand side and others (Conzelmann et al., 2005, p. 2; Weidlich & Veit, 2008, p. 1733). Grid congestion and other restraints can be modelled which might influence the agent's decisions (Veit, Weidlich, & Krafft, 2009, p. 4132). AB models incorporate a variety of results from several research areas such as game theory, social sciences and software engineering (Müller et al., 2007, p. 4285).

Realistic markets with AB modelling

Compared to the UC market modelling, AB modelling allows the application of market practice into a model with possibilities to adapt for the market participants. These markets are usually modelled as AB market models. Within these constraints, the models provide information on the optimum design of the market. This approach can model scenarios and real data, allowing for a reality check of the scenarios. The introduction of AB models led away from the rational behaviour and equilibrium models approach (UC models) towards a more realistic and adaptive one (Weidlich & Veit, 2008, p. 1756). This complexity has become manageable through the availability of sufficient computing power and allows us to investigate certain aspects in detail (Weidlich & Veit, 2008, p. 1729). The market equilibrium is a result of the interaction of the different agents and may differ from the optimum obtained from the UC modelling approach. Therefore AB models account for system immanent inefficiencies and are capable of modelling the real electricity market adequately (Weidlich & Veit, 2008, p. 1756). The AB approach with its multitude of agents participating in the markets is able to investigate different bidding strategies, risk aversion preference and decision making patterns (North et al., 2002, p. 17).

Drawbacks of AB modelling

The quality of the results in AB models largely depends on the design of the modelling system and the agents' behaviour. By no means can AB modelling be considered a mature method. Standard modelling approaches have not been identified (Heath, Hill, & Ciarallo, 2009, p. 18). The selection and adoption of techniques and algorithms from other areas of research is an important factor and may influence the results from this modelling approach in various ways (Heath et al., 2009, p. 18).

Suitability according to the defined requirements

The AB model approach has to be evaluated against the requirements in chapter 3.4.2 in order to evaluate its suitability. The first requirement that the approach has to fulfil is the capability of addressing issues with the regulatory framework. AB modelling allows the investigation and testing of different regulatory frameworks before implementing them in the real market (Conzelmann et al., 2005, p. 2). This allows identification of the ideal changes in the market and regulatory framework to accommodate for fluctuating RES. The inefficiencies in the market can be modelled to achieve out-of-equilibrium economics (Müller et al., 2007, p. 4285). AB modelling does not provide a single optimized solution (optimized market equilibrium) for the entire system, which could be obtained by optimizing one sole objective, e.g. to minimize cost, as in the UC model approach (Macal & North, 2010, p. 153). Since the emphasis of the AB approach is on the behaviour of the agents (i.e. market participants), a holistic approach can only be achieved by extensive scenario variations. This is computationally demanding and yet unlikely to capture all effects on the system level since the agents change their behaviour constantly. However it is likely to observe a large range of the agents' possible behaviours (Macal & North, 2010, p. 153). Current computational constraints require limitations of the number of agents. For example, participation of ancillary services markets is often modelled after the spot market has closed and therefore is not part of the optimization process (Conzelmann et al., 2005, p. 3).

Agent-based modelling provides a better solution, is not yet capable of answering the research question

The same optimization problems as with the UC models are present and exaggerated by the implementation of various agents. By their behaviour, agents may become price makers, even knowingly exploiting that if their skill set allows them to take advantage of it. Price forecast may or may not be of concern to the agents. Perfect price forecasts are unlikely to be realistic since the market results will not be the economic optimum and will be subject to the agents' behaviour. AB modelling allows us to gain detailed knowledge the activities of the seller and buyer (Weidlich & Veit, 2008, pp. 1752–1753). Despite the fact that a multitude of possible solutions are presented through the agents' behaviour, one cannot be assured that all possible solutions have been captured. AB models provide a more suitable and flexible solution to simulate market behaviour than UC models.

3.4.3.4 Summarizing the suitability of approaches

Summarizing the suitability of approaches

In this chapter, the suitability according to chapter 3.4.2 is summarized and a conclusion is drawn. The overview of all three approaches presented can be seen in Table 3-7. Criteria being fulfilled by an approach are marked with ✓ whereas an unfulfilled criterion is indicated with ×.

Requirement	Fundamental analysis cost minimizing UC model	Profit maximizing UC models	Agent-based model
1. Regulatory framework	×	✓	✓
2. Ideal market changes for fluctuating RES	×	✓	✓
3. Inefficiencies as is	×	✓	✓
4. Holistic approach	✓	×	×
5. Separate clearing	✓	×	✓
6. Price taker	×	✓	×
7. Perfect price forecast	×	✓	×
8. Detailed knowledge seller and buyer	×	✓[14]	✓
9. Range of possible solutions	×	×	×

Source: Own analysis

Table 3-7: Suitability of different modelling approaches to the requirements laid out in chapter 3.4.2

[14] Seller side only

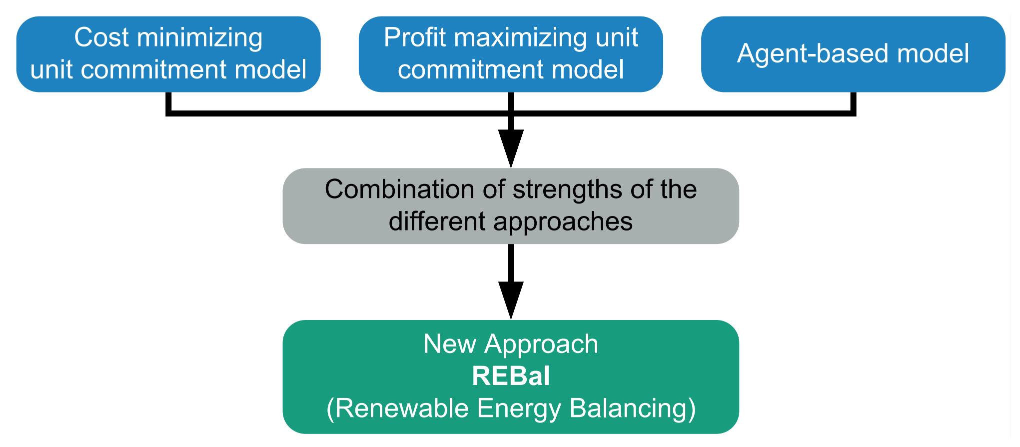
None of the approaches presented in chapter 3.4.3 was able to fulfil all given criteria in chapter 3.4.2. The cost optimizing UC model approach was able to fulfil two of nine criteria, the profit maximizing UC model approach six of nine, and the AB modelling approach five out of nine. The different models have different strengths (criterion fulfilled) and weaknesses (criterion not fulfilled). If all strengths were combined, eight out of nine criteria could be fulfilled. All approaches fell short on the criterion pertaining to the assessment of the entire range of possible solutions from the sellers' point of view, which will be necessary to assess the social welfare gain.

Summary of criterion fulfilment

3.4.4 Development of a customized new approach

None of the presented approaches would be able to answer the research question appropriately. Since the research question is about the economics of control reserve delivery of fluctuating RES and the subsequent induced changes in system costs an additional approach must be considered. This new approach has to be developed with the aim of supplementing the available approaches and investigating the research in detail where the aforementioned approaches would fail. At this point, a simulation approach is suggested, which combines the benefits of all aforementioned approaches. This is in line with Ventosa et al. (Ventosa et al., 2005, p. 3) as they concluded that simulation models can be better suited for individual applications. They emphasize considering the influence of the assumptions in the approach when interpreting the results.

New approach uses the strengths of the possible methodologies and combines them into a new tailor-made new approach



Source: Own analysis

Figure 3-19: Linking the presented approaches with a new model

Linking the presented approaches with a new model

The proposed new approach shall also combine the different approaches from chapter 3.4.3. The three approaches are not in competition with the new approach. They can merely model the framework around it; providing the bigger picture as they cannot provide information detailed enough to answer the research question. The aim is to isolate individual effects without questioning the model of a system. Assuming that the external conditions are constant and unaffected by the introduction of wind farms and PV systems to the control reserve market, one can assess their participation in detail. Results from the new approach can be used as an input for other models. This could be, for example, the impact of changed prices in the control reserve market or changed residual load due to specific curtailing patterns of fluctuating RES. The new approach is presented in chapter 4 in detail.

4 Modelling the economics of control reserve provision by fluctuating RES

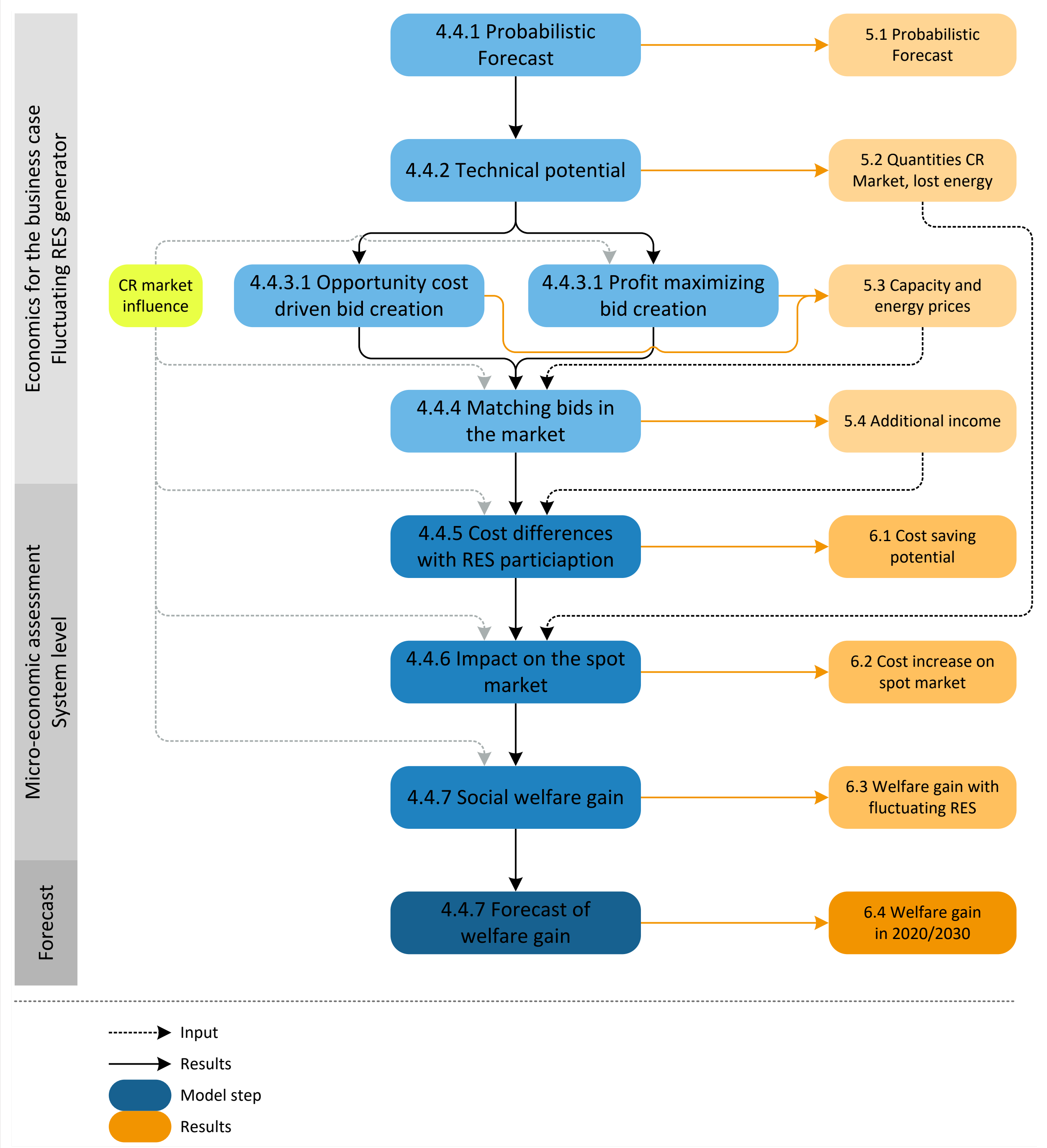
4.1 Introduction to the econometric modelling approach with REBal

New methodology REBal has been presented before

Concluding the findings in chapter 3.4.4 the necessity for a new methodology has been identified. An approach that suits the previously listed requirements has been conceived previously. The methodology that is presented is called the REBal model (Renewable Energy Balancing). The structure of the model described in this chapter has been presented at several conferences and in reviewed papers by this author (Jansen, 2014; Jansen et al., 2014; Jansen & Speckmann, 2013a; Jansen, Speckmann, & Baier, 2012, Jansen, Speckmann, Harpe et al., 2013, 2013; Jansen, Speckmann, Schneider et al., 2013; Jansen, Speckmann, & Schwinn, 2012; Rohrig et al., 2013). The results from the modelling were calculated with different stages of development of the REBal model. Therefore, results in the previous publications might differ when compared to the results of this publication. This thesis will describe the methodology used in the REBal model in detail and elaborate on the many additional aspects that have not been presented before. Results were computed with a common model setup for several years and different types of fluctuating RES generators. It provides the information required to answer the research question and fulfils the requirements from chapter 3.4.2.

Econometric model REBal

REBal is an econometric model that quantifies the welfare gain of fluctuating RES in the market, and thus applies the welfare economics theory. The model provides insight into the economics of control reserve provision of fluctuating RES for the supply side and the demand side. The modelling steps are visualized in Figure 4-1 and explained below the figure.



Source: Own analysis

Figure 4-1: Flow chart of REBal

Implementation in the REBal model

The REBal model presented here identifies the potentials and constraints for the delivery of control reserve from fluctuating RES generation (onshore and offshore wind farms and PV systems). The model is structured according to the following steps, which are explained in detail in the subchapters 4.4.1 to 4.4.8:

1. The offers placed on control reserve markets need to be at least as reliable as offers from the current market participants. Therefore, **probabilistic forecasts** (methodology 4.4.1; results 5.1) are used. The REBal model uses a kernel density estimator with Gaussian kernels. The result is a probabilistic forecast with different levels of reliability.

2. The **technical potential** (methodology: 4.4.2; results: 5.2) of the fluctuating RES is calculated for different combinations of restraining factors. These factors can be e.g. product length, gate closure time and security levels of the offer. The results are the offerable amounts on the reserve market.

3. The **opportunity costs** (methodology: 4.4.3.1; results: 5.3.1) for the provision of control reserve by fluctuating RES generators are calculated, resulting in tradable standard market products, i.e. **price/quantity pairs** according to Table 3-3. Different opportunity costs can be expected with varying regulatory framework conditions.

4. Additionally to the previous step, tradable **profit maximizing price/quantity pairs** (methodology: 4.4.3.2; results: 5.3.2) are created based on the expected additional income in the selected control reserve market. Since this approach is influenced by the market participants' expectancy, various combinations of bidding strategies can result.

5. The **bids** (price/quantity pairs) from number 3 and 4 are **matched** (methodology: 4.4.4) with the bids in the existing merit-order lists. If the bid of the fluctuating RES generator is cheaper than the bid in the market, the bid is accepted and replaces the current bid in the merit-order list. Based on the bid the possible **additional income** (methodology: 4.4.4, 4.4.5; results: 5.4) is calculated.

6. The **changes in costs** (methodology: 4.4.5; results: 6.1) through the participation of fluctuating RES generators are calculated using a **full dispatch simulation** for the capacity and energy bids. Costs of the

provision and dispatch of merit-order lists with and without bids from fluctuating RES are compared.

7. The **influence of the proof mechanism** (see Figure 3-17 and Figure 3-18) on the bidding behaviour of the fluctuating RES generators and their implications **in the spot market** (methodology: 4.4.6; results: 6.2) are investigated. If the unit has to be curtailed when reserve are contracted this energy is not available in the spot market. The economic value is determined.

8. The participation of wind farms and PV systems in the market allow to access **welfare gains** (methodology: 4.4.7; results: 6.3) in the market. The social welfare can increase or decrease depending on the market design.

9. Based on the welfare gains in the previous number the **welfare gains for the future are forecasted** (methodology: 4.4.8; results: 6.4). The forecast is performed for the year 2020 and the year 2030.

Classification of REBal

The outlined methodology of the REBal model shall be classified in order to relate this to other approaches. In chapter 3.4.3, different approaches have been presented and it has been concluded that a new methodology has to be developed. It has also been stated that a modelling for this specified task is likely more suitable than a more universal UC or AB model. In summary the REBal model would best be described as follows:

> **"REBal is an econometric hindcasting[15] model, using stochastic methods to calculate the value of fluctuating RES in the control reserve markets. "**

Previous approaches that have used methodologies that were adapted in REBal

REBal borrows several methodologies from different modelling approaches, which have been shown previously. The simplification of a stochastic problem to a deterministic problem has been previously applied by

[15] Hindcasting is also known as backcasting, backtesting, re-analysis, or retrodiction.

Zhang et al. (2013, p. 890) using analytical solutions. In REBal, this is the case for assessing the different levels of reliability as separate results. Zhang et al. have also used the technique of using real market data. The forecasting and application methods in step 1 and 2 have been presented previously by various authors (Bessa et al., 2012; Bowman & Azzalini, 1997; Foley et al., 2012; Juban, Fugon et al., 2007; Juban, Siebert et al., 2007). REBal uses the technique of cost-based assessment in step 3. The revenue maximizing approach in step 4 has been used in UC and AB models. Steps 5 and 6 can be commonly described as the merit-order principle (Sensfuß, 2010; Sensfuß et al., 2007). Step 6 follows the argumentation in Consentec (2008). Step 7 has previously been shown in Hirth (2013) and Hirth and Ziegenhagen (Hirth & Ziegenhagen, 2015) as the impact of fluctuating RES in the market, also called the merit-order effect.

4.2 Modelling assumptions

Main assumption for the REBal model

This chapter explains and justifies the underlying assumptions of the model. For further details, please also see chapter 3.4.1 and 3.4.2.

- The entire portfolio of the German wind farms and PV systems can be pooled (see chapter 4.3.5). According to the prequalification rules however, this would only be possible within one control area.

- The portfolio of offshore wind power plants is derived from a varying portfolio over time. In the beginning of the time series, a single wind power forecast represents the entire portfolio. Later on, data of a few wind farms are included, where data was available. Spatial variations of the feed-in between those wind farms are found to be high (Durante, Westerhellweg, & Jimenez, 2012, p. 67). To counteract possible inconsistencies arising from the data, the forecasts errors are calculated based on weather models (also see chapter 4.3.3.1). They are not derived from the feed-in and forecast time series of each individual wind farm, as it is the case for the other portfolios in this doctoral thesis. Therefore, data accuracy of the offshore wind farm pool is inferior when compared to the other portfolios. Weighing the inferior data accuracy against the possible additional information gained by including the offshore wind farm in the assessment, suggests using the data despite initial concerns. Using simulated forecast errors removes inconsistencies arising from changing portfolios compositions for the forecast error simulation. Figure 5-4 proves that the required quantiles of the simulated error data are met and the potentials to deliver control reserve are not overestimated due to underestimation of forecast errors. Later results suggest that the potential is as dependent on the forecast quality as much as it is dependent on the value of the point forecast (see onshore wind farm pools in Figure 5-7). The value of the point forecasts in total correlate to the energy available at each wind farm. Although a timely spatial difference between different wind farms exists, it can be assumed that the energy yield for the different wind farms is similar due to similar average wind speeds at FINO 1 and FINO 3 (Kindler, 2011, p. 13).

- Grid connection issues are not considered, especially n-1 security problems for offshore wind farms. It is assumed that the grid operators are responsible for providing adequate infrastructure in the future.

- The nominal installed capacity of the German portfolios is normalized to 30 GW. The technical potential (see chapter 5.2) can be displayed on a per unit (p.u.) basis, such as offering potential per MW installed. For comparability reasons, a constant installed capacity is assumed, disregarding growing portfolios over time. The installed capacity is essential for the economic assessment (chapter 5.3 and following) where results are expected to be changing in relation to the installed capacity. An installed capacity of 30 GW roughly averages the installed capacities of the years between 2010 and 2014.

- For the German pool of offshore wind power plants, an installed capacity of 1 GW is assumed. Considering that the real installed capacity was about 1 GW at the end of 2014 (AEE, 2015) it would be unrealistic to assume a pool of 30 GW as well.

- Growing portfolios are normalized to one constant value. The 1 GW pool of PV systems and the 1 GW pool of offshore wind farms have seen an especially large increase in installed capacity. It is likely that in the beginning these portfolios had bigger forecast errors than at a later points. Since the economic impact does not scale linearly, it is necessary to maintain the installed capacity constant to eliminate those effects from the results.

- It is assumed that prequalification requirements (chapter 3.2.4.2) are fulfilled by all fluctuating RES for all types of control reserve. There is good evidence that the technical requirements can be fulfilled by onshore wind farms and indicative evidence for PV systems (see chapter 3.3.1 and 3.3.2). Although more research is needed for offshore wind farms, the assumption is extended since the technology is similar to onshore wind farms.

- Due to uncertainties regarding technical capabilities, primary control reserve is not addressed in this thesis.

- The calculation of the offer assumes that all units in the pool are capable of delivering reserve power. They uniformly must be able to be curtailed freely between the available active power and zero. This assumption disregards the possibility that it might not be the case for all units at all the times.

- Daily bidding in the control reserve market is assumed since fluctuating RES cannot be forecasted reliably for more than 72 hours (Giebel, Brownsword, Kariniotakis, Denhards, & Draxl, 2011, pp. 47–48; Holttinen, Miettinen, & Samuli, 2013, p. 10). For the tertiary control reserve market a week-daily tendering is currently carried out. Secondary and tertiary control reserve markets are tendered weekly (see Table 3-3 Control reserve specifications). Merit-order lists are used from the weekly tendering and treated as if they were tendered on a daily basis. If those markets were tendered daily one could expect price changes (Haucap et al., 2012, p. 28) which are being disregarded. However, fluctuating RES could participate in the control reserve market today through a control reserve pool.

- The desired security levels are only influenced by the forecast errors. Other reasons such as outages by units, connection line outages, unprecedented redispatch or the error from determining the available active power signal are not considered. This is mainly because those factors cannot be accounted for accurately enough.

- The finest data resolution is 15 minutes. Fluctuations on a shorter basis cannot be accounted for due to the lack of data. It is assumed that those short variations are balanced out due to the pooling and dispersion effects of fluctuating RES.

- FIT can be used as an average value for an entire portfolio. Due to the minor fluctuations of the FIT for (onshore) wind farms, this assumption is extended to offshore wind farms and PV systems (see Figure 3-1). The feed-in tariffs used for the assessment are 89.5 EUR/MWh for onshore wind farms, 150 EUR/MWh for offshore wind farms and 90 EUR/MWh for PV systems. For onshore and offshore wind farms, this is the initial FIT. For PV systems, this represents the FIT by the end of the year 2014 for non-rooftop PV systems.

- It is also assumed that market participants are perfectly informed about future prices (perfect price forecast). This is necessary to identify the maximum additional income in the profit maximizing strategies (see number 4 in chapter 4.1 and chapter 4.4.3.2). Imperfect price forecasts would lead to a different bidding behaviour and would not identify the welfare gains accurately. Price forecasting is challenging and would require separate investigations as in Kian and Keyhani (2001).

4.3 Data used in the model

The impact of fluctuating RES on the control reserve markets is assessed based on historical data. For this reason, the data used in the REBal model are presented in this chapter. The assessment period stretches from the year 2010 to 2014. All data is processed in the time zone UTC+1 (CET)

Hindcasting uses real data

4.3.1 Market prices

4.3.1.1 Wholesale market prices

The price information and market data of the wholesale electricity market are obtained from EPEX SPOT (EPEX SPOT SE, 2015d). The day-ahead auction data can be downloaded freely from the homepage on a day-to-day basis (EPEX SPOT SE, 2015a). The same applies for the intraday auction data (EPEX SPOT SE, 2015b) and the intraday continuous trading data (EPEX SPOT SE, 2015c). More conveniently all three data sets can be downloaded through a fee-based ftp-server (EPEX SPOT SE, 2015e). All data is based on hourly price information.

Data sources for the spot market

An intraday call auction was introduced on the 9th of December 2014 (EPEX SPOT SE, 2014d), was 15-minute intraday continuous trading on the 14th of December 2011 (EPEX SPOT SE, 2011). The data does not span the entire assessment period and is therefore not used. Resulting errors even out over the year and are disregarded.

Using hourly data in REBal

The gate closure of the spot market is assumed to be one hour throughout the assessment period. It has been reduced several times during the assessment period. Lastly, the lead time of the intraday market was reduced to 30 minutes from the 16th of July 2015 (EPEX SPOT SE & European Commodity Clearing, 2015).

One-hour gate closure time in REBal

4.3.1.2 Balancing energy prices

Balancing energy price reBAP at regelleistung.net

The balancing energy price has to be paid by the balancing responsible parties (BRP) for imbalances between the schedule and the physical delivery. The balancing energy price reBAP (see chapter 3.1.1) is calculated by the German TSOs (50Hertz Transmission GmbH et al., 2012b). It can be acquired at the website of regelleistung.net. The reBAP has been calculated for all four TSOs together since the 1st of May 2010 (50Hertz Transmission GmbH, 2015).

Changes in the price calculation methodology over time

Prices prior to that exclude the control area of Amprion. For the time before the 1st of May 2010, it is assumed that the reBAP was applicable in all four balancing areas. The calculation schemes of the reBAP have changed in December 2012 (Bundesnetzagentur, 2012a), but despite these changes the reBAP can be seen as a price input only. Therefore, behavioural changes are very unlikely since they could only be exploited with strategic bidding that has been excluded in the modelling approach.

4.3.1.3 Control reserve prices

Control reserve merit-order lists at regelleistug.net

The control reserve prices in the form of complete merit-order lists can be obtained from regelleistung.net (50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH et al., 2013). They are available for the entire assessment period. The product lengths were shortened by the Federal Network Agency (BNetzA) in 2011 (Bundesnetzagentur, 2011c, 2011d, 2011e).

Price changes in 2011

The primary and tertiary control reserve product lengths were shortened as of June 27th 2011. Exact product details are discussed in chapter 3.2.4.1. From the 1st of December 2011, the minute reserve was tendered week-daily for four-hour blocks. Subsequently, price changes in the tertiary control reserve market were observed (Haucap et al., 2012, p. 9). One has to take into account that the results may differ depending on the product length. Shortening the product length has led to decreasing prices. Therefore, the economic potential of fluctuating RES in the control reserve markets might be reduced. The availability of other data sets for the year 2010 (i.e. single wind farms) encourages use of the market data despite possible concerns.

4.3.2 Electricity consumption

ENTSO-E electricity consumption data

The energy consumption for Germany can be retrieved from the ENTSO-E website at (ENTSO-E, 2015). The data is available for the entire assessment period. Although the data of the original source does not add up to the official statistical values (Bundesministerium für Wirtschaft und Energie, 2015a), the ENTOS-E data is multiplied by a factor to account for the error. This guarantees that the sum of the data is equal to the official statistics whilst maintaining the information on the shape of the load curve.

4.3.3 Time series of fluctuating RES generators

4.3.3.1 Wind farm data

Entire German 30 GW wind farms portfolio

Wind farm data can be obtained from (eex, 2015b) or through a ftp-server (eex, 2015a). The day-ahead forecasts are available at (eex, 2015f) and the extrapolated feed-in at (eex, 2015d). The data is provided for each control area individually. The data is available for the entire assessment period. The one-hour intraday forecast is created according to chapter 4.4.1.3, due to the lack of data from official sources. The 30 GW pool has a day-ahead forecast that has an nRMSE (normalized root mean square error) of 4.74 %, which is in line with the findings by Lange et al. (2011) and Schulz (2011, p. 13). The nRMSE for a one-hour-ahead intraday forecast is 1.12 %, which is significantly lower than the 1.5 % in Lange et al. (2011) and slightly lower than in Schulz (2011, p. 13). The better forecast quality might be due to better knowledge of the state of the wind farms and the persistency-based forecast.

1 GW portfolio of individual wind farms for the years 2007-2010 and 2012- 2013

Wind farm data on individual wind farms include the day-ahead forecast, the intraday forecast and the measured actual feed-in. These data sets were also gathered and created in the project “Regelenergie durch Windkraftanlagen”

(Brauns et al., 2014, pp. 54–55). The data basis is the same as used in the thesis of Dobschinski (2016). The data used is available for the day-ahead and the feed-in time series for the years 2007-2010 and 2012-2014. The intraday forecast is also based on the persistency forecast, which facilitates the comparability with the 30 GW pool. The pool of 1 GW was assembled by hand from a large range of data sets of individual wind farms and subsequently aggregated. The wind farms were selected by their overall data quality and availability. Apparent measuring errors were removed selectively. The pool of 1 GW is chosen since it represents an average wind farm pool of a direct marketer. The arithmetic average size of a direct marketer's wind farm pool is 1,375 MW and the median is 900 MW, based on a survey by Energie&Management (2016),. Twelve out of 27 direct marketers have a portfolio size of 1 GW and more.(Energie&Management, 2015b, p. 35) For the calculation of the probabilistic forecast, only the data from 2007 to 2010 were used, since these data produced better results than if the entire span was used. The resulting nRMSE of the day-ahead forecast is 5.98 % whereas the nRMSE of the one-hour ahead intraday forecast is 1.56 %. This shows that the forecasts are less reliable than for the 30 GW pool in total. However, the size of 1 GW for the pool appears to be large enough so that portfolio effects can be accessed. All wind farm data is available on a 15-minute time resolution.

German 1 GW pool of offshore wind farms

The German 1 GW pool of offshore wind farms includes the day-ahead forecast as a meta forecast[16] as well as the measured actual feed-in for the years 2010/2011 and 2013/2014. These data were obtained during the course of several projects. The data are not publicly available although they can be approximated with the data from the TSO TenneT TSO GmbH which publishes the share of offshore wind energy (TenneT TSO GmbH, 2015). The data can be further approximated with the help of official data by the Danish TSO energinet.dk (Energinet.dk) since the German and Danish wind farms are in relative proximity and have similar production patterns. As mentioned

[16] Meta forecast describes a forecast that is joined from different forecasts according to desirable selection criteria

in the modelling assumptions, wind speeds have significant temporal spatial variations (Durante et al., 2012, p. 67). The forecast error is modelled based on weather data and is not dependent on the spatial temporal variations of the wind power feed-in. The average wind speeds at the two offshore wind measuring platforms FINO 1[17] and FINO 3[18], which are approximately 135 km apart, have very similar average wind speeds, 9.4 m/s for FINO 1 and 9.9 m/s for FINO 3 with otherwise similar monthly wind speed patterns (Kindler, 2011, p. 13). The similar results for both platforms allow generating the data from combining the aforementioned sources, since the forecast error time series for the probabilistic forecast is used as per the approach in Rohrig et al. (2013, pp. 40–43), using simulated forecast errors based on realistic assumptions and weather data. However, it is possible that not all extreme values are modelled correctly. This aspect of the fat-tails-theory (Hodge et al., 2012) was mentioned in chapter 3.3.2. The nRMSE of the day-ahead forecast is 8.48 %, and the nRMSE of the one-hour ahead intraday forecast is 7.85 %. The nRMSEs from the used methodology (Rohrig et al., 2013, pp. 40–43) are 7.64 % and 1.49 %.

4.3.3.2 PV systems data

German 30 GW pool PV systems available at eex-transparency.com

The PV systems data for the entire German 30 GW pool can be obtained from eex-transparency.com (eex, 2015b). The day-ahead forecast of PV systems can be obtained from (eex, 2015e). The feed-in data are based on an upscaling algorithm since not all units are measured directly. Based on the units that are actually measured, the generation of all PV systems is extrapolated. These data can be downloaded at (eex, 2015c). The data are normalized over the entire assessment period using the installed capacity. Equally to the market data (chapter 4.3.1) these data can be accessed through a fee-based ftp-server (eex, 2015a). The data are provided for each control

[17] Coordinates FINO 1: 54°0.86' N 6°35.26' E (Durante, Westerhellweg, & Jimenez, 2012, p. 69)
[18] Coordinates FINO 3: 55°11.7' N 7°9.5' E (Durante, Westerhellweg, & Jimenez, 2012, p. 69)

area individually. The data are available for the entire assessment period between January 2010 and December 2014.

Data quality of the 30 GW pool and creation intraday forecast

The data quality of the day-ahead forecast of the 30 GW pool has an nRMSE (normalized root mean square error) of 5.21 %, excluding hours without generation. The forecast accuracy is higher than shown in Lange et al. (2011) and is close to fulfilling the requirements in (Schulz, 2011, p. 13). Since the publication is from 2011 one can assume that the improvement over the recent years has increased the forecast quality. The intraday forecast is generated according to chapter 4.4.1.3, due to the lack of data from official sources. Persistency forecasts are less reliable for PV systems than for wind farms, due to the periodicity of the feed-in. The nRMSE for a one-hour-ahead intraday forecast is 2.02 % which fails to fulfil the required forecast quality in (Schulz, 2011, p. 13)

1 GW pool of PV systems

PV systems data on individual systems include the day-ahead and intraday forecast as a meta forecast as well as the measured actual feed-in. The data sets were obtained during several research projects at the Fraunhofer IWES, in collaboration with the project partners. One of these is the project "Regelleistung durch Wind- und Photovoltaikparks" (Stromnetze, 2015). The data from this project is not publicly available. The day-ahead forecast and the actual feed-in are available from the 31st of October 2012 to the end of 2014. The intraday forecast is available from the 1st of October 2012 to the end of 2014. All data of the PV systems are available with a 15-minute time resolution. The nRMSE of the day-ahead forecast is 6.95 %, and the nRMSE of the one-hour ahead intraday forecast is 3.19 %. Compared to the 1 GW pool of onshore wind farms this value is significantly lower. The 1 GW pool of PV systems is based on real forecasts whereas the pool of onshore wind farms is based on persistency forecasts. Persistency forecasts assume the online measurement of the entire portfolio, which cannot be assumed for the real forecast of the pool of PV systems. Certain weather effects pose an additional challenge for the forecast accuracy of PV systems.

4.3.3.3 Installed capacity of wind farms and PV systems

Installed capacity

The installed capacity of the wind farms and PV systems was published in the EEG-Stammdaten until the 31st of July 2014. A refinement of this data set is available at energymap.info (EnergyMap, 2015), the use of which is highly recommended as this refined data set is more reliable than the official statistics. Since the 31st of July, data have been collected by the BNetzA. However, these data are not published yet and according to EnergyMap it is unlikely that usable data will be published in 2016. For the period between the 31st of July and the 31st of December 2014, errors may occur when the data is normalized. This may lead to increased forecast errors and therefore decreased potentials for the offering of control reserve. As a result, the economic impact could be slightly underestimated.

4.3.4 Control reserve dispatch

Control reserve dispatch data

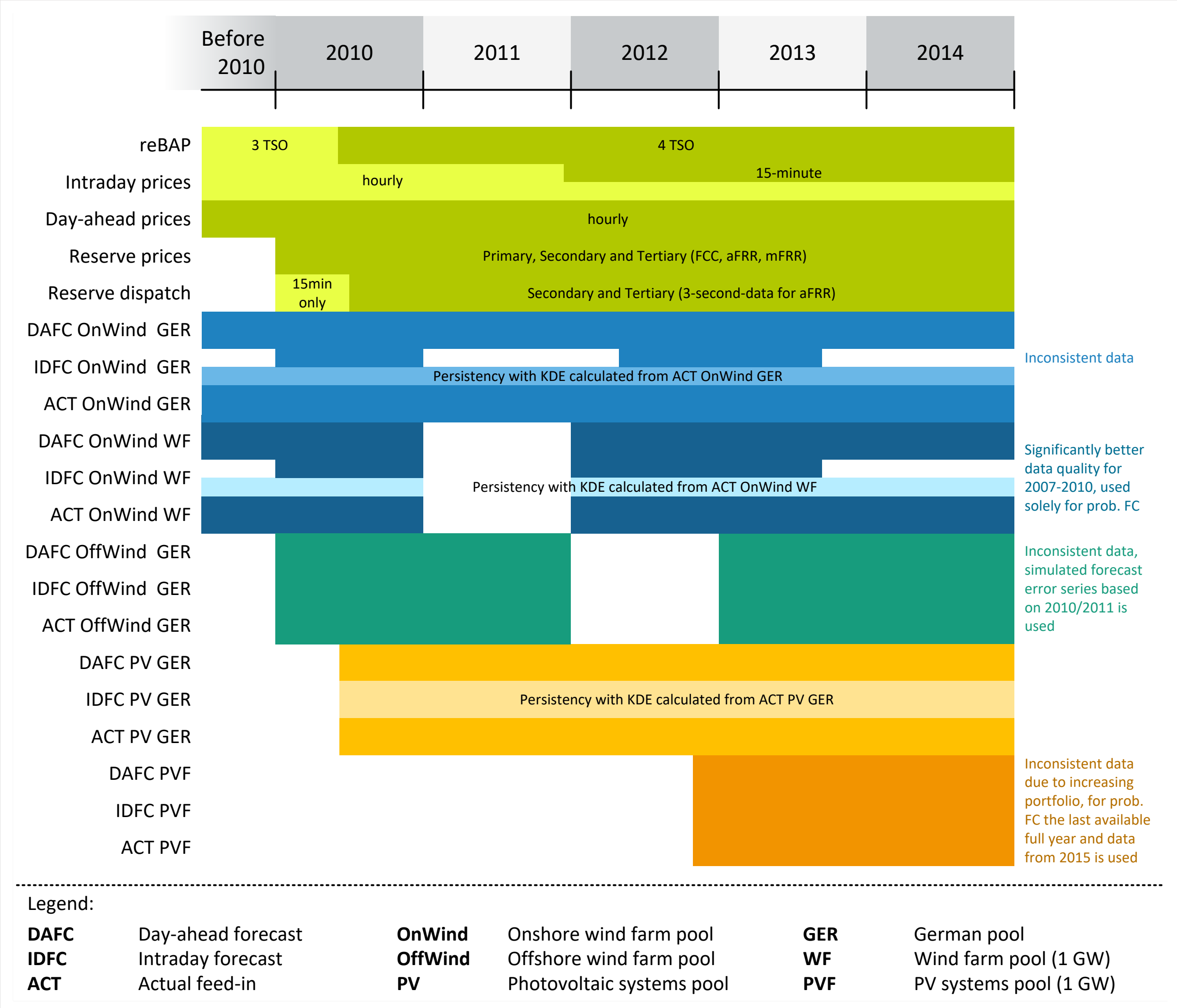
The dispatch of secondary and tertiary control reserve is used to calculate the costs of the dispatch. Data with a time resolution of 15 minutes can be downloaded at regelleistung.net (50Hertz Transmission GmbH et al., 2015d) for the entire assessment period. A higher time resolution is necessary for the correct calculation of the dispatch costs of the secondary control reserve. The signal for the dispatch of secondary control reserve provides data with a 4-second time resolution, which allows a precise cost calculation. The data are available through personal contact with one of the four TSOs. High resolution data used in this thesis are available from the 1st of July 2010 onwards. Prior to the 1st of July, the 15-minute data are used instead. This may introduce a small error in the dispatched energy for the year 2010 that will be disregarded in order to be able to model an entire year. The total dispatched energy for negative and positive secondary control reserve for the entire year 2010 with 4-second data from July to December and 15-minute data from January to June is 4.76 TWh. The dispatched energy with 15-minute data only is 4.65 TWh, which is 2.2 % less than with the high-resolution data. Similarly, for the year 2011 the dispatched energy with

4-second data for the entire year is 5.66 TWh. 15-minute data yields 5.41 TWh, which 4.3 % lower.

4.3.5 Summary and overview

Data availability

The following figure summarizes the availability of the data sets used and indicates important aspects where data consistency or quality might be affected.



Source: Own analysis

Figure 4-2: Availability of data used in REBal

Colour coding of the data sets

The data availability is summarized graphically in Figure 4-2. The control reserve related data and market prices are shown in lime green. Inconsistent data sets are marked with a lighter shade of lime green. The 30 GW pool of wind farms is shown in blue. The intraday forecast is available in the data but not used. If the persistency forecast is used it is indicated by the text and the lighter colour shade. The 1 GW pool of individual wind farms is shown in dark blue whereas the 1 GW pool of PV systems is green. The 30 GW pool of PV systems is marked in yellow, the 1 GW pool in darker yellow. The colour coding of the fluctuating RES generators will be used in the results chapters 5 and 6.

4.4 Modelling Steps in detail

This subchapter explains the modelling steps in detail, which includes the implementation of REBal in the Matlab environment.

4.4.1 Probabilistic forecast with kernel density estimators

"Unpredictability" of fluctuating RES with current forecasts

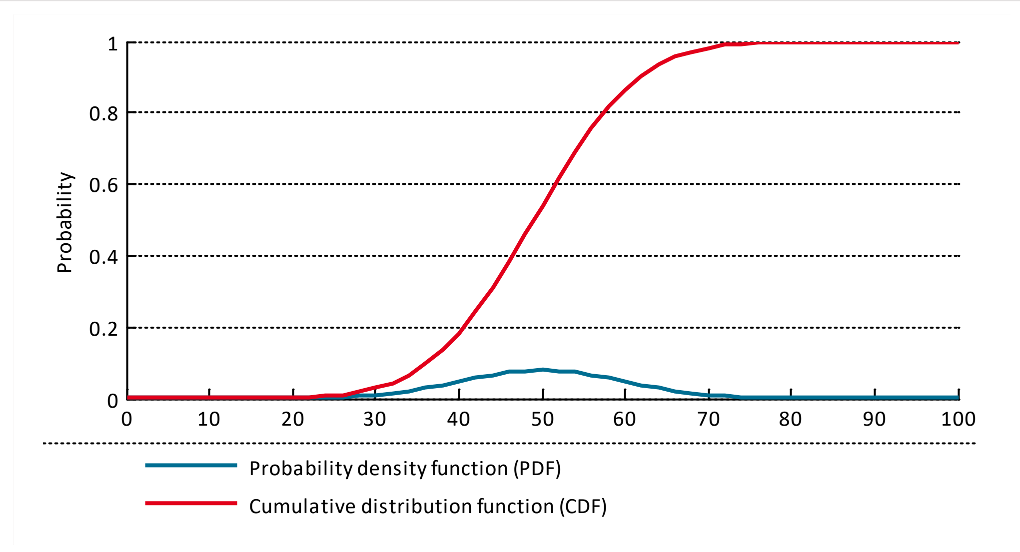
The offers placed on control reserve markets from fluctuating RES need to be as least as reliable as offers from the current market participants. Due to the fluctuating nature, this cannot be guaranteed with the current methods applied. This specifically addresses the forecasts used. Current forecasts for fluctuating RES only provide values with the highest probability, the so-called expected value. The level of reliability is 50 %, with a 50 % chance that the observed value will surpass the forecasted value or fall short of it. Other levels of reliability are not considered. This is called deterministic forecasting.

How often/long can the forecast not be met?

Probabilistic forecasts with very high levels of reliability are influenced by extreme values. If the reliability of a forecast over a year is 99.99 % then the time where the forecasted data exceeds the feed-in shall not be more than 52 minutes per year. Accordingly, increasing the forecast reliability to 99.999 % changes this number to 5 minutes.

Gaining additional information with probabilistic forecasts

Offering control reserve with wind farms and photovoltaic systems requires a defined level of reliability that has to be guaranteed by the market participant. The use of probabilistic forecasts allows the allocation of probabilities to a forecast value (see e.g. (Pinson, 2006)). Probabilistic forecasting allows the generation of several values for the same time horizon. This means that for one event in the future several forecast values can be generated. Each value is given with its related probability. These can be displayed as a continuous probability function, which would not be possible with the aforementioned deterministic forecasting. The continuous functions are called the probability density function (PDF) and cumulative distribution function (CDF), as shown in Figure 4-3. The CDF is the integral of the PDF and is monotonously increasing with values from 0 to 1. By deriving the CDF one holds the PDF again (see e.g. (Walck, 2007, pp. 119–120)). For discrete forecast values (e.g. 99 %), predictive intervals are calculated from the PDF and the CDF. Figure 4-3 shows the CDF in blue and the PDF in red for a normal distributed random variable.



Source: Own analysis based on (Walck, 2007, pp. 119–200)

Figure 4-3: Gaussian probability density function (PDF) and cumulated probability function (CDF)

4.4.1.1 Kernel density estimator

Comparing the kernel density estimator with other probabilistic forecasting methodologies

Previously several different approaches for the creation of probabilistic forecasts have been shown (also see chapter 3.3.2). A summary of three selected forecast algorithms can be seen in Brauns et al. (2014, pp. 34–42). The investigated methodologies are the kernel density estimation, the quantile regression and the physical-stochastic model. Based on the same input data, all three options provide similar results (Brauns et al., 2014, p. 42). The KDE approach is found to be equal or superior to other forecasting methods in terms of sharpness[19] and resolution[20] (Juban, Fugon et al., 2007, pp. 8–9; Juban, Siebert et al., 2007). Juban, Fugon et al. (2007, p. 8) state that the KDE approach, even with an un-optimized bandwidth (see further down), is marginally superior over quantile regression based forecasts. The quantiles of the KDE approach deviate less from the perfect reliability than the quantiles of the quantile regression approaches (Juban, Fugon et al., 2007, p. 8).

Advantages and disadvantages of the KDE approach

The advantage of the KDE approach is the complete estimation function, which can be used to extract any desired quantiles from it. Quantile based methodologies only calculate the estimation function for pre-defined quantiles (Juban, Fugon et al., 2007, p. 9). Since the KDE approach is a non-parametric model, the approach is universal enough to be applied to other problems as well (Juban, Fugon et al., 2007, p. 5,10). One of the disadvantages are the relatively high computational intensity (Juban, Fugon et al., 2007, p. 3), especially when large data sets are used. This is overcome with the use of a high performance cluster by the REBal model.

Choosing the KDE approach for the calculation of probabilistic forecasts

Evaluating the different options to calculate the probabilistic forecasts, the KDE approach holds the most advantages. It is therefore applied in the REBal model and used in this doctoral thesis. The kernels of the KDE are Gaussian kernels; it is therefore called Gaussian KDE.

Choosing the KDE in the REBal model

In Pinson and Madsen (2009, p. 141) it is argued that any probability density function can be approximated as a sum of Gaussian kernels. Bowman and Azzalini (1997, p. 3) state that the exact shape of the kernels is not essential. It should be pointed out, that the most suitable forecasting algorithm has yet to be identified by research. Therefore, the REBal forecast module can be

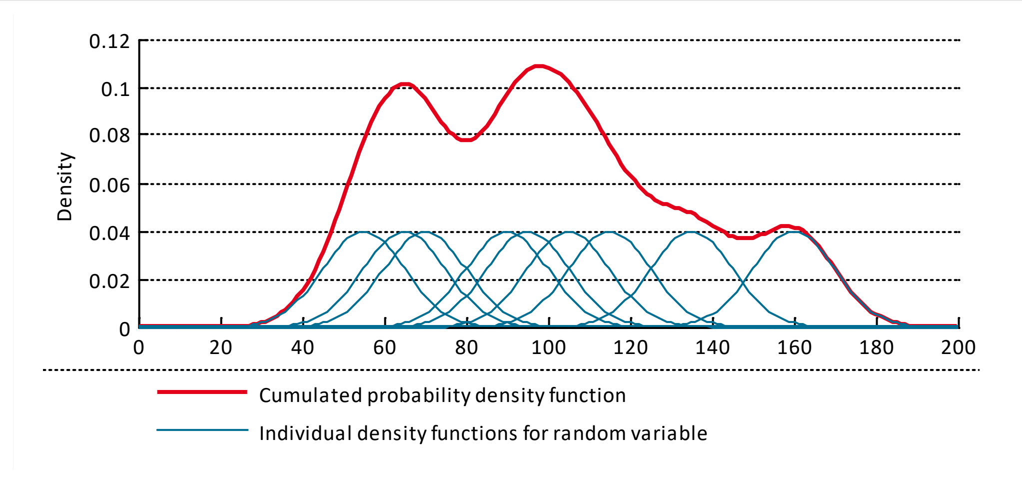
[19] Sharpness describes an indicator that measures the ability of a forecasting methodology to forecast extreme probabilities at the tails of the distribution. It allows assessing the usefulness of the methodology to provide reliable information under uncertainty. (Juban, Fugon, & Kariniotakis, 2007, pp. 8–9)

[20] Resolution is an indicator that measures the ability to provide situation dependent forecasts, i.e. the entire range of fluctuating RES forecasts. (Juban, Fugon, & Kariniotakis, 2007, pp. 8–9)

changed to accommodate other algorithms. The forecast creation presented here is also presented in Speckmann (2016). This is due to the fact that Speckmann relied on the REBal model to create the forecasts in the thesis. This has been marked in the thesis of Speckmann accordingly.

The principles of kernel density estimation (KDE)

The Gaussian KDE is a non-parametric technique[21] that can be used to estimate the probability density function of a given forecast for the future, based on historic forecast and feed-in data. This is based on the approach that each value of a random variable is replaced by a kernel (blue curves in Figure 4-4). This kernel can have different probability functions in itself. For this thesis Gaussian kernels are chosen. Subsequently these kernels are aggregated which results in a normalized PDF. (Bowman & Azzalini, 1997, p. 3)



Source: Own analysis based on (Bowman & Azzalini, 1997)

Figure 4-4: Illustration of a one-dimensional kernel density estimator probability density function based on Gaussian kernel function for one random variable

One-dimensional KDE

The equation for a one-dimensional generalized KDE can be written as equation (4-1) (Bowman & Azzalini, 1997, p. 3). At this point, it has to be noted that a one-dimensional KDE will only be able to predict a single random variable and that is not in relation with a second variable.

[21] No preselected distribution is fitted to the data. The shape of the PDF is a result of the input data.

$$\hat{f}(y) = \frac{1}{n}\sum_{i=1}^{n} w\,(y - y_i, h) \tag{4-1}$$

with:

$\hat{f}$	: density estimation
w	: probability density
$y - yi$	: observed value pairs
h	: bandwidth of kernel function
n	: number of value pairs

Two-dimensional KDE for day-ahead forecasts

A two-dimensional KDE is needed for day-ahead forecasts for fluctuating RES where one random variable (i.e. day-ahead forecast) is dependent on a second random variable (i.e. forecast error). According to (Bowman & Azzalini, 1997, p. 6) equation (4-1) can be expanded to account for an additional variable which yields equation (4-2). In the case of the probabilistic forecast $y_1 - y_{1i}$ are the forecast values (observed in the past) and $y_2 - y_{2i}$ the according forecast errors for the same time.

$$\hat{f}(y_1, y_2) = \frac{1}{n}\sum_{i=1}^{n} w(y_1 - y_{1i}, h_1) \cdot w(y_2 - y_{2i}, h_2) \tag{4-2}$$

with:

$\hat{f}$	: density estimation
w	: probability density
$y_1 - y_{1i}$	: observed value pairs of first random variable
$y_2 - y_{2i}$	: observed value pairs of second random variable
h_1	: bandwidth of first kernel function
h_2	: bandwidth of second kernel function
n	: number of value pairs

n-dimensional KDE for intraday forecasts

This function can be expanded into the n-dimensional space to accommodate for additional factors. In the case of the probabilistic forecast for fluctuating RES, these are conditional pre-errors, which are incorporated into the KDE forecasting module of REBal. The inclusion of pre-errors for short-term forecasts allows an increase of the reliability and sharpness of the forecasts, although the amount of necessary data does also increase. REBal uses two sets of pre-errors for the KDE, represented by the value pairs $y_3 - y_{3i}$ and $y_4 - y_{4i}$.

Pre-errors in a KDE

Pre-errors are errors between the forecast and the feed-in that have been observed prior to the creation of the forecast for the target time period. The information from a forecast deviation that has previously occurred is correlated with the probability density from equation (4-2). The described pre-error setup is exemplary for a forecast that is created at 14:00 for the time between 15:00 and 15:15. In this case, the forecast errors that occurred between 13:45 and 14:00 and between 13:30 and 13:45 are used as forecast errors for a one-hour-ahead probabilistic forecast. Expanding equation (4-2) by two more dimensions yields equation (4-3) (Bowman & Azzalini, 1997, p. 10):

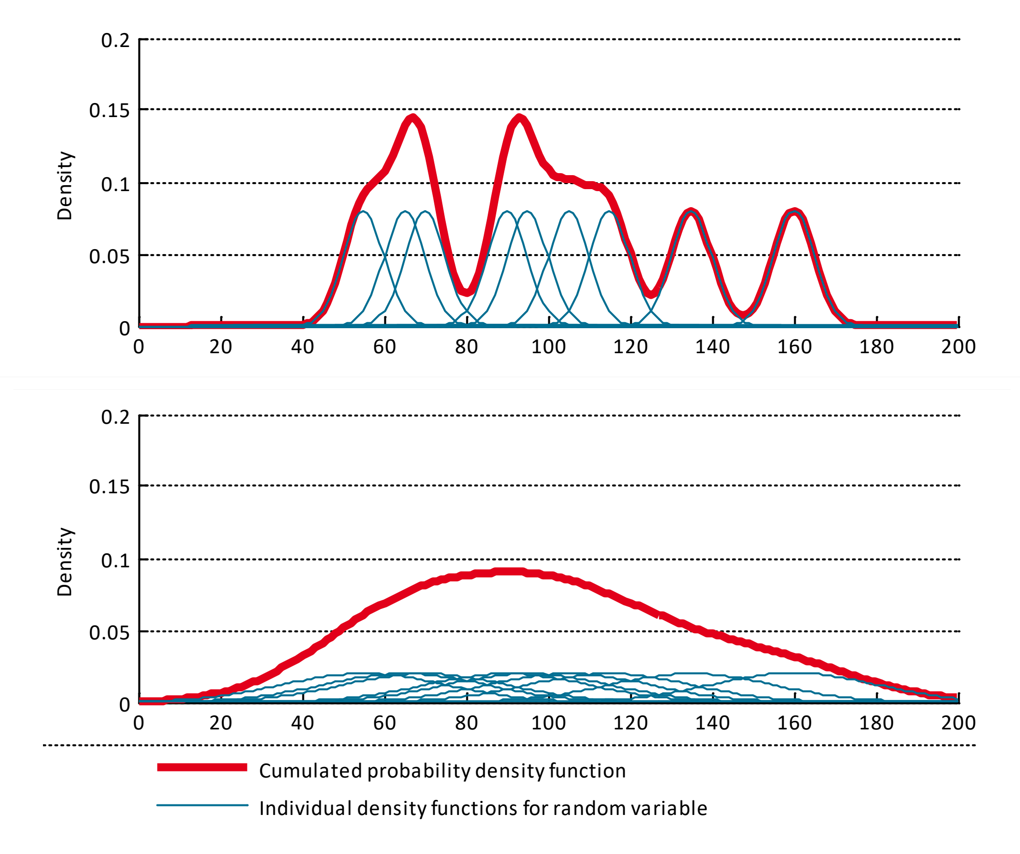
$$\hat{f}(y) = \frac{1}{n}\sum_{i=1}^{n} w(y_1 - y_{1i}, h_1) \cdot w(y_2 - y_{2i}, h_2) \cdot w(y_3 - y_{3i}, h_3) \cdot w(y_4 - y_{4i}, h_4) \tag{4-3}$$

with:

$\hat{f}$	: density estimation
w	: probability density
$y_1 - y_{1i}$	: observed value pairs of first random variable
$y_2 - y_{2i}$	: observed value pairs of second random variable
$y_3 - y_{3i}$	: observed value pairs of third random variable
$y_4 - y_{4i}$	: observed value pairs of second random variable
h_1	: bandwidth of first kernel function
h_2	: bandwidth of second kernel function
h_3	: bandwidth of first kernel function
h_4	: bandwidth of second kernel function
n	: number of value pairs

Bandwidth of the kernel function in the KDE

The determination of the bandwidths h_1 and h_2 of the kernels w in equation (4-2) and $h_1, \ldots, h_4$ in equation (4-3) has been subject to various scientific discussions (Chaudhuri, Chaudhuri, & Murthy, 1996, p. 1720; Kristan, Leonardis, & Skočaj, 2011, p. 2632). The bandwidth determines the smoothing of the kernels in the KDE. The effect of different bandwidths on the probability density estimation can be seen in Figure 4-5. In both cases, the same input and kernel functions have been used as in Figure 4-4, only the bandwidth was adjusted. Compared to Figure 4-4 the bandwidth in the upper graph was multiplied by 0.5 whereas in the lower graph it was multiplied by two.



Source: Own analysis based in (Bowman & Azzalini, 1997, pp. 3–4)

Figure 4-5: The effect of different bandwidths on the probability density estimation for a one-dimensional and two-dimensional KDE

The influence of the bandwidth

It can be seen that small bandwidths might be too sensitive whereas large bandwidths might smear out the probability density estimation too much. Small bandwidths allow for the identification of single data points, while larger bandwidths show more of the functional relationship between the data points. The accurate estimation of forecast errors for the probabilistic forecast is only possible if the bandwidths of the kernels are calculated appropriately. In this thesis the bandwidth for the calculation of probabilistic forecasts is based on the approach in Bowman et al. (Bowman & Azzalini, 1997, pp. 31–32). For all $h_1, \dots, h_4$ the bandwidth h_i is then:

$$h_i = \left(\frac{4}{(d+2)n}\right)^{\frac{1}{d+4}} \cdot \sigma_i \qquad (4\text{-}4)$$

with:

with:	d	: number of dimensions
	σ_i	: standard deviation of dimension i
	i	: dimension number
	n	: number of value pairs

Accounting for the tails of the distribution estimation

Bowman and Azzalini also propose to alter the calculation of σ_i to counteract undesirable effects in the tails of the density distribution estimation. Replacement of the standard deviation σ_i with the median absolute deviation estimator $\tilde{\sigma}_i$ has been suggested (Bowman & Azzalini, 1997, p. 31).

$$\tilde{\sigma}_i = \frac{median|(y_i - \tilde{\mu})|}{0{,}6745} \tag{4-5}$$

with:
- $\tilde{\sigma}_i$: median absolute deviation estimator
- y_i : value set of value pairs $y_1 - y_1$ to $y_4 - y_{4i}$.
- $\tilde{\mu}$: median of the sample

Replacing the kernel function with the normal distribution function

As described earlier, the kernel function w can have different functions. For this assessment a Gaussian kernel function was chosen, as discussed earlier. Therefore w is then replaced with a normal distribution function (Bowman & Azzalini, 1997, p. 3).

$$w(y - y_i, h) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\left(-\frac{(x-\mu)}{2\sigma^2}\right)} \tag{4-6}$$

with:
- w : kernel function
- $y - yi$: value pairs
- h : variance of kernel function
- σ : standard deviation
- μ : median deviation
- x : value of random variable

2-dimensional KDE with Gaussian kernels

In equation (4-3) the kernel function w is filled with Gaussian kernels from equation (4-6) The KDE with Gaussian kernels is the probability density function $\hat{f}_{DA}$ for the day-ahead probabilistic forecast with the input of the forecast and the forecast error, following Speckmann (2016).

$$\hat{f}_{DA}(P_f, P_e) = \frac{1}{n}\sum_{i=1}^{n} \frac{e^{-\frac{1}{2}\left(\frac{P_f - P_{f,i}}{h_f}\right)^2}}{h_f\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_e - P_{e,i}}{h_e}\right)^2}}{h_e\sqrt{2\pi}} \tag{4-7}$$

with:
- $\hat{f}_{DA}$: density estimation for the day-ahead forecast
- $P_f - P_{f,i}$: forecast value pair
- $P_e - P_{e,i}$: forecast error value pair
- h_f : bandwidth forecast
- h_e : bandwidth forecast error

Forecast values and forecast errors

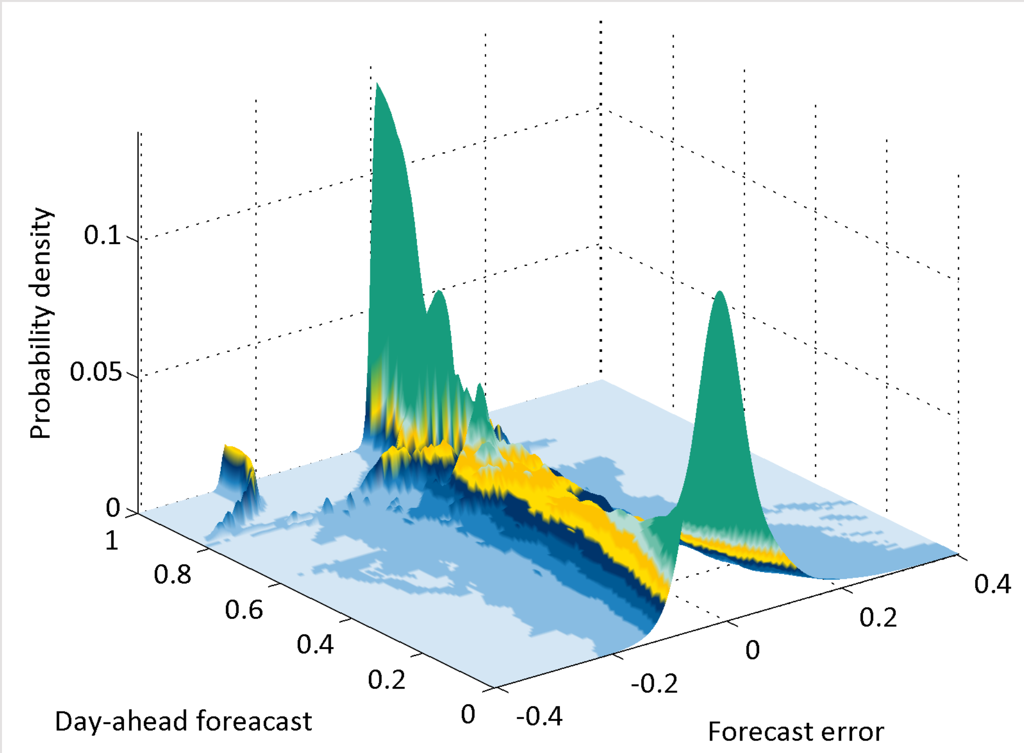
P_f and P_e are the value pairs of the forecast and the forecast error for which the probability estimation is created. $P_{f,1}$ to $P_{f,n}$ are the values of the forecast, and $P_{e,1}$ to $P_{e,n}$ are the values for the forecast error over the number of value pairs n.

Graphical results of the distribution estimation

The estimation function gained from the KDE for the day-ahead data can be seen in Figure 4-6 below for the 30 GW wind farm pool. The KDE for the intraday data is omitted at this point due to problems of plotting five-dimensional graphs. The estimation functions for the other pools can be seen in Appendix A. The x-axis shows the normalized day-ahead forecast from zero to one, with one equal to the installed capacity, and the y-axis shows the forecast error from -0.4 one to 0.4, where minus one and one would be equal to 15 standard deviations of the probability density function. Therefore -0.4 and 0.4 equals six standard deviations. On the z-axis, the normalized probability distribution for each day-ahead forecast from zero to one is depicted. For each forecast value on the x-axis, a CDF (see Figure 4-3) can be extracted that has the maximum value of one. The z-values are formed by the PDF functions for each x-value from one to zero; their sum therefore cannot be one. The probability density function (z-values) is an approximation of individual forecast (x-values) and forecast error (y-values) data points that were fitted with Gaussian kernels and integrated subsequently.

Interpreting of the two-dimensional KDE

The resulting estimation function has two peaks, one at full load and one at zero. This means that the forecast at this point has a high certainty and the distribution of forecast errors is narrow. This is due to the fact that full load and idle can be forecasted relatively easily. However, a small ridge in the bottom left corner indicates that single events can deviate significantly from the main peak, in this case a single storm event. One can identify single data points and the shape of each Gaussian kernel in this section. In the middle section of the graph, approximately between 0.2 and 0.8, the forecast errors are less narrow. This can be explained by the highest forecast errors during ramping of the wind turbines, where a small change in the wind speed leads to a relatively high change in power output.



Source: Own analysis

Figure 4-6: Illustration of the two-dimensional KDE based for the day-ahead probabilistic forecasting of the German 30 GW onshore wind farm pool

4-dimensional KDE with Gaussian kernels

Likewise, the kernels in equation (4-3) are replaced with Gaussian kernels from equation (4-6). The KDE with Gaussian kernels is the probability density function $\hat{f}_{ID}$ for the intraday probabilistic forecast.

$$\hat{f}_{ID}(P_f, P_e, P_{pe,1}, P_{pe,2}) = \frac{1}{n}\sum_{i=1}^{n} \frac{e^{-\frac{1}{2}\left(\frac{P_f - P_{f,i}}{h_f}\right)^2}}{h_f\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_e - P_{e,i}}{h_e}\right)^2}}{h_e\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_{pe_1} - P_{pe_1,i}}{h_{pe_1}}\right)^2}}{h_{pe_1}\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_{pe_2} - P_{pe_2,i}}{h_{pe_2}}\right)^2}}{h_{pe_2}\sqrt{2\pi}} \quad (4\text{-}8)$$

with:

$\hat{f}_{ID}$	: density estimation for the intraday forecast
$P_f - P_{f,i}$	: forecast value pair
$P_e - P_{e,i}$	: forecast error value pair
$P_{pe_1} - P_{pe_1,i}$	: first pre-error value pair
$P_{pe_2} - P_{pe_2,i}$	: second pre-error value pair
h_f	: bandwidth forecast
h_e	: bandwidth forecast error
h_{pe_1}	: bandwidth of first pre-error
h_{pe_2}	: bandwidth of second pre-error

The density estimation functions are calculated prior to the calculation of the probabilistic forecast. The probability forecast for the deterministic forecast value $P_{f,fix}$ for the time t is searched. The density estimation functions $\hat{f}_{DA}$ and $\hat{f}_{ID}$ are used for $P_{f,fix}$. Since REBal uses hindcasting techniques it also uses values to create $\hat{f}_{DA}$ and $\hat{f}_{ID}$ from a later point in time than $P_{f,fix}$. This ensures a consistent forecast quality throughout all assessment years and eliminates possible artefacts from the modelling. Data around the time t is not used to avoid self-correlation. Data from 14 days prior to time t and two days after is omitted when $\hat{f}_{DA}$ and $\hat{f}_{ID}$ are created. Since self-correlation can be avoided by excluding data, it can be justified to use these data points since they facilitate the aim of making results comparable between different years. It is encouraged to use these when perfect price forecasts are assumed as well. It also allows calculation of the potentials as close to reality as possible and the drawing of conclusions from consistent data sets. The accuracy gained from this is expected to be higher than the accuracy lost by having a slightly better forecast quality available.

Inclusion of values from the future due to hindcasting

For the calculation of the probabilistic forecasts, the forecast value $P_{f,fix}$ is inserted into the density estimation functions $\hat{f}_{DA}$ and $\hat{f}_{ID}$ (equations (4-7) and (4-8)). For the density estimation function $\hat{f}_{DA}$ this yields equation (4-9). Equal to equation (4-9) the forecast value $P_{f,fix}$ is inserted into $\hat{f}_{ID}$ accordingly. This can also be seen similarly in Speckmann (2016).

Density estimation functions for the day-ahead case

$$\hat{f}_{DA,fix}(P_e) = \hat{f}_{DA}\left(P_{f_{fix}}, P_e\right) = \frac{1}{n}\sum_{i=1}^{n} \frac{e^{-\frac{1}{2}\left(\frac{P_{f_{fix}}-P_{f,i}}{h_f}\right)^2}}{h_f\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_e-P_{e,i}}{h_e}\right)^2}}{h_e\sqrt{2\pi}} \tag{4-9}$$

with:

$\hat{f}_{DA,fix}$	: density estimation for a fixed day-ahead forecast
$P_{f_{fix}} - P_{f,i}$	: fixed forecast value pair
$P_e - P_{e,i}$	: forecast error value pair
h_f	: bandwidth forecast
h_e	: bandwidth forecast error

Gaining the error distribution for a fixed forecast value

In both cases (DA and ID) the resulting PDF is a one-dimensional cut-out of $\hat{f}_{DA}$ and $\hat{f}_{ID}$ (see also Figure 4-3)for a fixed forecast value. The integral of the one-dimensional PDF has to be normalized to 1 again.

$$\int_{-\infty}^{\infty} \hat{f}_{DA,fix}(P_e)\, dP_e \doteq 1 \qquad (4\text{-}10)$$

with: $\hat{f}_{DA,fix}$: density estimation for a fixed day-ahead forecast
P_e : forecast error values

Restricting the error distribution to the physical limits

Gaussian kernels as the kernel functions for KDE are selected since ongoing research (Bessa et al., 2012, pp. 30–34) has not clearly identified the most suitable kernel function. Due to this, possible problems in the tails of the distribution may occur, as they might have values that are physically not possible. These values will have to be within the physical boundaries.

$$0 \leq P_{e,x} \leq P_{,n} \qquad (4\text{-}11)$$

with: $P_{e,x}$: forecast error values with the probability x
P_n : nominal capacity

Normalizing the error distribution

Values Pe, x < 0 or >1 are floored and capped at 0 and 1. This could lead to the integral of the PDF (or the CDF against infinity) being unequal to one. This is addressed by normalizing the distribution to one again, as described in equation (4-12):

$$\int_{0}^{Pn} \hat{f}_{DA,fix}(P_e) \doteq 1 \qquad (4\text{-}12)$$

with: $P_{e,x}$: forecast error values with the probability x
P_n : nominal capacity

Obtaining the final probabilistic forecast value

Based on the individual probability density functions $\hat{f}_{DA,fix}(P_e)$ for each $P_{f,fix}$ the probabilistic forecast P_{e,L_r} for a defined level of reliability is extracted. REBal uses a numerical search algorithm since $\hat{f}_{DA,fix}(P_e)$ are described numerically.

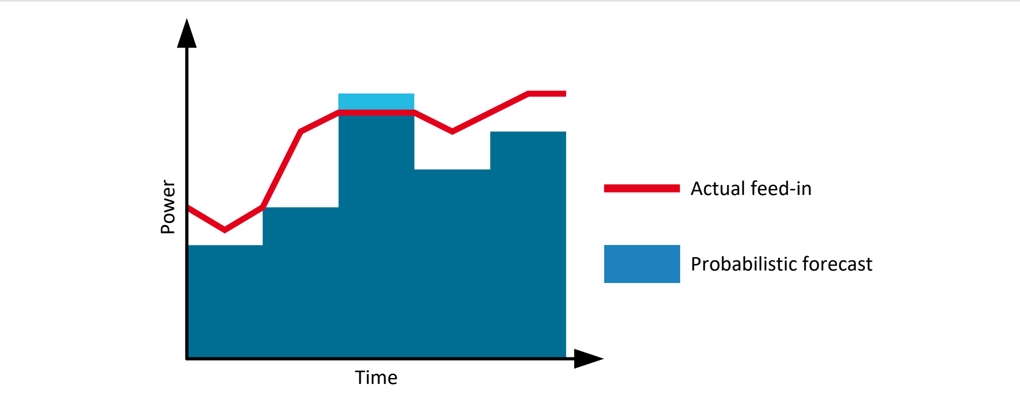
$$1 - L_r = \int_{P_e=-\infty}^{P_e=P_{e,L_r}} \hat{f}_{DA,fix}(P_e)dP_e \tag{4-13}$$

with:
P_{e,L_r} : probabilistic forecast of a defined level of reliability
$\hat{f}_{DA,fix}$: density estimation for a fixed day-ahead forecast
L_r : level of reliability
P_e : forecast error values

4.4.1.2 Definition of the forecast reliability

Assessed levels of reliability of the forecasts

In the course of this thesis, different levels of forecast reliability are assessed. Since today's requirements of 100 % reliability cannot be fulfilled by any technical unit, reliability levels from 95 % to 99.999 % reliability are assessed stepwise. In fact, a reliability of 99.994 % would ensure that the reliability does not fall short of the reliability of current market participants (Brauns et al., 2014, p. 33). Therefore, this level of reliability will have a special emphasis throughout this work. The assessed levels of reliability throughout this work are 95 %, 99 %, 99.5 %, 99.9 %, 99.99 %, 99.994 % and 99.999 %. The definition of reliability of probabilistic forecasts is important since it has implications for the probabilistic forecast itself. Two different definitions of reliability can be distinguished. Both definitions are depicted in Figure 4-7.



Source: Own analysis

Figure 4-7: Two different approaches to measure reliability of a probabilistic forecast for fluctuating RES

Reliability definition with time

The first possible definition of reliability uses the number of times when the forecast exceeds the actual feed-in. In the example above, five time intervals are shown. In one of these intervals, the forecast (in blue) exceeds the feed-in (red). If the reliability is defined according to the time intervals this would mean that the reliability of this forecast is four out of five, also expressed as 80 %.

Reliability definition with energy

The second possible definition is related to the energy content that was unsupplied. Assuming the contents of the blue area (light blue and dark blue) equals 1 and the contents of the light blue area 0.02, then the reliability of the forecast is forty-nine out of fifty, or 98 %.

Selection of approach for the REBal model

In any case, when the reliability is predefined this would lead to different values for the probabilistic forecast, while the definition using the energy contents will lead to higher values for the forecast. Since it is unknown which definition will be applied in the future when fluctuating RES provide control reserve, the more conservative, time-based approach is selected.

4.4.1.3 Intraday forecasts

Intraday forecast created from persistency

As stated in chapter 4.3, data availability is an issue in some cases. This is especially true for the intraday forecast time series for the German portfolios that are not published by the German TSOs. Therefore, an approach has to be used to emulate those intraday forecast time series. An appropriate approach is the creation of a persistency forecast, called persistence or naïve predictor (BM Intermittent Gen WG, 2010, p. 7; Dobschinski et al., 2010; Ela et al., 2011, p. 14; Giebel et al., 2011, p. 10; Juban, Fugon et al., 2007, p. 7; Pinson, 2006, pp. 24–25). Persistence uses online measurement data and extrapolates the data into the near future. Forecast errors are the largest during wind and solar gradients (Dobschinski et al., 2010, p. 9). Giebel et al. state that the persistency forecast provides a robust and yet precise forecast algorithm that delivers betters results than weather-model based approaches for short forecast horizons (Giebel et al., 2011, p. 10). It provides a solution that will not overestimate the potential (Pinson et al., 2007, p. 6). The persistency forecast can be written as the following (Frunt, 2011, p. 110):

$$P_f(t) = P(t - \tau_{pred}) \tag{4-14}$$

with: $P_f(t)$: forecast for time t
τ_{pred} : forecast horizon
t : time for forecast

Forecast improvements with local regression methods

Applying additional algorithms to the time series calculated with equation (4-14) improves the forecast quality. Using local regression methods as proposed by (Cleveland, 1979; Cleveland & Devlin, 1988) can increase the forecast quality. Specifically a two-dimensional locally weighted regression (LOESS) function is used, which employs quadratic polynomials instead of the linear polynomials of the original locally weighted scatterplot smoothing (LOWESS) function in Cleveland. For the sake of brevity, the description of the LOESS function is omitted here. The idea of the LOESS function is the application of several regression functions to data that are valid only for parts of it. The result is a piece-wise regression function for the given data set.

Further improvement using 4-dimensional KDE for the expected value

The forecast quality can be increased by applying the kernel density estimator in chapter 4.4.1.1. The KDE is used to calculate the expected value forecast, i.e. 50 % reliability. This technique allows the inclusion of pre-errors that occurred in between previous forecast and feed-in values, as shown in equation (4-8). This approach increases the forecast quality significantly.

4.4.2 Determining the technical potential

Creating capacity bids for the market

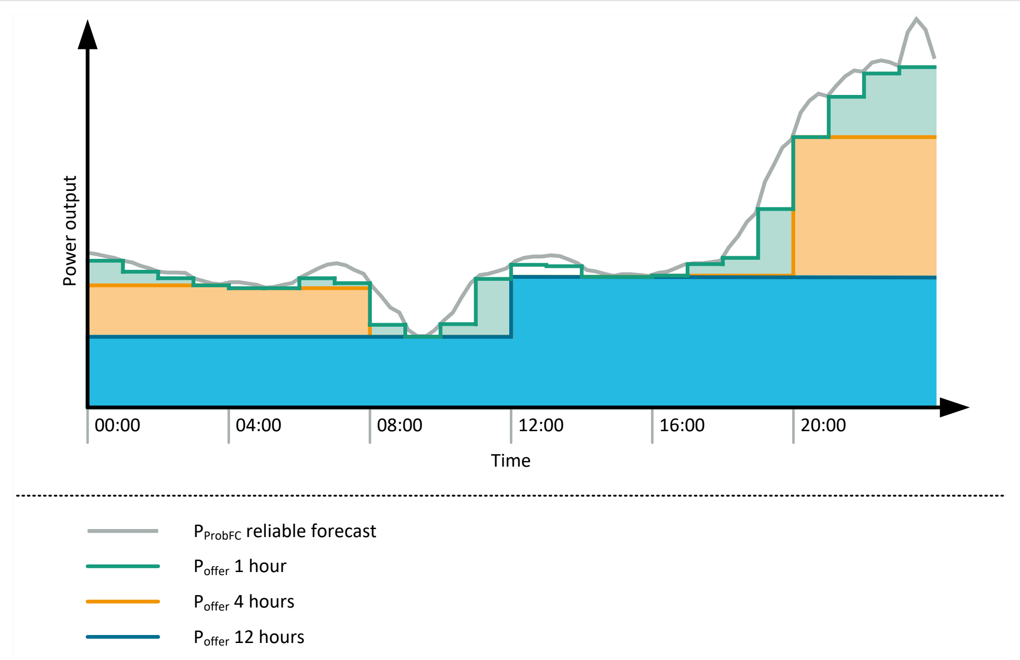
The probabilistic forecasts from the previous step are used to calculate the amount that can be bid into the control reserve market at the desired level of reliability. The offerable capacity from wind farms and PV systems depends on different factors such as the time between the creation of the forecast and the actual feed-in or the time span that the services are procured for. These are usually expressed as the gate-closure time and product length. The potential is calculated for different combinations of these influencing factors. The product lengths investigated in this thesis are one hour, two hours, four hours, eight hours, twelve hours and 24 hours. This step provides information on the energetic potentials of fluctuating RES generators to provide control reserve. Real market constraints, such as week-daily tendering, can be taken into account as well as additional conditions.

The offerable amount is the minimum of the probabilistic forecast in each time period

The determination of the offers follows the simple method of using the minimum of the probabilistic forecast for each product. Figure 4-8 shows the principles for the product lengths of one hour, four hours and twelve hours, based on a probabilistic wind power forecast with a 15-minute time resolution. The offerable amount $P_{offer}(t)$ is obtained from:

$$P_{offer}(t) = min(P_{probFC,DA,1}, P_{probFC,DA,2}, \dots, P_{probFC,DA,x},) \quad (4\text{-}15)$$

with: $P_{offer}(t)$: Offerable amount
$P_{probFC,DA,1,\dots n}$: Probabilistc forcast values within time t



Source: Own analysis

Figure 4-8: Principles of calculating the offerable amount of control reserve P_{offer} with the probabilistic forecast P_{ProbFC}

4.4.3 Bid creation of fluctuating RES generators in the control reserve market

4.4.3.1 Opportunity cost driven bid creation

This step uses the information on potentials and combines it with market information. Depending on the regulatory framework, fluctuating RES generators have certain opportunity costs for the provision of control reserve. This depends on the regulatory framework and market rules, for example whether the fluctuating RES generator has to be curtailed in order to provide control reserve or if has only to be curtailed when control reserve is actually dispatched. These aspects are taken into account and opportunity costs are calculated.

The principles of bid creation based on opportunity costs

In the previous subchapters, the creation of probabilistic forecasts and their conversion into quantities for offers in the markets are described. In this chapter, the price for the offer is calculated based on opportunity costs. Two prices are computed. The first one is the capacity price of the bid, which is also the award criterion in the control reserve markets. The second price is the energy price of the bid, which determines the price paid when the unit is dispatched in the control reserve market. The next subchapter will show how the price can be calculated to maximize the income generated from control reserve market participation.

Capacity prices and dispatch prices based on opportunity costs

The opportunity cost based capacity price is expressed in EUR/MW/h. For the provision of negative control reserve, it is unequal to zero only with the balance control proof method applied. The available active power proof method does not require curtailment and therefore does not create opportunity costs caused by participation in the control reserve market. Provision of positive control reserve leads to curtailment in both cases. Therefore, capacity prices are computed for both proof mechanisms.

Differences caused by the proof mechanism

The capacity prices, based on the opportunity costs, compare the overall income situation of fluctuating RES at the time t. The income with market participation in the control reserve market $I_{CRMarket}(t)$ is compared to the income $I_{noMarket}(t)$ without market participation in the control reserve

Capacity prices compare costs with and without market participation market. For comparability, the unit will be given in EUR/MW/h. Therefore, it is expressed in relation to the product length $T_{product}$ and the offerable amount $P_{offer}(t)$.

$$CP_{op}(T) = \frac{I_{noMarket}(T) - I_{CRMarket}(T)}{\sum P_{offer}(t) \cdot T_{product}} \tag{4-16}$$

with: $CP_{op}(T)$: opporunity costs based capacity price
$I_{noMarket}$: income without control reserve market participation
$I_{CRMarket}$: income with control reserve market participation
$T_{product}$: product period

Income without control reserve market participation

The income without market participation $I_{noMarket}$ is the reference for operation of fluctuating RES according to the RES scheme. The chosen RES support scheme option is the direct marketing option (chapter 3.1.1 and 3.2.5). Accordingly, the income is calculated from the trading on the day-ahead spot market, and the intraday trading. The intraday trading is used for forecast corrections only. Non-strategic bidding has to be assumed. The costs and income from the imbalance settlement mechanism are not included since they cannot be predicted as reliably as the spot market prices.

$$I_{noMarket}(T) = \sum_{t=1}^{n} \Big[P_{FC,DA}(t) \cdot S_{DA}(t) + \big(P_{FC,ID}(t) - P_{FC,DA}(t)\big) \cdot S_{ID}(t)\Big] \cdot t \tag{4-17}$$

with: n : number of time steps t in product period T
t : time step t in the product period T
$P_{FC,DA}(t)$: day-ahead forecast
$P_{FC,ID}(t)$: intraday forecast
$S_{DA}(t)$: day-ahead market price
$S_{ID}(t)$: intraday market price

Income with control reserve market participation

The income with participation in the control reserve markets can be calculated, which leads to a different income situation due to curtailment in some cases. Instead of the deterministic forecasts $P_{FC,DA}$ and $P_{FC,ID}$, the probabilistic forecasts $P_{probFC,DA}(t)$ and $P_{probFC,ID}(t)$ are traded. Analogue to equation (4-17), the income can be calculated for the case of fluctuating RES participation in the control reserve markets.

$$I_{CRMarket}(T) = \sum_{t=1}^{n} \Big[(P_{probFC,DA}(t)) \cdot S_{DA}(t) + \left(P_{probFC,ID}(t) - P_{probFC,DA}(t)\right) \cdot S_{ID}(t) \Big] \cdot t \qquad (4\text{-}18)$$

with:
- n : number of time steps t in product period T
- t : time step t in the product period T
- $P_{FC,DA}(t)$: day-ahead forecast
- $P_{FC,ID}(t)$: intraday forecast
- $P_{probFC,DA}(t)$: probabilistic day-ahead forecast
- $P_{\mathrm{probFC,ID}}(t)$: probabilistic intraday forecast
- $S_{DA}(t)$: day-ahead market price
- $S_{ID}(t)$: intraday market price

Conclusion on the calculation of capacity prices

If the capacity is bid to the positive control reserve market then $P_{probFC,DA}(t) \doteq P_{probFC,DA}(t) - P_{offer}(t)$. Concluding from equation (4-16) with equation (4-17) and equation (4-18) the capacity prices $CP_{op}(t)$ for each product period T can be calculated.

Opportunity cost based energy prices

The opportunity cost based energy prices $EP_{op}(t)$ only occur during the dispatch of control reserve from the tendered units. The prices therefore are calculated based on the trading in the markets and the RES support scheme framework conditions. Prices are given in EUR/MWh and only paid when the energy is requested by the TSO. The adaption of equation (4-16) allows the formulation for the calculation of the energy prices. The income without the control reserve market participation is governed by the current market prices and the feed-in tariff of the fluctuating RES generator. Control reserve is dispatched shortly before real-time production and after the last trading possibility in the intraday market. The only income difference occurs in payments by the RES support scheme, which are based on the actual feed-in P_{feed}. Decreasing the feed-in by the contracted amount P_{offer} yields a new actual feed-in $P_{act,dispatch}$. Therefore the energy prices for the dispatch of control reserve are:

$$EP_{op}(T) = \frac{1}{n}\sum_{t=1}^{n}\frac{(P_{act}(t) - P_{act,disp}(t)) \cdot (MP(t) + MB(t))}{P_{offer}(t)} \qquad (4\text{-}19)$$

with: $EP_{op}(\mathrm{T})$: average opporunity costs based energy price
t : time steps in product period T
n : number of time steps t in activation period
$P_{act}(t)$: actual feed-in
$P_{act,disp}(t)$: actual feed-in during dispatch
$MP(t)$: market premium
$MB(t)$: manangement bonus

Forming market suitable bids

The opportunity cost based capacity and energy prices as well as the offerable amount for each product period are merged. A standard market product data set according to the market rules is created.

4.4.3.2 Profit maximizing bid creation

The principles of bid creation based on achievable market prices

The aim of this chapter is to maximize the income that could be generated by fluctuating RES in the control reserve market. The possible revenue could be maximized with a different bidding strategy. Since the control reserve market is a pay-as-bid priced market, the bids submitted to the market have a direct impact on the additional income. Therefore, it is favourable to develop a strategy that creates bids that are as high as possible and still being accepted in the market. This requires that the merit-order lists in the control reserve market are used to create the bids. Therefore, perfect price forecasts have to be considered. This presented methodology can be considered a conservative maximization approach. In contrast to the opportunity cost based approach the bids from the profit maximizing approach depend on the market environment. The offerable amount P_{offer} will be bid with different prices, depending on the chosen market.

Profit maximizing capacity price is located at the intersection of the offerable capacity with the merit-order list

The market price based capacity price is expressed in EUR/MW/h. The prices are equal under both proof method regimes, as long as the prices are higher than the bids from the opportunity cost approach. The market price based capacity price can be derived from the market data. The market price based capacity price CP_{mp} for the product period T is the value of the monotonous function $f(C)$ of the capacity $C(p)$ at the merit-order position p.

$$CP_{mp}(T) = f(C(p)) \qquad (4\text{-}20)$$

with: p : merit-order list position
C : capacity price
$CP_{mp}(T)$: market price based capacity price

Finding the merit-order position p

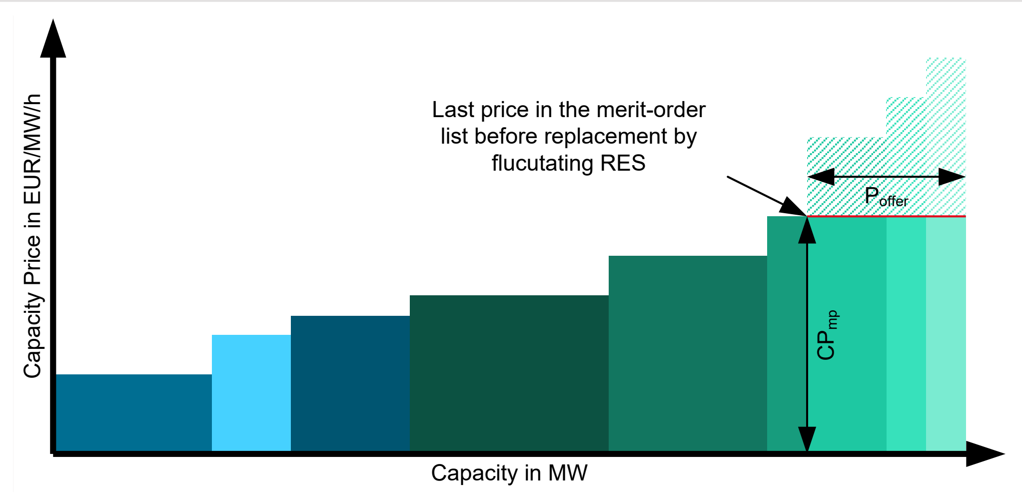
The capacity and the capacity price at the position P_{offer} is to be determined by the offerable capacity P_{offer} and the tendered amount C_{max}.

$$C(P_{offer}) = C_{max} - P_{offer} \qquad (4\text{-}21)$$

with: C_{max} : tendered amount
P_{offer} : offerable capacity
$C(P_{offer})$: capacity price at the position P_{offer}

Numerical processing of merit-order lists

The values of the merit-order list $CP = f(C)$ are processed numerically in REBal. The following graph illustrates the principles.



Source: Own analysis

Figure 4-9: Determination of market price based capacity price of fluctuating RES with original merit-order list in lighter colours

Market price based energy price

The market price based energy price EP_{mp} is expressed in EUR/MWh. The energy price is equal to the bid that was replaced in the capacity merit-order lists. After the auction in the capacity segment, the merit-order lists are sorted by the energy bids, starting from the lowest energy bid. Since the energy prices are not an award criterion, any energy price could be set by the market participants, as visible in Figure 3-13 and Figure 3-15.

Energy prices are created with the same principles as capacity prices

However it is assumed that fluctuating RES will follow the same approach for EP_{mp} as for CP_{mp}. This would ensure that the results are within reasonable bounds, as they do not use extreme values that are likely to disappear once fluctuating RES enter the market. Therefore, equations (4-20) and (4-21) as well as Figure 4-9 can be applied to EP_{mp} as well. If the opportunity cost based energy price EP_{op} is higher than the market price based energy price EP_{mp}, then the opportunity cost based energy price is used.

4.4.4 Matching of bids with the bids in the market

Entering the bids into the merit-order lists

Once a control reserve market is chosen the bids from the fluctuating RES are entered in the merit-order lists. The different alternatives for creating bids are presented in chapter 4.4.3. These bids replace the existing bids in the market if the bid of the fluctuating RES generator is cheaper than the bid in the market. When the bid is accepted, it replaces the current bid in the merit-order list. The award criterion is the capacity price. For obvious reasons the bids from the profit maximization approach will always be accepted.

Bid replacement for every merit-order list

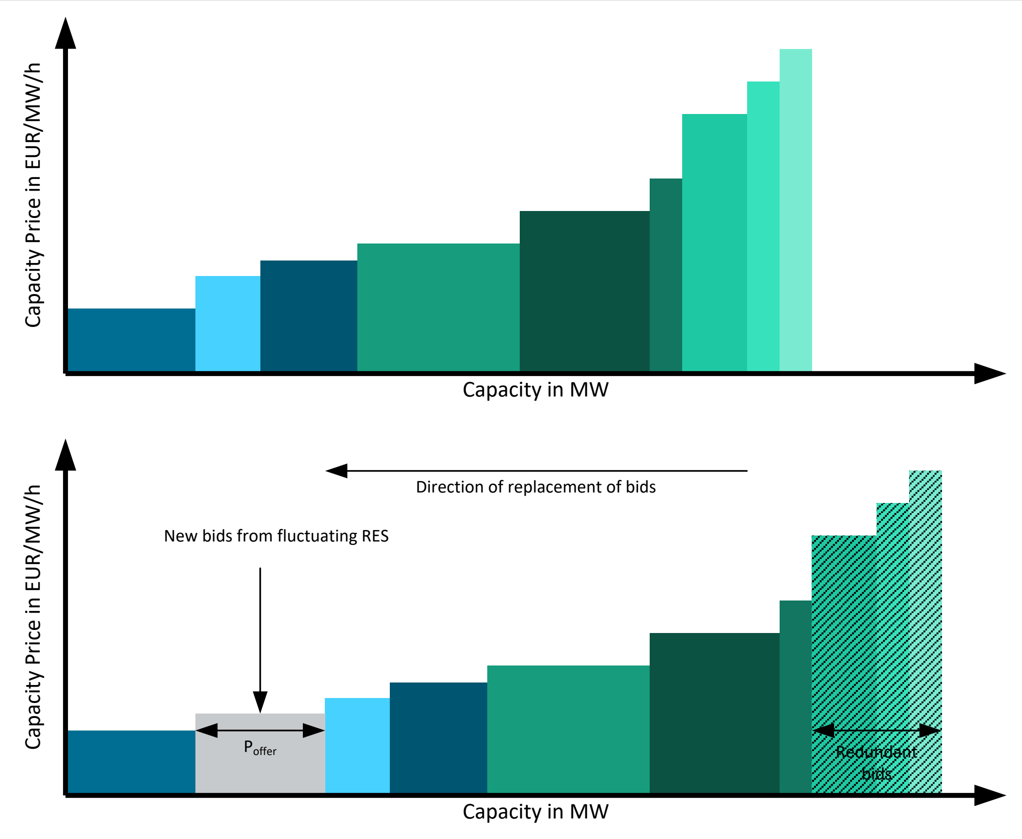
The procedure is repeated for each individual bid in the merit-order list position p in the merit-order list $C(p)$ at each product period T. REBal uses the methodology of the merit-order principle (Sensfuß et al., 2007). In fact, the resulting cost reductions (see chapter 4.4.5) can be called the merit-order effect in the control reserve market. The bids are replaced according to the following condition, starting with the highest bid position $p = n$.

$$\forall CP_{bid}(T) < CP(p,T) \vee \sum_{p=n}^{1} C(p,T) \leq P_{Offer} \rightarrow CP(p,T) \doteq CP_{bid}(T) \quad (4\text{-}22)$$

with:
- CP_{bid} : capacity price of the fluctuating RES for the auction time T
- $CP(p,T)$: capacity price in the original merit-order list
- $C(p,T)$: capacity in the original merit-order list
- P_{Offer} : offerable amount of the fluctuating RES
- T : auction period

Description of equation (4-22)

To clarify, this means that all bids $CP(p,T)$ at the position p in the merit-order list will be replaced by the bid from the fluctuating RES $CP_{bid}(T)$ as long as the capacity price is lower and the offerable amount P_{Offer} has not been exhausted by the replacement of the previous bids. CP_{bid} can be formed from either approach in chapter 4.4.3 and may therefore vary in height. This will be important when the total welfare is discussed in chapter 4.4.5. Graphically this can presented as follows:



Source: Own analysis

Figure 4-10: Replacement of bids in the merit-order list by list of the fluctuating RES

Naming convention of the altered merit-order lists

The new merit-order lists will be called $CP_{RES}(p,T)$. Naming differs depending on whether the cost based approach or the market price based approach was used. The cost-based approach is indexed as $CP_{RES,op}(p,T)$ whereas the market price based approach is indexed as $CP_{RES,mp}(p,T)$. Following the argumentation in chapter 4.4.3.2 equation (4-22) is used for the energy prices. Bids for the control reserve market incorporate capacity prices and energy prices that are inseparable. For each capacity bid replaced, energy bids are also replaced. EP_{bid} is derived from EP_{op} or EP_{mp}.

$$\forall CP_{bid}(T) < CP(p,T) \vee \sum_{p=n}^{1} C(p,T) \leq P_{Offer}$$
$$\rightarrow EP(p,T) \doteq EP_{bid}(T) \tag{4-23}$$

with:

CP_{bid}	: capacity price of the fluctuating RES
$CP(p,T)$	: capacity price in the original merit-order list
$C(p,T)$	: capacity in the original merit-order list
P_{Offer}	: offerable amount of the fluctuating RES
$EP_{bid}(p,T)$	: energy price of the fluctuating RES for the auction time T
$EP(p,T)$	: energy price in the original merit-order list
T	: auction period

Naming of new energy price merit-order lists

The merit-order list position p indicates the same position for the inseparable bids. The new merit-order lists $EP_{RES}(p,T)$ are sorted after the replacement of the bids. The cost based approach merit-order lists are named $EP_{RES,op}(p,T)$. The market price based approach is named $EP_{RES,mp}(p,T)$.

4.4.5 Determining the changes in costs

Capacity cost and dispatch simulation to identify cost changes

A full dispatch simulation is performed to assess the economic impact of the participation of fluctuating RES generators. A dispatch simulation includes the changes in cost for reserve provision and dispatch for one selected control reserve type.

Benchmark for cost changes of fluctuating RES in the market

The original (unaltered) merit-order lists are used as a benchmark. They provide information on the cumulated overall costs for one control reserve type C_{BM} in the status-quo. This is applied over the entire assessment period for all $T = 1 \dots m$. The cost consists of the capacity costs CC_{BM} and the dispatch cost DC_{BM}.

$$C_{BM} = CC_{BM} + DC_{BM} \tag{4-24}$$

with:

C_{BM}	: cumulated overall cost over all T
CC_{BM}	: capacity costs
DC_{BM}	: dispatch costs

Capacity costs

The provision of control reserve means the provision (reservation) of capacity for the later dispatch, if needed. The costs for the provision of control reserve for the benchmark are calculated as follows:

$$CC_{BM} = \sum_{T=1}^{m} \sum_{p=1}^{n} CP(p,T) \tag{4-25}$$

with:
- CC_{BM} : cumulated capacity cost over all T
- $CP(p,T)$: capacity prices in the original merit-order lists
- p : position in the original merit-order list
- n : maximum position in the original merit-order list at T
- T : auction period
- m : total number of auction periods

Dispatch costs

The dispatch costs of control reserve only occur when certain positions p of the merit-order list are activated. The costs for the dispatch of control reserve for the benchmark are calculated as follows:

$$DC_{BM} = \sum_{T=1}^{m} \sum_{p=1}^{P_{disp}} EP(p,T) \cdot C(p,T) \tag{4-26}$$

with:
- DC_{BM} : cumulated capacity cost over all T
- $EP(p,T)$: capacity prices in the original merit-order lists
- $C(p,T)$: capacity of single bid
- p : position original merit-order list
- P_{disp} : position at dispatched control reserve
- T : auction period
- m : total number of auction periods

Cost changes due to fluctuating RES generators

Changes introduced into the merit-order lists by fluctuating RES generators will lead to different costs than in the benchmark scenarios. These cost changes between the benchmark case and the case with participation of fluctuating RES in the control reserve market can be expressed as follows:

$$\varDelta C = C_{BM} - C_{RES} \tag{4-27}$$

with:
- C_{BM} : cumulated overall cost for the benchmark
- C_{RES} : cumulated overall cost with fluctuating RES participation
- $\varDelta C$: change in costs

Sum of capacity and dispatch costs from RES merit-order lists

The cost for the provision and the dispatch of control reserve is calculated based on the merit-order list that include the bids from the fluctuating RES. Equally to equation (4-24) the total costs of C_{RES} are:

$$C_{RES} = CC_{RES} + DC_{RES} \tag{4-28}$$

with: C_{RES} : cumulated overall cost over all T with fluctuating RES
CC_{RES} : capacity costs with fluctuating RES
DC_{RES} : dispatch costs with fluctuating RES

Capacity cost with the fluctuating RES

The costs for the provision of control reserve with the fluctuating RES in the merit-order lists uses the merit-order lists CP_{RES} and EP_{RES}. CP_{RES} may either be determined by $CP_{RES,op}$ or $CP_{RES,mp}$. Accordingly, EP_{RES} can either be $CP_{RES,op}$ or $CP_{RES,mp}$. Derived from equation (4-25) this yields:

$$CC_{RES} = \sum_{T=1}^{m} \sum_{p=1}^{n} CP_{RES}(p,T) \tag{4-29}$$

with: CC_{RES} : cumulated capacity cost over all T
$CP_{RES}(p,T)$: capacity prices in the altered merit-order lists
p : position in the altered merit-order list
n : maximum position in the altered merit-order at T
T : auction period
m : total number of auction periods

Equivalently, using equation (4-26), the dispatch costs are:

$$DC_{RES} = \sum_{T=1}^{m} \sum_{p=1}^{P_{disp}} EP_{RES}(p,T) \cdot C(p,T) \tag{4-30}$$

with: DC_{RES} : cumulated dispatch cost over all T
$EP_{\mathrm{RES}}(p,T)$: capacity prices in the altered merit-order lists
$C(p,T)$: capacity of single bid
p : positions altered merit-order list
P_{disp} : position at dispatched control reserve
T : auction period
m : total number of auction periods

4.4.6 Impacts of the proof mechanism on the spot market

Behaviour of fluctuating RES generators due to proof method

The choice of the proof mechanism for the delivery of control reserve, as presented in Figure 3-17 and Figure 3-18, has implications on the behaviour of fluctuating RES generators. It affects how much energy is available on the wholesale market in total. The impact of the proof method on the spot market prices and the subsequent costs changes are assessed. The curtailment of fluctuating RES will lead to energy losses and increased CO_2 emissions due to the merit-order shift. At the same time, this will lead to additional costs in the energy system. Energy losses are shown in chapter 5.2.2 and additional costs are shown in chapter 6.2.

Cross-market implications

The energy losses that are induced by the regulations in the control reserve market have impacts on other markets than the control reserve market. These cross-market dependencies may work both ways. For example, the unavailability of power plants due to low spot market prices may lead to unavailability in the control reserve markets. In the other direction the commitment to provide control reserve could lead to certain units having to deliver energy to the spot market and thus having to cope with the low prices there. The latter is also known as control reserve market introduced must-run capacity in the spot market and can reach up to 25 GW (FGH et al., 2012, p. 1; Grünwald et al., 2015, p. 107).

Less RES payments due to curtailment under balance control proof method

The balance control (BC) proof mechanism requires the fluctuating RES generator to be curtailed when control reserve is contracted. Despite the cost increase in the markets, decreasing costs might also occur. Negative costs can come from reduced payments in the RES support scheme due to less feed-in. However, those payments guarantee the existence of fluctuating RES in the energy system. In the current market environment, few wind farms and PV systems would have been built without it. This also endangers political targets of maximizing the RES feed-in.

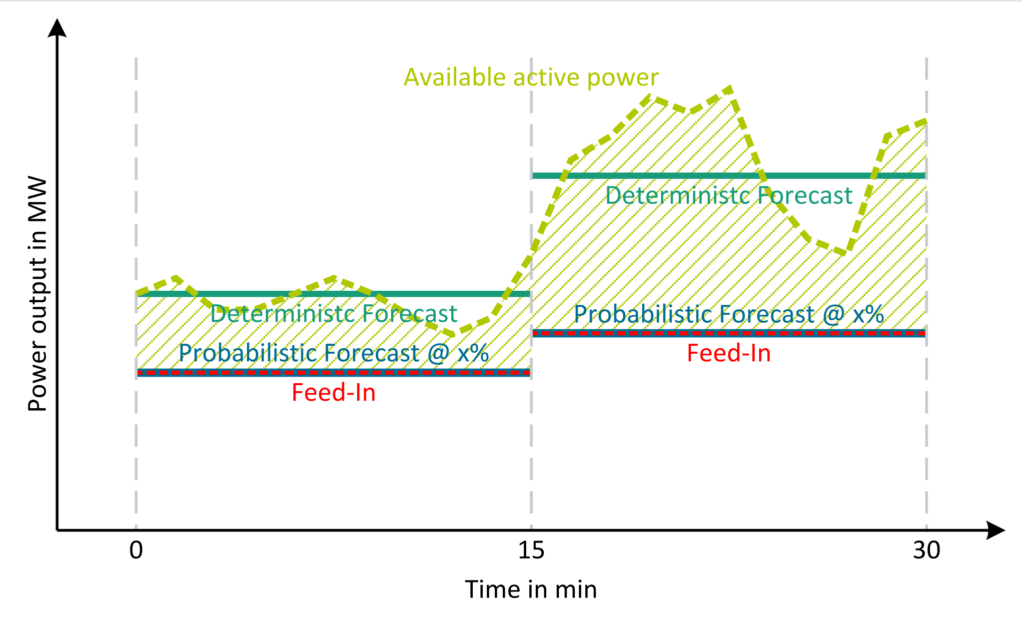
Cost reductions due to less reserve demand

A second potential cost decreasing effect of the proof method is on the demand for control reserve itself. In the case of the balance control proof method, the forecast errors are minimized. This is due to the curtailment to a secure forecast. The forecast errors disappear almost entirely. This reduces the balancing needs since the forecast error of fluctuating RES is one contributing factor in the Graf-Haubrich-method described in chapter 3.2.3. Previous assessments (Jansen, Speckmann, Schneider et al., 2013, p. 4) have shown a decrease in reserve demand by approximately 5 %. However, cost implications are small and largely depend on the probabilistic forecast used.

Since the forecast quality in this thesis has improved sufficiently, this effect can be disregarded.

Cost increase due to replacement costs and merit-order effect

The application of the balance control proof method withholds energy of fluctuating RES from the markets. The curtailment of the fluctuating RES generators creates energy losses that have to be replaced by other units in the market to satisfy the demand. The principles of the energy losses can be seen in Figure 4-11 which is adapted from Figure 3-17 and shows the provision of control reserve only. The contracted control reserve is not requested by the TSO. Therefore, both 15-minute intervals show the energy losses. The lost energy is the green and white striped area between the probabilistic forecast and the available active power signal. The available active power signal would have been the energy production with the available active power proof method applied.



Source: adapted from (Brauns et al., 2014, p. 74)

Figure 4-11: Illustration of the energy losses with the balance control proof method applied marked as green striped area, adapted from Figure 3-17

The lost energy can be calculated for each time interval t, which is the 15-minute balancing period in this case.

Calculation of lost energy

$$E_l(t) = (P_{act}(t) - P_{probFC}(t)) \cdot \frac{n_t}{h} \quad (4\text{-}31)$$

with:
$E_l(t)$: lost energy in time interval t
$P_{act}(t)$: actual power feed-in of fluctuating RES
$P_{probFC}(t)$: power forecast of fluctuating RES
$\frac{n_t}{h}$: number of time interval t per hour h

Annually this can be accumulated to allow quantification of the energy losses $E_{l,total}$ for the entire assessment period, i.e one year.

Annual energy losses

$$E_{l,total} = \sum_{t=1}^{n} E_l(t) \quad (4\text{-}32)$$

with:
$E_l(t)$: lost energy in time interval t
$E_{l,total}$: annually cumulated lost energy
n : number of time intervals

These losses will have to be compensated, presumably by conventional generation. Using conventional generation to replace the lost energy creates the energy replacement price $EP_{rep}(t)$ that is an energy price, measured in EUR/MWh.

Energy replacement costs

$$\Delta C_{BC} = \sum_{t=1}^{n} [E_l(t) \cdot EP_{rep}(t)] \quad (4\text{-}33)$$

with:
ΔC_{BC} : cost changes due to BC proof method
$E_l(t)$: lost energy in time interval t
$EP_{rep}(t)$: energy replacement price
n : number of time intervals

The determination of $\mathrm{EP_{rep}(t)}$ cannot be performed using simple techniques. A possible approach will have to be robust and also account for uncertainties. In this case, more than one approach is chosen to carry out this task. Two different approaches will provide the upper and lower boundaries. In reality, the results will likely be located between those boundaries. The curtailed energy can be valued with the average fuel prices or the market prices. The

Two possible approaches for the energy replacement costs first approach yields the cost changes ΔC_{FC} whereas the latter yields ΔC_{MP}. In addition to the energy replacement costs, the merit-order shift can be evaluated, leading to the cost changes ΔC_{MO}.

4.4.6.1 Cost of energy losses valued with average fuel price

Average fuel cost for lost energy

The first approach uses average fuel costs. In this approach $EP_{rep}(t)$ is equal for all t, called EP_{FC}. A more sophisticated approach would be to model the merit-order of the different fuels. In low demand situations, figures for cheaper priced fuel such as lignite would have to be applied, whereas natural gas is used during high demand situations. It is likely that using the market based merit-order approach will yield similar or better results. Table 4-1 shows the fuel costs assessed for the years 2010 and 2013 and the installed capacities for the most commonly used fuel types in Germany. For the REBal model the average of those fuel costs are used.

Fuel Type	**Electricity generation costs EUR/MWh$_{el}$**	**Installed capacity GW[4]**
Nuclear	51.6[1] - 124.0[3]	12.1
Hard Coal	47.8[1] - 71.5[2]	26.3
Lignite	36.9[1] - 45.5[2]	20.2
Natural Gas	75.1[1] - 86.5[2]	26.5

Source: [1](Wissel, Fahl, Blesl, & Voß, 2010, p. 34) [2](Kost et al., 2013, p. 2) [3](DECC, 2013) [4](50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH, 2013, p. 35)

Table 4-1: Specific cost of electricity generation for the years 2010 and 2013

Average fuel cost is 65.9 EUR/MWh

The average energy replacement cost based on average fuel prices EP_{FC} is 65.9 EUR/MWh. Using the average fuel cost for the energy replacement price allows simplifying equation (4-33).

$$\Delta C_{BC,FC} = E_{l,total} \cdot EP_{FC} \tag{4-34}$$

with:
- $\Delta C_{BC,FC}$: cost changes due to BC proof method
- $E_{l,total}$: cumulated lost energy
- EP_{FC} : average fuel cost energy replacement price

4.4.6.2 Cost of energy losses valued with spot market prices

Market price based replacement costs

The second approach uses the market prices to calculate the energy replacement costs $EP_{MP}(t)$. In this approach, the market price changes throughout the year can be accommodated using the spot market prices. The losses are valued with their respective market prices at that time. The market price based energy replacement cost is applied to all $E_l(t)$ individually.

$$\Delta C_{BC,MP} = \sum_{t=1}^{n} [E_l(t) \cdot EP_{MP}(t)] \tag{4-35}$$

with:
- $\Delta C_{BC,MP}$: cost changes due to BC proof method
- $E_l(t)$: lost energy in time interval t
- $EP_{MP}(t)$: market based energy replacement price
- n : number of time intervals

Day-ahead spot market due to high liquidity

The day-ahead spot market data is used, since it can be considered the most reliable price information due to the high liquidity of the market. Price occluding fluctuations from strategic bidding will be minimized when compared to markets with low liquidity.

4.4.6.3 Costs due to increased spot market prices for all market participants

Merit-order principle

The dispatch at the electricity market is determined by the power plants used. Power plants with increasing marginal costs are used during high load situations. The introduction of renewables requires that only the residual load L_{res} be generated. The residual load is the electricity load L_D minus the feed-in of the fluctuating RES $P_{fluctRES}$. Increasing RES feed-in leads to lower residual loads. The spot market electricity prices MP can be expressed as a function of the residual load

$$EP_{MP}(t) = MP(t) = f(L_D(t) - P_{fluctRES}(t)) \tag{4-36}$$

with:
- $EP_{MP}(t)$: market based energy replacement price
- $MP(t)$: spot market price
- $L_D(t)$: electricity load
- $P_{fluctRES}$: feed-in fluctuating RES

Change of residual load due to proof method

The balance control proof method has impacts on the dispatch of fluctuating RES. The generators will be curtailed when they provide control reserve, as required by the proof method. This changes the available P_{fluctRES} on the market and leads to changing market prices.

$$P_{fluctRES,BC}(t) = P_{fluctRES}(t) - E_l(t) \tag{4-37}$$

with:
$P_{fluctRES}$: feed-in of fluctuating RES
$P_{fluctRES,BC}$: feed-in of fluctuating RES with curtailment
$E_l(t)$: lost energy

Relationship between the market prices and residual load

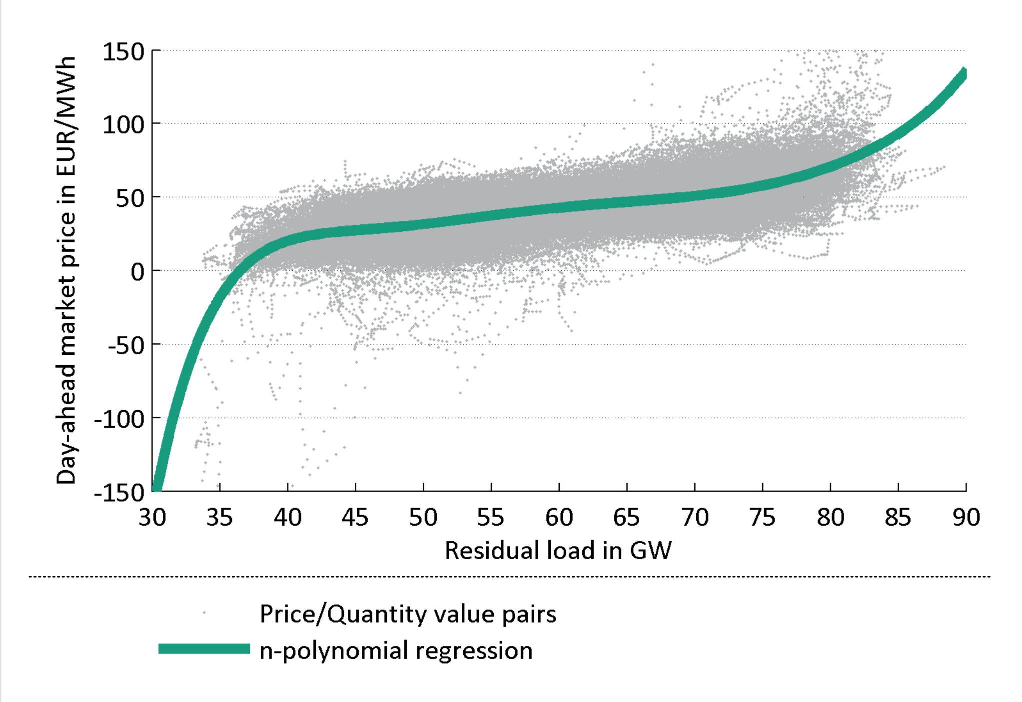
The relationship between the market prices and changing residual loads is investigated, to calculate the merit-order effect (Sensfuß et al., 2007). The correlation between the residual load and the market price can be fitted with a polynomial using polynomial regression (see e.g. (Heiberger & Neuwirth, 2009, pp. 269–283). This is helpful since volatility caused by price events is a "natural" phenomenon in electricity markets (Weron, 2006, p. 69). It is necessary to use methods that are able to account for outliers in order to recover the prevailing trend in the data (Forrest & MacGill, 2013, p. 124). The scatter plot in Figure 4-12 shows the relationship between the residual load and the spot market prices (grey dots) and an n[th] grade polynomial (green line) which can be written as:

$$f_{poly}(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + \cdots + a_nx^n + b \tag{4-38}$$

with:
$a_1 \dots a_n$ (~) : spot market price
x (~) : independent variable
b (~) : random error term

Monotonicity as a selection criterion for the polynomial fit

For the fitting of the polynomial to the data it is necessary that the $f_{poly}(x)$ is monotonously increasing. REBal applies different grade polynomials to the data. The highest-grade polynomial that fulfils the monotonicity criterion is chosen, provided that all the previous lower grade polynomials also fulfilled the criterion.



Source: Own analysis

Figure 4-12: Correlation of residual load and the day-ahead spot market price with its highest-grade possible monotonously increasing polynomial fit

Additionally the criterion shall be tested for values $< min(MP)$ and $> max(MP)$. This ensures that the fitted function is valid even in areas without original data. It is reasonable to extend the merit-order list fitting by a certain value, which can be chosen freely. Once the polynomial is fitted, the energy replacement can be calculated.

Extending the Monotonicity criterion beyond the initial data set

$$MP_{BC}(t) = MP(t) + \left(f_{poly}\left(L_D(t) - P_{fluctRES,BC}(t)\right) - f_{poly}\left(L_D(t) - P_{fluctRES}(t)\right)\right) \quad (4\text{-}39)$$

with:

f_{poly}	: nth grade polynomial of the market price
$MP(t)$	: spot market price
$MP_{BC}(t)$	: spot market price with BC curtailment
$L_D(t)$	: electricity load
$P_{fluctRES}$	: feed-in fluctuating RES
$P_{fluctRES,BC}$	: feed-in fluctuating RES with BC curtailment

The changed availability of fluctuating RES increases the market prices for all market participants since less RES generation shifts the supply curve. This

Cost changes due to the merit-order effect increases the equilibrium market price which is known as the merit-order effect (Sensfuß et al., 2007). The merit-order cost changes can be quantified

$$\varDelta C_{MO} = \sum_{t=1}^{n} \left[MP_{BC}(t) \cdot L_{res,BC}(t) - MP(t) \cdot L_{res}(t) \right] \tag{4-40}$$

with:

	MP	: spot market price
	MP_{BC}	: spot market price with BC proof method
	$L_{res}(t)$	: residual load
	$L_{res.BC}(t)$	: residual load with BC proof method
	$\varDelta C_{BC,MO}$	: cost changes due to merit-order shift

4.4.7 Welfare gain from fluctuating RES

Use of welfare economics

The changes of costs $\varDelta C$ can be interpreted as changes in the welfare. Welfare is a term in micro-economic theory, often used when the supply and demand allocation in a market is assessed. The concept of welfare economics is a long standing theory (Pigou, 1920). More recent readings can be found in e.g. Broadway and Bruce (2011) or Johansson (1997). The total welfare consists of the consumer surplus and the producer surplus. The control reserve market requires the adaption of the welfare economics theory due to the presence of strategic bidding and the pay-as-bid pricing mechanism.

A very short introduction to welfare economics

The theory on welfare economics states that an economic system is improved if the financial situation of one market participant is improved (in this case the fluctuating RES) without impairing the financial situation of other market participants (in this case the TSO). The starting point is a non-optimal situation (Pareto optimal) which is improved towards a better non-optimal situation where everybody is better off than before. Therefore, welfare economics ranks different non-optimal situations, as well as the influence of regulatory entities. The theory is based on two theorems. The first theorem states that one market participant's generated revenue is a second market participant's expenditure. If the economic situation improves for the first market participant and does not worsen for the second, an improvement is achieved (Pareto improvement). The second theorem states that an increase in Pareto efficiency is gained by good regulation of the market mechanisms. Occasionally a third theorem is mentioned; this states that the allocation of resources and revenues cannot be optimal for all market participants simultaneously. Despite its usefulness, the theory has been challenged in the past. Discussion of this will not be presented here, however. (see e.g. (Boadway & Bruce, 2011; Johansson, 1997; Pigou, 1920))

With the help of Figure 4-13 the application of the concept of welfare in the control reserve market is explained. The supply function SF is based on the example merit-order lists in Figure 4-9 to Figure 4-10 showing the capacity prices. In reality, the supply function depends on many different variables, such as the time of day, the market segment and product as well as the current power plant availability. The procedure for energy prices is not presented at this point. It follows an equal principle with the difference that the demand function is constantly moving according to the dispatch, yet is still inelastic.

Welfare gain in the control reserve market

The control reserve demand function DF is calculated according to the Graf-Haubrich-methodology described in chapter 3.2.3. The total control reserve demand C_{Dim} is dependent on the desired system security. The steepness of a demand function that determines its sensitivity to price changes is called elasticity E. This quantifies the changes as a function of the price change. Elasticity in the case of control reserve markets can only be expected when the costs for provision of the reserve exceed the value of lost load (VoLL). Since this value is currently significantly higher than reserve cost (see e.g. (London Economics, 2013)) it can be assumed that the demand is completely inelastic. This is indicated by the vertical orange line for DF.

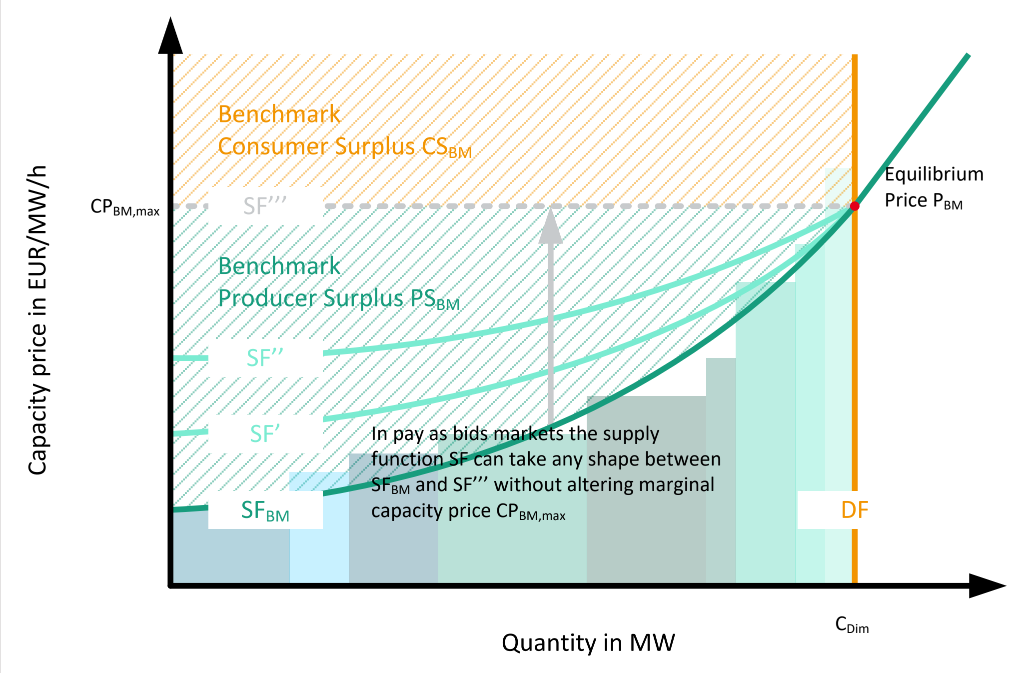
Control reserve demand function DF

$$E(DF) = \frac{\Delta Q}{\Delta P} = 0 \tag{4-41}$$

with: ΔQ : Change in quantity
ΔP : Change in price

The consumers in the case of control reserve are the TSOs and hence ultimately all grid users. The consumer surplus CS_{BM} is infinite in Figure 4-13; it extends infinitely beyond the boundaries of the graph. In reality, it will be finite and limited by the value of lost load (VoLL).

TSOs and grid users are the consumers



Source: Own analysis

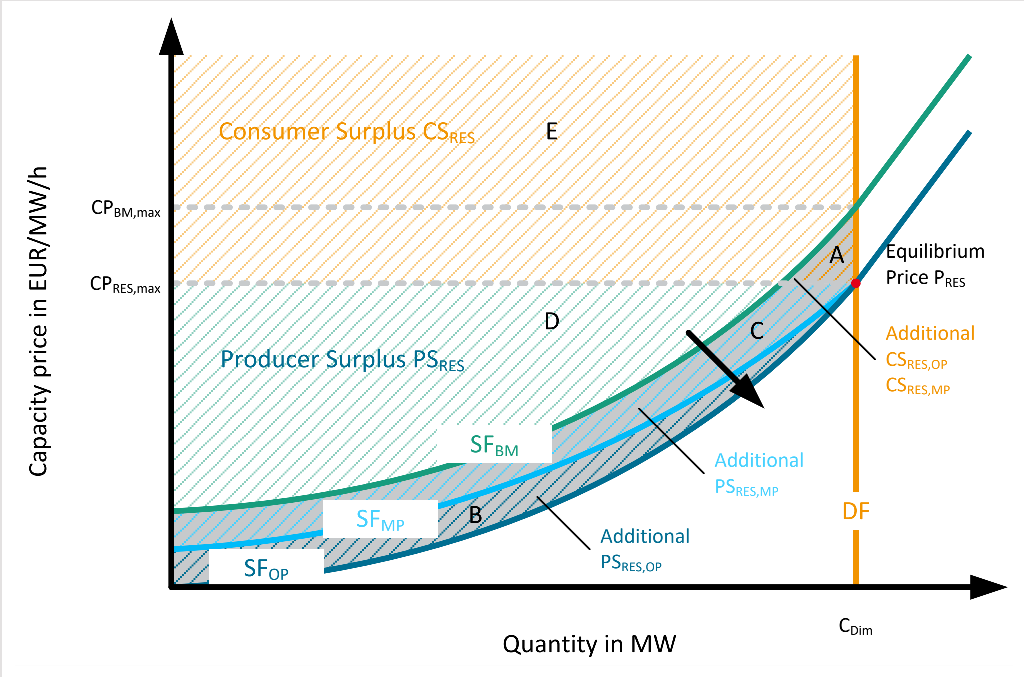
Figure 4-13: Supply and demand function for the capacity bids of the control reserve market with inelastic demand

Specialties due to pay-as-bid pricing

Due to the pay-as-bid pricing mechanism, the producer surplus PS_{BM} above the merit-order list will be realized by the TSOs, not by the producers. The supply function SF can lie between the benchmark merit-order list SF_{BM}(green line) and the maximum achievable prices at SF''' (grey dotted line). This is the case when all producers can "guess the clearing price" (Heim & Goetz, 2013, p. 1) correctly. The SF becomes flatter, as indicated by SF', SF'' (light green lines) and SF'''. Ideally the producers are able to recover the entire benchmark producer surplus PS_{BM}. In this case PS_{BM} is equal for pay-as-bid and marginal pricing. In a real market, imperfect price forecasts and strategic bidding will prevent this from happening. Therefore, the real merit-order list will be used as a benchmark, assuming that the producer surplus cannot be maximized further.

Fluctuating RES shift supply function from SF_{BM} to SF_{RES}

The introduction of fluctuating RES into the control reserve market will shift the supply function SF_{BM} to the right to form SF_{RES}. Depending whether SF_{RES} is made out of the merit-order list with the opportunity cost approach SF_{OP} or the market price approach SF_{MP} it could have a different shape. $CP_{RES,max}$ could differ between the two bidding strategies that have an influence on the accepted quantities from fluctuating RES. For reasons of simplicity in Figure 4-14 it is assumed that $CP_{RES,max,op} = CP_{RES,max,mp}$ and only the shape of SF_{OP} and SF_{MP} between 0 and C_{Dim} is altered. In reality, however this will most likely not be the case.



Source: Own analysis

Figure 4-14: Supply and demand function for the capacity bids of the control reserve market with inelastic demand and the fluctuating RES generators with bids from the opportunity cost approach (OP) and the profit maximizing approach (MP)

Identifying the producer and consumer surplus in the pay-as-bid control reserve market

The shift of the supply function SF leads to changes in the consumer surplus CS and the producer surplus PS. The orange and white striped area (area E) plus the orange and grey striped (area A) area make up the consumer surplus CS_{RES}. Compared with Figure 4-13 this is increased by the additional consumer surplus CS_{RES}, indicated as area A. The additional producer surplus consists of the green and white striped area (area D) as well as the dark blue and grey (area B) and light blue and grey (area C) striped areas. Areas D and C cannot be accessed by the producers due to the pay-as-bid pricing mechanism.

Relation between cost changes and welfare gain

These changes in welfare are now set in relation to the cost changes from chapter 4.4.5, meaning the increase or loss in welfare can be calculated with equation (4-27) in chapter 4.4.5. If $CP_{RES,max,op} = CP_{RES,max,mp}$ then $CS_{RES,OP}$

is equal to $CS_{RES,MP}$. The cost changes induced by the fluctuating RES bidding their opportunity costs can be calculated as following:

$$\Delta C_{OP} = CS_{RES,OP} + PS_{RES,OP} + PS_{RES,MP} \tag{4-42}$$

with:
- $CS_{RES,OP}$: additional consumer surplus (area A)
- $PS_{RES,OP}$: additional producer surplus (area B)
- $PS_{RES,MP}$: additional producer surplus (area C)
- ΔC_{OP} : change in costs with opportunity cost merit-order lists

Cost changes of market based bidding and possible additional income

The fluctuating RES, oriented to the market price bidding, generate the additional income $PS_{RES,OP}$, which is the difference between the opportunity cost and profit maximizing bidding approach. The principles are equally applied to the capacity component as well as the energy component of the existing control reserve markets. The cost changes for market-based bidding can be calculated as follows:

$$\Delta C_{MP} = CS_{RES,MP} + PS_{RES,MP} \tag{4-43}$$

with:
- $CS_{RES,OP}$: additional consumer surplus (area A)
- $PS_{RES,MP}$: additional producer surplus (area C)
- ΔC_{MP} : cost change with market price merit-order lists

Interpretation of the results

$PS_{RES,OP}$ is the possible additional income for the fluctuating RES generators through their market participation. Results are displayed in chapter 5.4. The cost changes ΔC_{MP} are the cost saving potential from the systems point of view, as shown in chapter 6.1. The welfare gain is obtained from ΔC_{OP} as presented in chapter 6.3.

4.4.8 Forecasting the welfare gain in 2020 and 2030

Forecast the welfare gain based on the results of the hindcasting model

The identification of the welfare gain in the previous chapter allows forecasting for the future. This chapter is based on the findings of the previous chapter as well as on the findings in chapter 6.3, which opens up the possibility of carrying out the forecast. Extrapolating the welfare into the future with results from the hindcasting approach allows an approach that is robust against short-term price changes.

The extrapolation is likely to capture the underlying fundamentals of the market development, as discussed by Lorenz and Gerbaulet (2015). The approach of Lorenz and Gerbaulet is based on a fundamental analysis model (see chapter 3.4.3.1) for the year 2025. The authors elaborate on the difficulties of estimated prices for negative control reserve markets. They conclude that the conditions in 2025 might lead to relatively lower costs for positive control reserve (secondary and tertiary) and higher costs for negative reserves (secondary and tertiary). In total however, lower costs could be observed. This would indicate that the negative control reserve markets would develop in a stable manner, with a downward slope due to the participation of wind and PV (Lorenz & Gerbaulet, 2015, p. 10).

Future market development and welfare gain follow fundamentals in the control reserve market

From the results in Figure 6-5 one can conclude that the contribution of fluctuating RES will strongly diminish in the future for the dispatch component. Current developments indicate an increase in competition in the energy price component of the control reserve markets (Bundesnetzagentur, 2015). The addition of an energy-only reserve market follows the previous announcements by Acer (2012) and ENTSO-E (2014). It is very likely that the suggested changes will increase the competition significantly, pricing the dispatch of control reserve energy by fluctuating RES out of the market. The forecast of welfare gains is based on the capacity component only.

Considering only capacity component of the markets

The provision of positive control reserve by fluctuating RES generators cannot create significant welfare gains in the market, based on the capacity component only (see Figure 5-17, Figure 6-1, Figure 6-2, Figure 6-5 and Figure 6-6). This is mainly due to the high costs of curtailments, which are not expected to change in the future. Even with the ongoing merit-order effect and subsequent negative prices, the market penetration in the positive reserve market will stay insignificant, due to the underlying fundamentals. This leads to the conclusion that the forecast of the welfare gains shall only be based on the negative control reserve market.

Only negative reserve markets

The changes currently being discussed by the Federal Network Agency suggest that the product lengths of the secondary and tertiary control reserve are both harmonized to a product length of four hours (Bundesnetzagentur,

Forecasts is created for secondary and tertiary markets together due to interchangeability of those markets

2015, p. 5,12). This not only increases the economics of a possible reserve provision by fluctuating RES generators, but also makes both markets interchangeable. Since fluctuating RES generators are technically able to provide both services, they will contribute to whichever market provides the larger benefits and hence creates the larger welfare gain. Therefore, the welfare gain in the markets should be forecasted jointly, without distinguishing between them. At the current time, the shares of the welfare gain of both market segments, as shown in Figure 6-7, are averaged and forecasted into the future.

$$\Delta WF_{total,2030} = \Delta WF_{total,2020} = \overline{\Delta WF_{total,2010\ldots2014}} = \frac{1}{n}\sum_{t=2010}^{2014}\frac{(\Delta WF_{SFC,t} + \Delta WF_{TFC,t})}{2} \tag{4-44}$$

with:

n	: number of years
$\Delta WF_{SCR,t}$	: observed welfare gain as the ratio between the capacity component welfare gain and the capacity cost market value of the secondary market in the year t
$\Delta WF_{TCR,t}$	: observed welfare gain as the ratio between the capacity component welfare gain and the capacity cost market value of the tertiary market in the year t
$\overline{\Delta WF_{total,t}}$	: average of observed annual welfare gains from both markets
$\Delta WF_{total,2020}$	: ratio of welfare gain and total market volume in 2020
$\Delta WF_{total,2030}$	: ratio of welfare gain and total market volume in 2030

Naïve predictor for the ratio between welfare gain and market size

Equation (4-44) explains how the ratio between the welfare gains for the capacity cost component and the capacity cost component market size is extrapolated into the future. The mean value of the ratio in the secondary and tertiary market is averaged over all assessment years. Since the average of the ratios is relatively stable for the assessment period, it is assumed that the fluctuating RES generators will achieve the same share in the future. The constant share can also be explained by the fact that the potentials are limited due to resource availability.

Extrapolating the market development from the past

Since the welfare gain of the capacity component is dependent on the market size in the future, this must first be forecasted. This can be done by considering the past development (for market volume data see Figure 3-7). The market size of the capacity component of the secondary and tertiary market has decreased significantly over recent years. Based on past development, the data is extrapolated into the future. The welfare gain from of the fluctuating RES generators can then be expressed as a share of the market size, as shown in equation (4-44).

Forecasting the market volume in the 2020 and 2030

The decreasing market size correlates with a decrease in the control reserve demand in Figure 3-10. The decrease in control reserve demand can be associated with the removal of inefficiencies in the power system design, especially in the balancing group contracts. It can be assumed that these inefficiencies have been removed for the most part. Further decrease in control reserve demand should not be expected. It is likely that the forecast errors of fluctuating RES will have an increasing influence on the demand. The dena II study concludes that the demand will not increase significantly (dena et al., 2010, p. 19) in the future. For this thesis, it is assumed that the demand stabilizes at the level of 2014. It can therefore be assumed to be constant in the future. However, since past market volume data was influenced by the by now removed inefficiencies, the data is adjusted to accommodate this effect. The market volume is derated in proportion to the amount that the demand exceeded pre-2014 levels. After this adjustment the market size can be extrapolated.

Choosing an appropriate extrapolation function

For the extrapolation the choice of the extrapolation function is paramount. It is assumed that the market volume will not reach zero at any time. It can be safely assumed that the market volume will stabilize at lower levels than today's levels, due to increased competition. The chosen function needs to fulfil this requirement. Two groups of functions have been identified to be particularly suited for this task. The first is the group of exponential functions (see e.g. (Papula, 2009, p. 103)) or the broken rational functions (see e.g. (Papula, 2009, p. 85)). The latter group of functions show undesirable asymptotic behaviour with the fitted data. Therefore exponential functions in the form of equation (4-45) are chosen:

$$f(x) = a \cdot e^{(b \cdot x)} \tag{4-45}$$

with: e : euler number
a : first coefficient
b : second coefficient

Application of market volume to welfare gain ratios

After fitting the market development to the function $f(x)$, the annual market volume is calculated for the years 2020 and 2030 ($f(2020)$ and $f(2030)$). The shares of equation (4-44) are applied for the results from the previous chapter, using different levels of reliability and product lengths.

4.5 Limitations of the chosen modelling approach

Drawbacks using the REBal model and dependencies

The modelling of the participation of fluctuating RES in the control reserve market fulfils the criteria. However, due to the chosen modelling approach several limitations can be observed. Since REBal is a hindcasting model, it is only able to model for the ex-post. Forecasting the economic impact in the future can only be carried out as an approximation from the results. Despite best efforts to model all eventualities, results may prove volatile as a result of changes of the input parameters. In general, results show a high dependency on price movements in the market.

Participation of other market participants cannot be modelled

It is likely that the addition of fluctuating RES will have an impact on the behaviour of other market participants in the control reserve market. REBal does not allow observation of those changes, which would require certain assumptions about the market participants' behaviour. It is therefore unable to measure changes in control reserve prices by any other means than fluctuating RES. Possible behavioural changes would decrease the possible additional income for new market participants. The welfare gain will be the same however, as the Pareto optimal is shifted and the gain is accessed by the demand side.

Regulatory framework changes

The results are subject to regulatory framework changes. A change of the pricing mechanism from pay-as-bid to marginal pricing would change the shape of the merit-order list completely. This can only be modelled with assumptions of the shape and must be considered highly speculative.

Economic gains might only realize on a short-time scale. The modelled merit-order effect does not include long-term capacity effects, which would have to be evaluated with a different approach.

No long-term capacity effects modelled

Changes to legislation could change the market structure significantly. The REBal model is flexible enough to accommodate for this, the results shown in this study might not reflect the new market structure.

Regulatory changes will change the market structure that would require recalculation

5 Economics of fluctuating RES in the control reserve markets

The results of the modelling are split into two parts. The first part assesses the behaviour of fluctuating RES in the control reserve markets, and shows the economic impact on the generators themselves. The second part assesses the micro-economic impact of the behaviour on a system-wide level. In this chapter, the key decision elements of fluctuating RES delivering control reserve are presented and their economic importance evaluated.

Economic impact assessment from the generators' point of view and the system point of view

The economic impact assessment for the fluctuating RES generators in this chapter purely focuses on the supply side. These generators as financial entities will strive to optimize their market participation and thus maximize their potential income. Achieving this goal encourages strategic bidding in the market. The relatively small size of the control reserve market with its potential lack in market liquidity could lead to a strong influence on the market results by single market participants. This influence of the fluctuating RES generators is quantified in chapter 6. However, only the influence of the new market participants is assessed, since strategic bidding hinders the modelling of the reaction of the other market participants.

Bidding behaviour in the market by market participants

The bids and results in this chapter are calculated for the combination of a multitude of parameters. In total 504 different combinations of bids were created for each one of the five different fluctuating RES generator types (data overview in Figure 4-2). The assessed pool of fluctuating RES generators are the 30 GW onshore wind farm pool in Germany, the 1 GW onshore wind pool of individual wind farms, the 1 GW offshore wind farm pool Germany, the 30 GW pool of PV systems in Germany and the 1 GW pool of individual PV systems. The bids for each generator type include bids for the secondary and tertiary control reserve market, each individually for negative and positive markets as well as with symmetric bidding. For the sake of brevity, symmetric bidding will not be presented. Primary control reserve could be modelled by REBal; although, while proven by some

Parameter variation for fluctuating RES generators in the secondary and tertiary control reserve market research results, the technical capabilities of the units are still disputed. Therefore, it does not form part of the assessment at any point.

Variation of product length, levels of reliability, proof method and markets

The investigated product lengths are one hour, two hours, four hours, eight hours, twelve hours and 24 hours. The levels of reliability are 95 %, 99 %, 99.5 %, 99.9 %, 99.99 %, 99.994 % and 99.999 %. For each of the scenarios an opportunity cost based approach and a market price based approach is calculated, implementing two different proof methods (see Figure 3-17 and Figure 3-18). This leads to 2520 individual sets of bids in four different market segments, namely negative and positive secondary and tertiary control reserve. A sensitivity analysis is not required due to the initial variation of all input parameters.

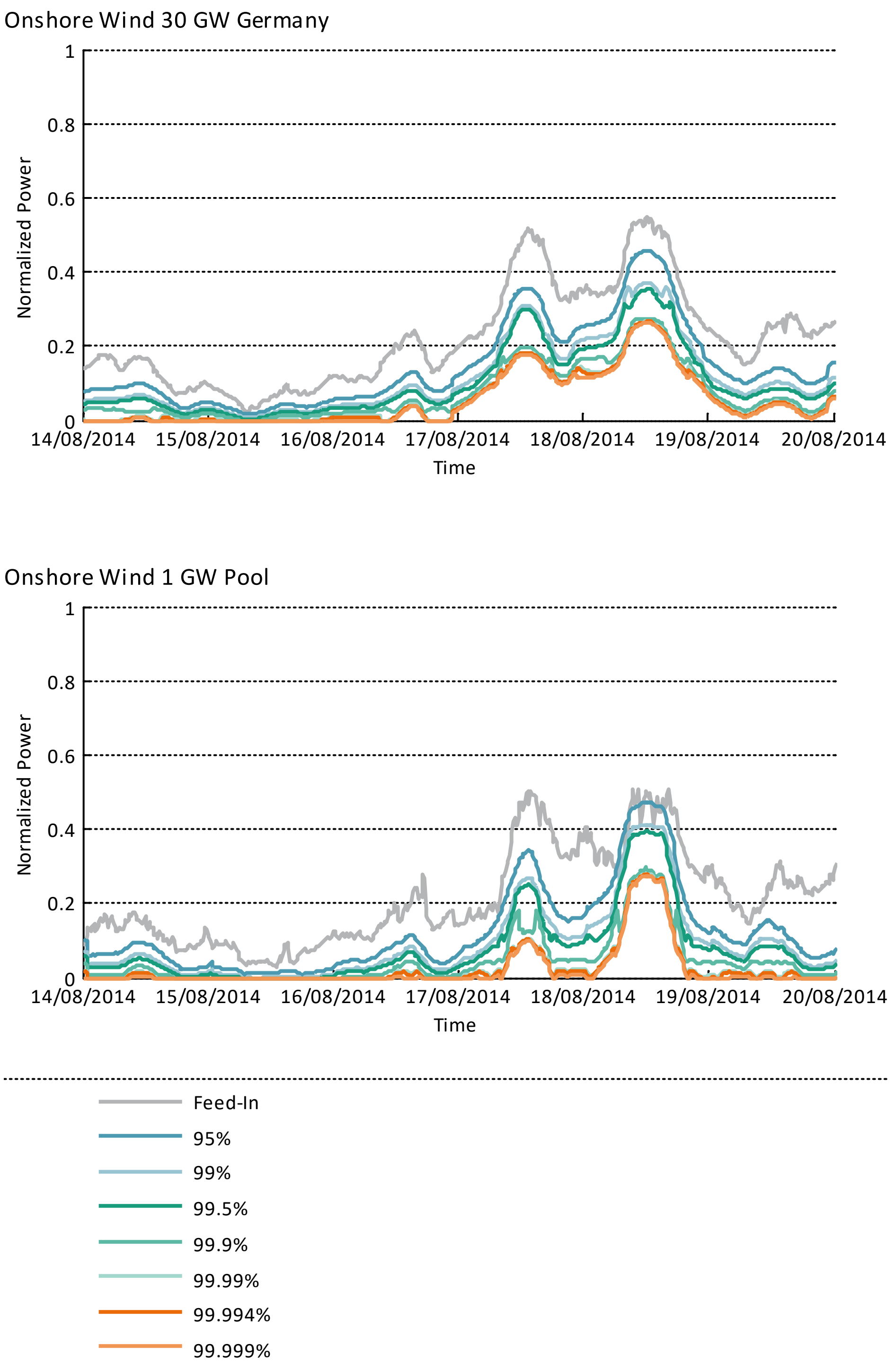
5.1 Probabilistic Forecasts

Probabilistic forecast for offering control reserve reliably

Based on the methodology in chapter 4.4.1 the probabilistic forecasts for the assessed fluctuating RES are examined. These forecasts are used to determine the offerable capacity for each generator type at each point in time. For the wind farms, this includes the entire German 30 GW wind farm pool, the 1 GW pool of individual wind farms, and the entire German offshore wind farm pool of 1 GW. The investigated PV systems include the entire German pool of 30 GW of PV systems and the 1 GW pool of PV systems.

Description of the following graphs

Exemplary data for the different onshore wind park pools are shown in Figure 5-1 for the period from the 14th of August 2014 to the 20th of August 2014. The German offshore wind farm pool of 1 GW is shown in Figure 5-2. For the PV systems, exemplary data are shown in Figure 5-3 for the same period. The probabilistic forecasts for the one-hour ahead intraday forecasts are shown in Appendix B-A. Each of the graphs shows the different quantiles of a probabilistic forecast. Lower reliability is indicated by blue colours, through greens to higher reliability shown in orange. The actual feed-in is shown in grey.

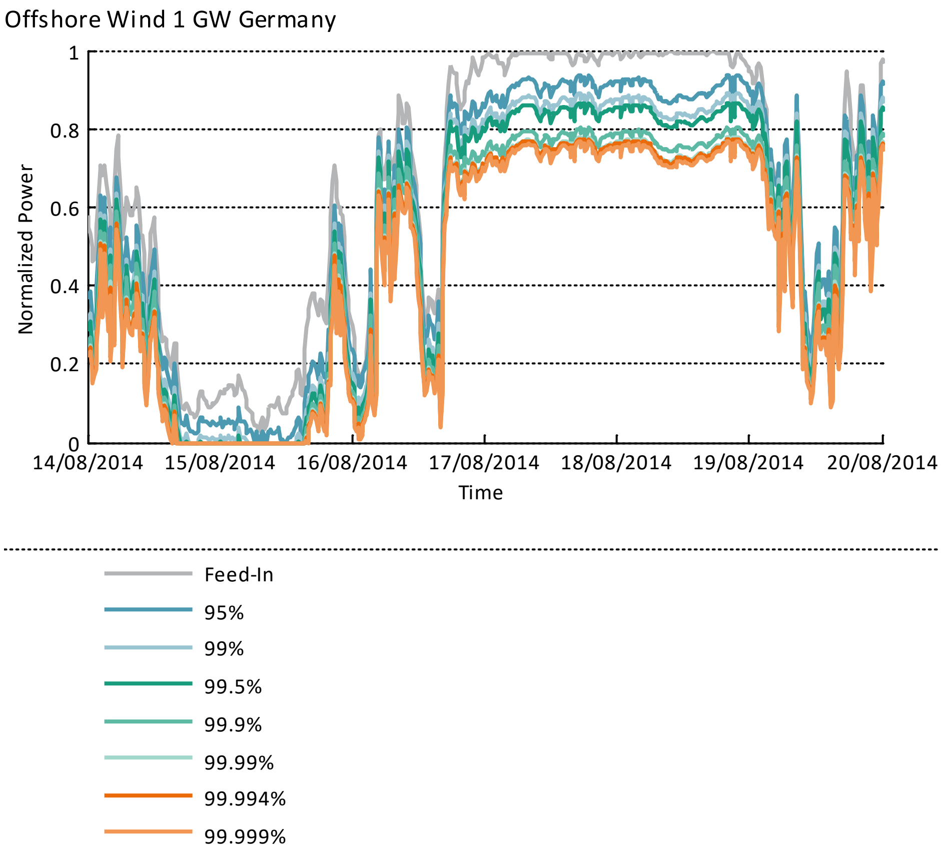


Source: Own analysis

Figure 5-1: Probabilistic day-ahead forecast of the German 30 GW onshore wind farm pool and the 1 GW onshore wind farm pool

Forecast security levels for five different data sets of fluctuating RES

The probabilistic forecast data in Figure 5-1 are presented for the forecast quantiles of 95 %, 99 %, 99.5 %, 99.9 %, 99.99 %, 99.994 %, and 99.999 %. One can observe the different feed-in characteristics of the three different sets of wind farms (Figure 5-1 and Figure 5-2) and the two sets of PV systems (Figure 5-3).

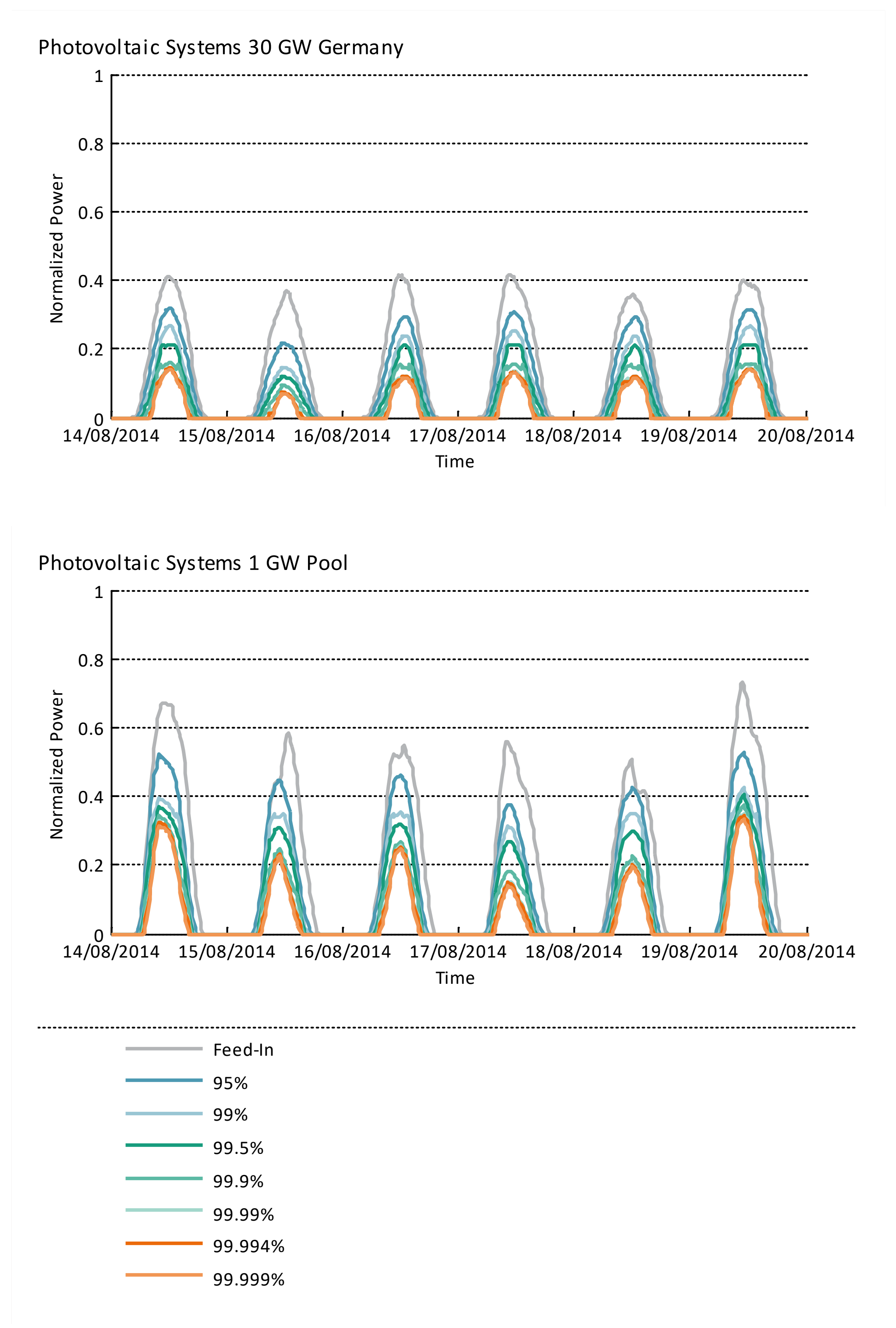


Source: Own analysis

Figure 5-2: Probabilistic day-ahead forecast of the German 1 GW offshore wind farm pool

Analysis of the forecast curves of the wind farm portfolios

With increasing forecast reliability the offerable amount decreases significantly. The amount depends on the quality of the initial forecast. The onshore wind farm pool of 1 GW has fewer smoothing effects than the 30 GW pool. At comparable day-ahead point forecasts, the 30 GW wind farm pool probabilistic forecast is significantly higher at the same level of reliability. The same behaviour can be seen in the one-hour ahead intraday forecast in the Appendix B-A. The forecasts for the offshore wind farm pool show that there is a high confidence in the forecast when full load is predicted. At the same time, the forecasts tend to show a high level of uncertainty in times with low or medium feed-in levels. Offshore wind forecasts suffer from changes in the portfolio's size over time, thus changing production and forecast patterns.



Source: Own analysis

Figure 5-3: Probabilistic forecast of the German 30 GW pool of PV systems and the 1 GW pool of PV systems

Analysis of the forecast curves of the PV systems portfolios

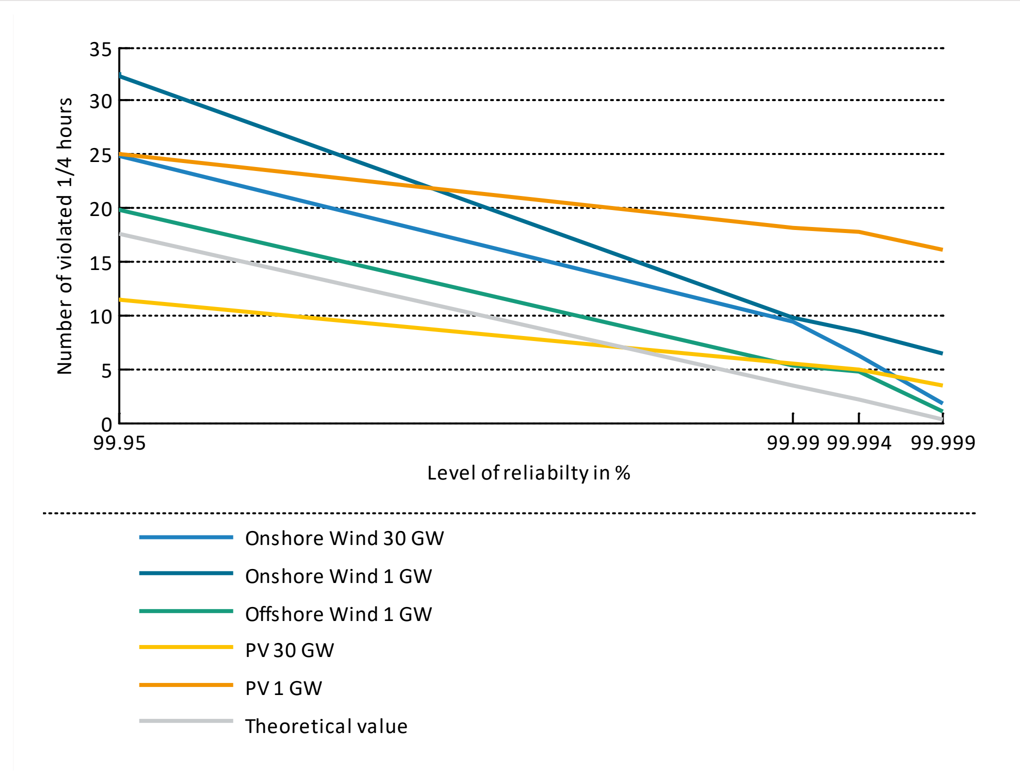
The forecasts of the PV systems, as shown in Figure 5-3, show a different behaviour compared to the 30 GW and1 GW wind farm pool. The German 30 GW pool of PV systems shows a weaker forecast performance than the forecast for the 1 GW pool. This is contrary to the previous findings. The pool size and geographical smoothing effect seem to have little impact on the forecast quality. The data for Germany are gathered by/for the TSOs. Therefore, one can safely assume that it lacks real-time data of measurements of all PV systems and relies heavily on upscaling algorithms. For the 1 GW pool real measurements are gathered ex-post. These data can be used to improve forecast quality. Additionally the 1 GW pool consists only of open field PV systems whereas the 30 GW is mostly installed on rooftops. Moreover, for the intraday forecast quality, the intraday forecast for the 30 GW pool was created with the persistency method as described earlier. The 1 GW pool uses real forecast data from a forecast service provider.

Prerequisites for a high performing probabilistic forecast

In any case, the probabilistic forecasts generated are significantly lower than the forecasted value of the point forecast. The results show the importance of the forecast quality. Additionally forecasting methods other than the KDE might deliver results that are more suitable. The difference between the probabilistic forecast and point forecast is highly dependent on the initial forecast quality and the characteristics of the error between the feed-in and the expected value forecasts of each data set.

Assessing the forecast quality for high levels of reliability

The following figure shows the frequency of forecast violations for the security levels from 99.95 % to 99.999 % as an average value for the entire assessment period. The curves indicate the number of times when the probabilistic forecast has exceeded the actual feed-in. In this case, the amount offered at the control reserve market would not have been fully available, causing a breach of contract. The theoretical values that would be allowed at that level of reliably are shown in grey, while the actual values are shown in different colours for the different RES generators. At a level of reliably of 99.994 % the forecast should only be violated in two ¼ hours of a year. Offshore wind and the 30 GW pool of PV systems have on average five ¼ hour violations each year, the 30 GW onshore wind farm pool has six, the 30 GW pool of wind farms eight. All of the fluctuating RES generators exceeded the required number of violations. The 1 GW pool of PV systems has on average 18 violations, although this is based on the least amount of data available for the probabilistic forecast. The deviations of all other fluctuating RES generators can be considered to lie within the allowance of the statistical scattering. It can be concluded that the kernel density estimator is a suitable approach to generate probabilistic forecast that provide the desired levels of reliability.



Source: Own analysis

Figure 5-4: Quantiles of the probability forecasts and the theoretical value for the probabilistic day-ahead forecast

Pool size and geographic location are influencing probabilistic forecast the most

One can conclude that the forecast quality increases with the pool size and the geographical dispersion of the fluctuating RES generators. The markdowns for the intraday forecasts are significantly lower and less dependent on the pool size and geographic location. This is in line with the findings in (Brauns et al., 2014, pp. 52–57).

5.2 Technical potentials

From probabilistic forecasts to a market suitable quantity bid

The probabilistic forecasts from chapter 5.1 are used to calculate the offers for the control reserve market by the fluctuating RES. The generation of market suitable quantity bids is explained in chapter 4.4.2. For each market segment the minimum of day-ahead and intraday forecasts are used to generate the offerable amount that can be bid into any market. The quantities are later allocated to a specific market when the prices are calculated.

5.2.1 Deriving quantity bids from the probabilistic forecast

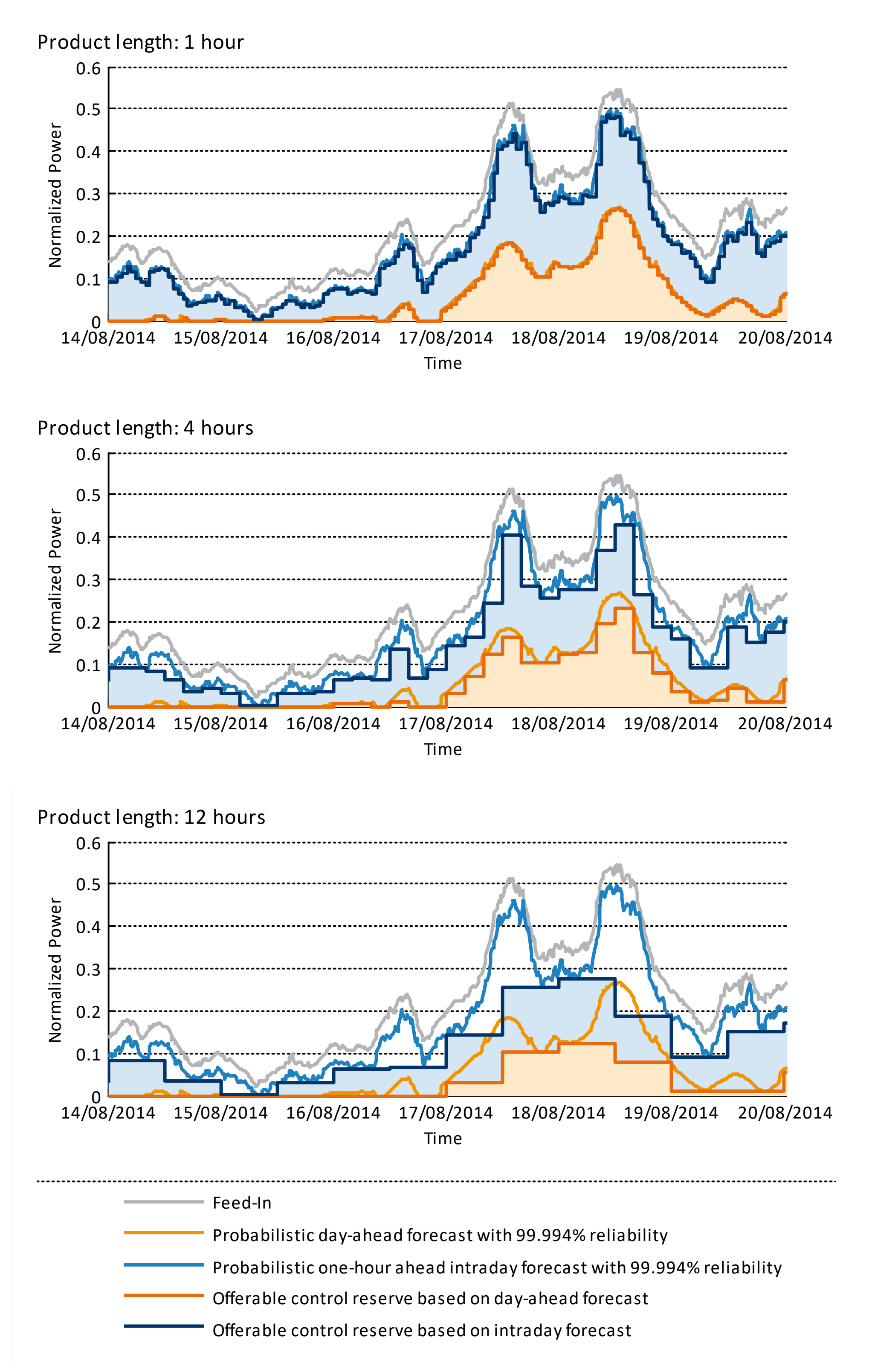
Shown time period and shown product lengths

Figure 5-5 shows probabilistic forecasts, offerable amounts in the control reserve market and the actual feed-in for the period from the 14th of August 2014 to the 20th of August 2014, the same time period as in Figure 5-1, Figure 5-2 and Figure 5-3. The reliability is 99.994 % and the product lengths are one hour (top), four hours (middle) and twelve hours (bottom). The four-hour length is used since it is the product length in the tertiary control reserve market. One hour is likely to be used in the future by pan-European balancing market as laid out by the network code on electricity balancing (NC EB). Twelve hours is the current product length of secondary control reserve[22].

Explanation of the presented data

In Figure 5-5 one can observe the relationship between the probabilistic day-ahead forecast (orange line) and the corresponding offerable amount based on the day-ahead forecast (orange area). The blue lines indicate the one-hour ahead probabilistic intraday forecast (blue line) and the offerable amount based on this forecast (blue area). The grey line indicates the maximum possible feed-in based on the available resource. Figure 5-6 shows the same relationship for the German 30 GW pool of PV systems.

[22] This is an approximation since the low tariff / high tariff structure requires covering longer periods on Sundays where only the low tariff control reserve providers are used. Additionally tendering is carried out on a weekly basis, therefore the product length is one week, separated into several blocks of twelve hours.



Source: Own analysis

Figure 5-5: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecast for the German 30 GW onshore wind farm pool for the reliability of 99.994 % and a product length of one, four and twelve hours

Further results in Appendix B-B

The data used for the German 30 GW onshore wind farm pool is the same as in Figure 5-1 and Appendix B-A. Results for the 1 GW onshore wind farm pool, the German 1 GW offshore wind farm pool and the 1 GW pool of PV systems are located in Appendix B-B, where results for selected levels of reliability and selected product lengths are also available. Results for the product lengths of one hour, two hours, four hours, eight hours, twelve hours and 24 hours are produced for the entire range of results.

From probabilistic forecasts to offerable quantities in the control reserve markets

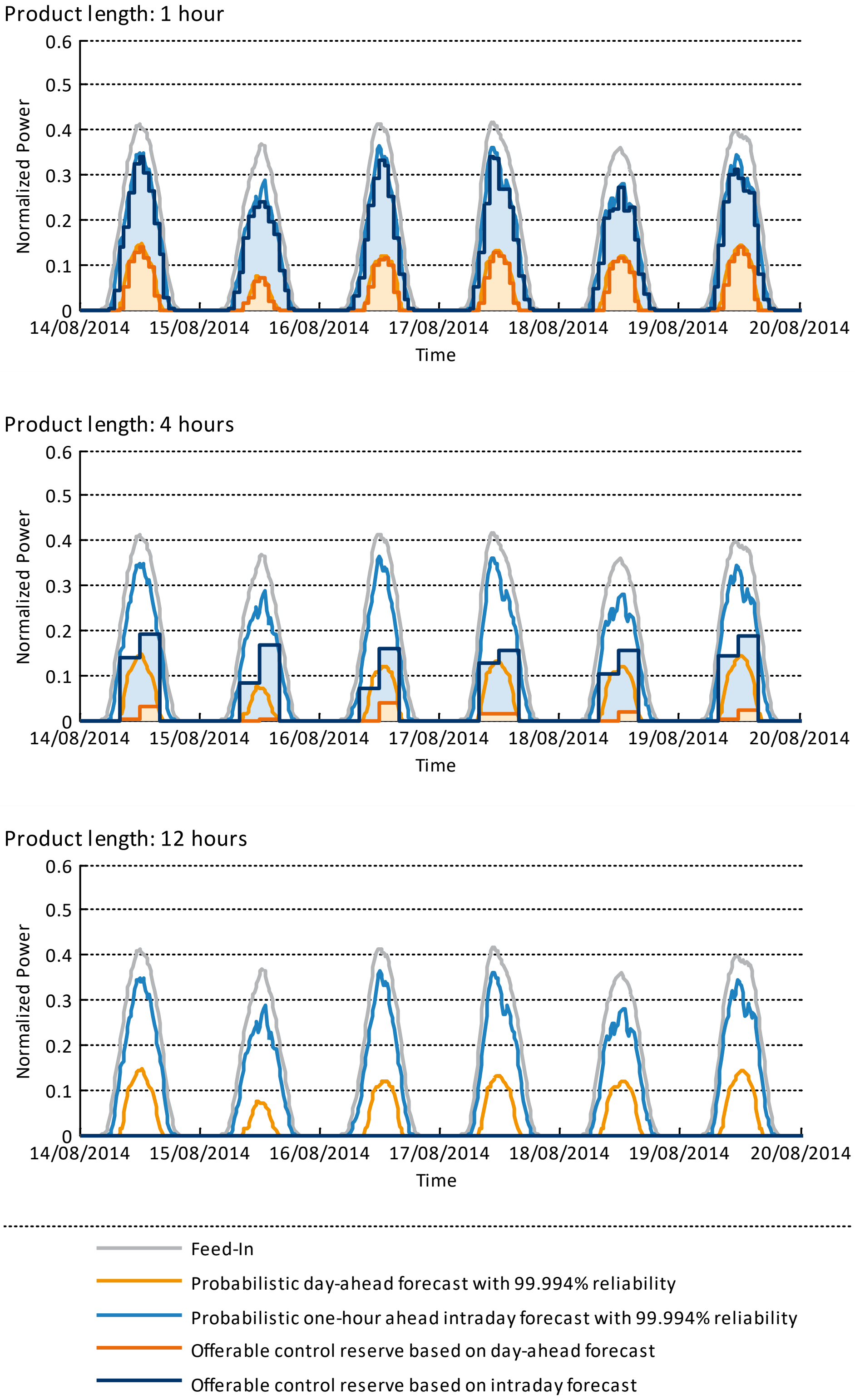
The results shown in Figure 5-5 and Figure 5-6 show the principles of using probabilistic forecast to provide quantities to the control reserve market. The aim is to identify suitable product lengths for the control reserve market that allow the participation of fluctuating RES.

Impact of the product length on the potential provision of control reserve by wind farms

For the given product lengths, wind farms are able to provide control reserve for up to 24 hours (see Appendix B-B). For product lengths of up to four hours the potential is not restricted. With longer product lengths, the potential decreases significantly. The 1 GW pool of wind farms is already very limited in its potential with a product length of twelve hours (Figure B-16 in Appendix B-B). The 1 GW pool of offshore wind farms, similarly to the entire German onshore pool, is not largely affected by increasing product lengths. In fact, the opposite is the case. The steady full load production of offshore wind is favourable for the provision of control reserve for longer time periods.

Impact of the product length on the potential provision of control reserve by PV systems

PV systems on the other hand already have limited capabilities to provide control reserve with product lengths of four hours or more. The significantly better forecast of the 1 GW pool also shows much higher potentials at a product length of four hours (Figure B-18). With product lengths of 12 hours or more, PV systems will not be able to deliver control reserve at all. It is therefore important to shorten the product lengths as much as possible. The impact of the product length on the capability to provide control reserve can also be seen on a cumulated basis in Figure 5-7, Figure 5-8 and Appendix B-C.



Source: Own analysis

Figure 5-6: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecast for the German 30 GW pool of PV systems for the reliability of 99.994 % and a product length of one, four and twelve hours

Intra-15-minute fluctuations not accounted for

Fluctuations that occur with a time-scale of less than 15 minutes are not accounted for in the REBal model. These intra-15-minute fluctuations could be accounted for by an additional markdown. For the assessment of pools of fluctuating RES, it can be assumed that these fluctuations are balanced stochastically throughout the pool. If the assessment were to be made for a single windfarm, these fluctuations would need to be accounted for.

'The offerable amount has a higher level of reliability than the original probabilistic forecast

It is also worth mentioning that the offerable amount has a higher reliability than the probabilistic forecast that it was derived from. This is because the minimum value of the entire product length determines the offerable amount. Therefore, all 15-minute intervals of the probabilistic forecast were higher than the value for the offerable amount, hence increasing the reliability of all other forecasts and the reliability of the offerable control reserve amount.

Showing the offerable amount as an indicator value

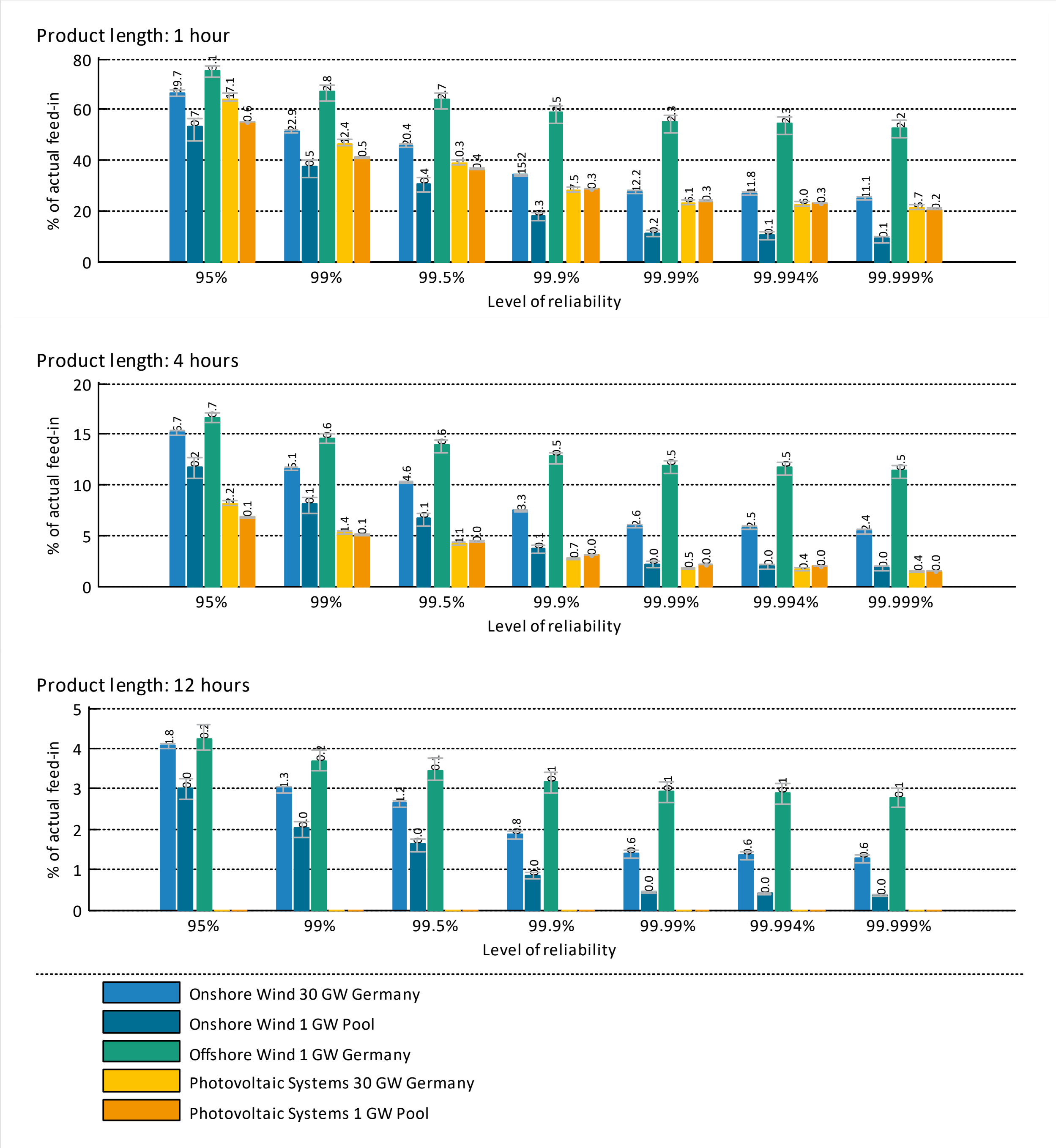
Since the results shown in Figure 5-5, Figure 5-6 and Appendix B-B vary significantly over time; it is desirable to display them as aggregated numbers. This facilitates comparability between the different fluctuating RES generators and allows the presentation of all assessed parameters. The indicator based values are the summarized annual offerable amount. In Figure 5-7 the annual offerable amount based on the day-ahead forecast is shown. The values correlate to the orange areas in Figure 5-5 and Figure 5-6. The figure shows the integral (sum) of the available capacity for all products. The integral of the capacity is expressed as its possible energy content, and therefore can be given in MWh.

Specific values based on feed-in

Due to different feed-in characteristics it is favourable to provide specific numbers for the ratio between the possible energy content for the control reserve market and the maximum possible feed-in based on the available resource. Setting the potentials in relation to the possible feed-in allows for the comparison of the different pool sizes.

Interpreting the bars, range indicators and values in the graph

Each bar in Figure 5-7 is the average value over different years of the assessment. In the case of the German 30 GW onshore wind farms portfolio this spans the entire five years whereas the 1 GW pool of PV system spans only two years, as per the data availability (also see Figure 4-2). The range indicator on the bars shows the difference between the minimum and maximum values in the different years. The total values on the bars show the mean energy content of the offerable amount expressed in TWh.



Source: Own analysis

Figure 5-7: Potentials for offering control reserve based on the day-ahead forecast for different fluctuating RES generators with varying levels of reliability and product lengths of one, four and twelve hours

Colour coding and levels of reliability

In each plot from left to right, the potentials are given for the different data sets. In line with the colour scheme in Figure 4-2 the 30 GW onshore wind farm pool is in blue, the 1 GW onshore wind farm pool in dark blue, the offshore wind farms pool in green, the 30 GW pool of PV systems in yellow and the 1 GW pool of PV systems in orange. From left to right different levels of security are displayed from 95 % to 99.999 %.

Choosing the product lengths

The top graph shows the potentials for the product length of one hour. This is chosen since it is likely that this product length will be relevant in the future, as e.g. in the white paper (Bundesministerium für Wirtschaft und Energie, 2015b) or the network code electricity balancing (ENTSO-E, 2014). The four-hour product length represents the current tertiary control reserve market, which is presented in the middle graph. The twelve-hour product length in the bottom graph can be found in the secondary control reserve market with its peak and off-peak products.

Shares of the available resource for the provision of control reserve

The potential for providing control reserve to the market differs with the product length and the level of security. About 26.5 % of the available wind reserve could be offered as control reserve by the 30 GW pool of onshore wind farms, assuming a product length of one hour and a level of reliability of 99.994 %. The pool of onshore wind farms could offer 10.6 %, and the offshore wind farms 54.4 % of their wind resource. Interestingly the offshore wind farms seem to realize the highest potential. This might correlate with the previously discussed issue of how well they can be forecasted reliably during full load operation. With offshore wind most of the production happens during full load operation. The 30 GW pool of PV systems could offer 22.5 % and the 1 GW pool 22.9 % of the available resource. With increasing product lengths, the offerable amounts decrease significantly. Additional graphs with different product lengths can be seen in Appendix B-C.

Small annual variations due to uniformly used error data in the probabilistic forecast

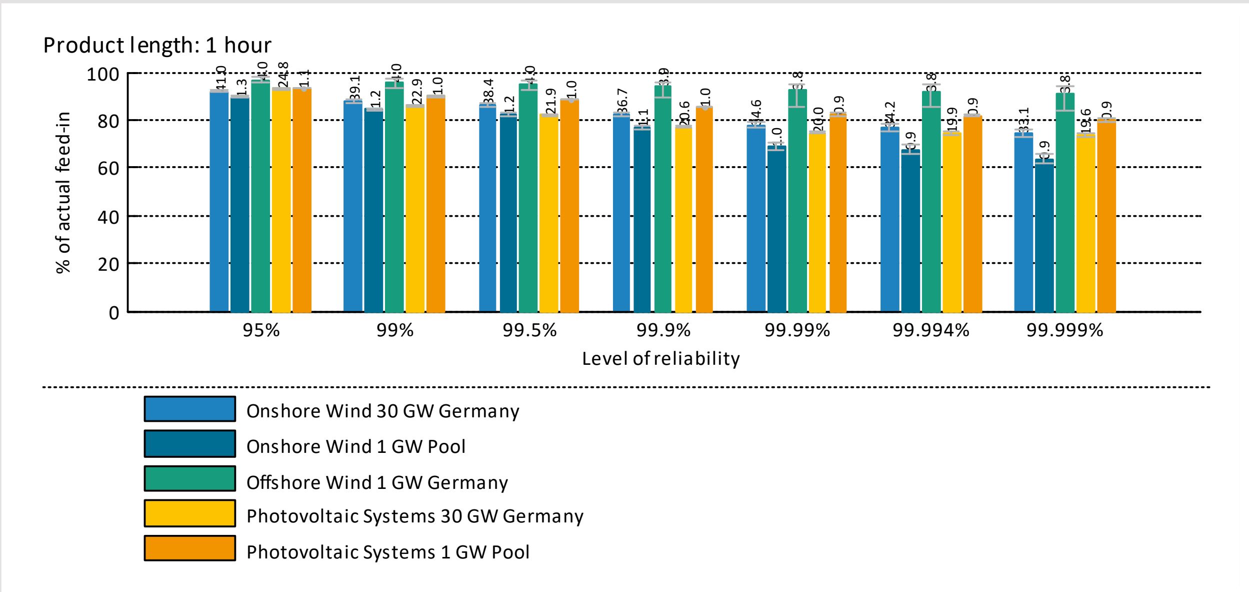
The potentials do not differ strongly between the different years. This is visible by the narrow range, indicated by the range indicators. However, it has to be mentioned that for all years the exact same error distribution for each data set has been used. Therefore small deviations can occur. Outside a modelling environment, probabilistic forecasts created for 2010 are based on different data sets for their error information to the data that are calculated for the year 2014.

Potentials might not be absorbed by the market

Due to a limited demand in the control reserve market, it may be that not all of the potential can be absorbed by the market. However, these potentials can be split and bid into different markets simultaneously. It is also more likely that bids for positive reserve products are less economical due to their higher opportunity costs.

Offerable potentials based on the one-hour ahead intraday forecast

The annual offerable amount based on the one-hour ahead intraday forecast is shown in Figure 5-8. These values are connected to the blue areas in Figure 5-5 and Figure 5-6. Similarly to Figure 5-8 the integral (or sum) of the available capacity is shown. Only the product length of one hour is generated. Longer product lengths would require a mixture of forecasts with different lead times. For a four-hour product length, for example the last hour of the forecast would be significantly less reliable than for the first hour. The product length of one hour is also relevant for the pan-European balancing market (ACER, 2012). The figure is arranged in the same way as Figure 5-7. The given values are in TWh.

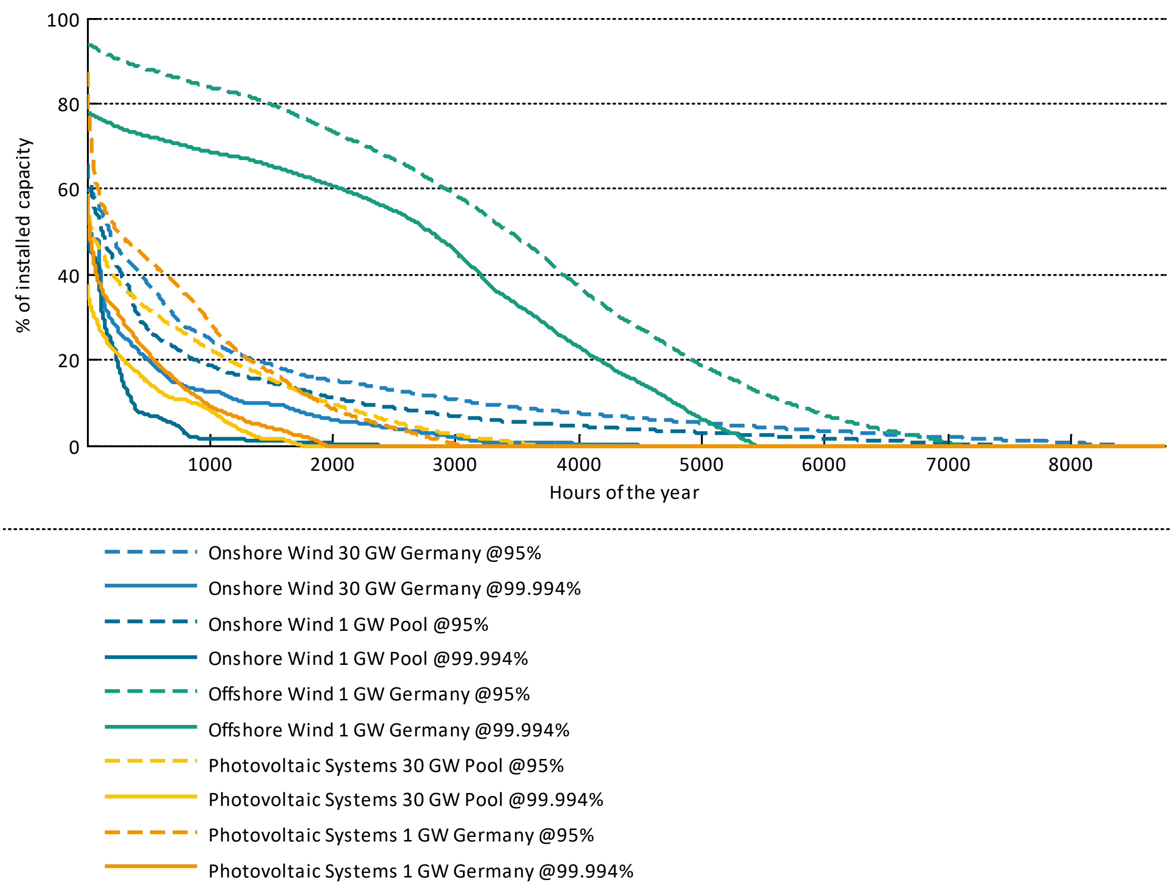


Source: Own analysis

Figure 5-8: Potentials for offering control reserve based on the one hour intraday forecast for different fluctuating RES generators with varying levels of reliability and a product length of one hour

Visualization as duration curves

The results in Figure 5-7 and Figure 5-8 can also be represented as duration curves as in Figure 5-9 for the day-ahead case and as in Figure 5-10 for the intraday case. Both graphs show the duration curve of the offerable amount of different RES generators. The values are expressed in percent of installed capacity, which enables comparability between the different pool sizes. A value of 30 % means that 30 % of the installed capacity can be used to provide control reserve. The duration curves are given for the year 2014 and a product length of one hour, since this displays the highest potential. Larger product lengths decrease the potential. It is not necessary to provide plots for additional years since all the probabilistic forecasts use the same base training data. The height of the curves only differs by the degree of the annual fluctuations of the feed-in. Annual fluctuations however have already been captured in Figure 5-7 and Figure 5-8.

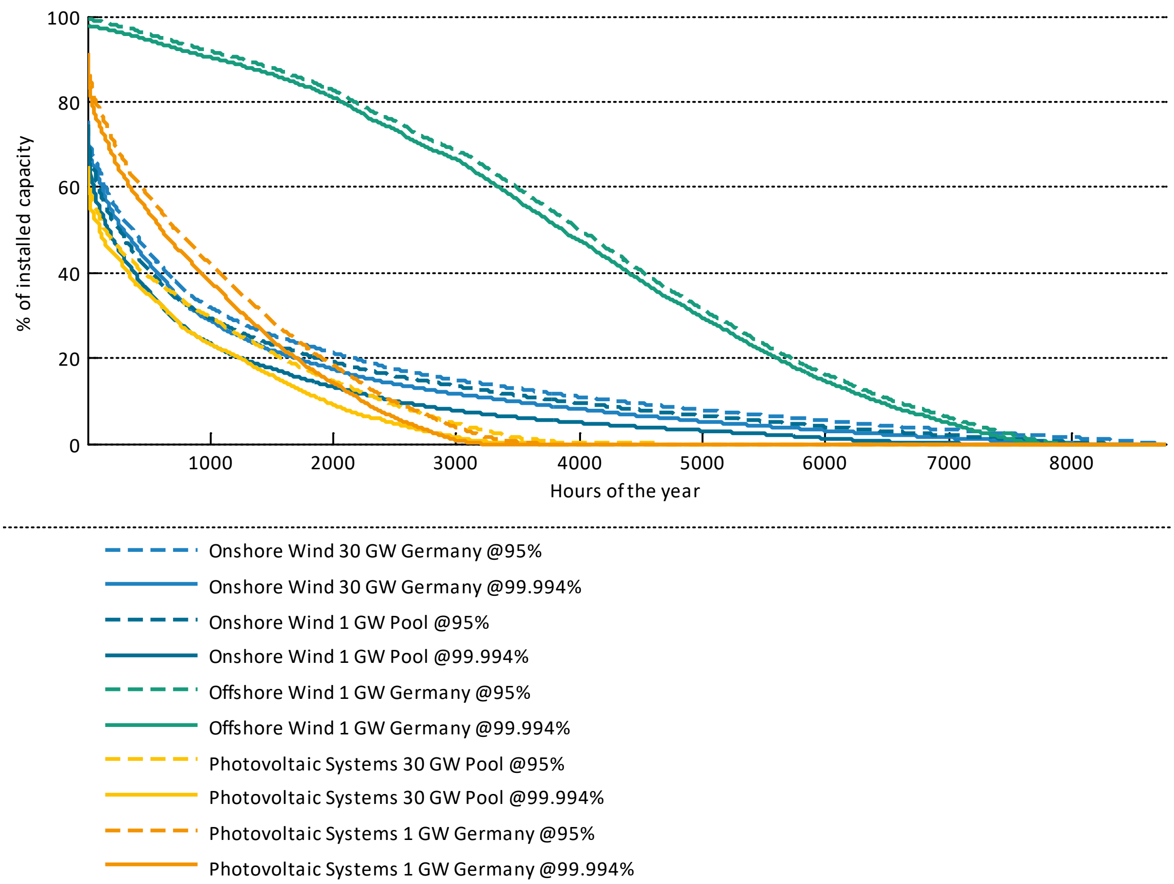


Source: Own analysis

Figure 5-9: Duration curve for the offerable control reserve based on the day-ahead forecast for different fluctuating RES generators for the levels of reliability of 95 % (dashed line) and 99.994 % for the year 2014 and a product length of one hour

In line with the results shown in Figure 5-8 the duration curve of the offerable control reserve based on the one-hour ahead intraday forecast can be seen. Similarly to Figure 5-8, the potentials in the duration curve are much higher in more hours of the year than in the day-ahead case and much closer to the maximum possible feed-in (not shown in this graph).

Duration curve for the intraday forecast



Source: Own analysis

Figure 5-10: Duration curve for the offerable control reserve based on the one hour ahead intraday forecast for different fluctuating RES generators for the levels of reliability of 95 % (dashed line) and 99.994 % for the year 2014 and a product length of one hour

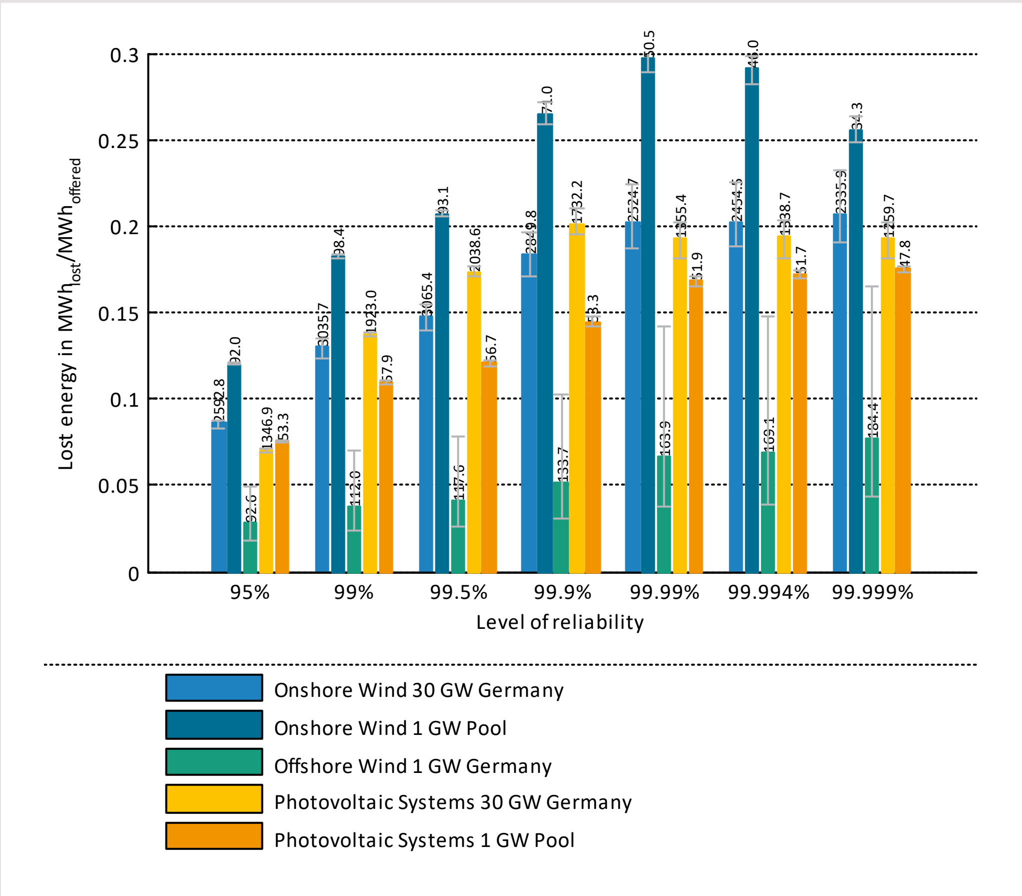
5.2.2 Energy losses due to the proof mechanism

If the wind farm were to be curtailed due to the application of the balance control proof method, as illustrated in Figure 4-11, then energy losses based on equation (4-32) would occur. These energy losses, as depicted in Figure 5-11, are created by the curtailment of the wind farms to the level of the probabilistic forecast. In line with the rest of the calculations, the losses

Energy losses due to curtailment on the schedule with the balance control mechanism would occur between the one-hour ahead intraday forecast and feed-in. The given values are the average of the ratio between the energy losses and the maximum possible feed-in (available active power) for the different types of RES generators. In the case that the RES generator does not place an offer for a specific product, then the energy losses do not occur, since operation would fall back to normal mode without curtailment. This graphic does not account for possible rejections of bids in the market due to high bid prices.

Description of data sets

The product length of one hour is chosen. The given average values span the entire data period available for each type of RES generators. The number on the bar provides the average annual lost energy in GWh. For additional product lengths, refer to Appendix B-C. The values given are the ratio between the energy lost (MWh_{lost}) per offered ($MWh_{offered}$).



Source: Own analysis

Figure 5-11: Average annual specific energy losses with control reserve being offered day-ahead under the balance control proof mechanism (bars) for different types of fluctuating RES generators for the product length of one hour and different levels of reliability and the average annual total losses as numbers on the bars in gigawatt hours

With possible energy losses, the impact of regulations on the economic feasibility and the environment becomes visible. It is paramount that regulations and market conditions are designed in such a way that unintended effects are avoided. For example, if too long product lengths are chosen, PV systems cannot offer control reserve at all. The application of the balance control proof mechanism is not favourable in terms of environmental impact. The financial implications of these losses are evaluated in chapter 6.2.

Conclusion on the energy losses

5.3 Calculation of bids for the control reserve market

Based on the technical potentials from the previous section, prices for bidding into the control reserve market are calculated from perfect price forecasts (see assumptions chapter 4.2). The calculation of prices is divided into two parts. The first part presents the resulting prices from the opportunity cost based approach and the second part gives the results from the profit maximizing approach. Later these two approaches are used in order to identify the possible income, according to chapter 4.4.7. Results are shown in chapter 5.4. The aforementioned energy losses only occur with the opportunity cost based bids and the balance control method applied. The losses themselves and the economic valuation are presented later in chapter 6.2 in the context of the power systems' point of view. The market price based bids are not dependent on the lost energy.

Structure of the chapter

Bids for the control reserve have three values. The first value is the quantity of the bid. The second value is the capacity price for the provision of control reserve. This is an availability payment, which is also the award criterion. Thirdly, every bid has to have an energy price that is paid to the market participant if the bid is activated. All of the bids presented fulfil these criteria.

Basic description of bids

5.3.1 Opportunity cost driven bids

Principles of the opportunity cost based bidding approach

The opportunity cost based approach creates bids for the control reserve market that are the cheapest bids possible for the fluctuating RES generators. This is done as described in chapter 4.4.3.1. This approach only covers expenses that are created through the provision of control reserve. With this approach, the operator of the fluctuating RES generators will not generate any additional revenue. Therefore, this approach is not very likely to be implemented by market participants; however, it leads to the lowest control reserve procurement costs for the system, revealing the possible market value. The prices generated in this step are independent from the chosen control reserve market.

Opportunity costs for capacity reservations differ based on the proof method

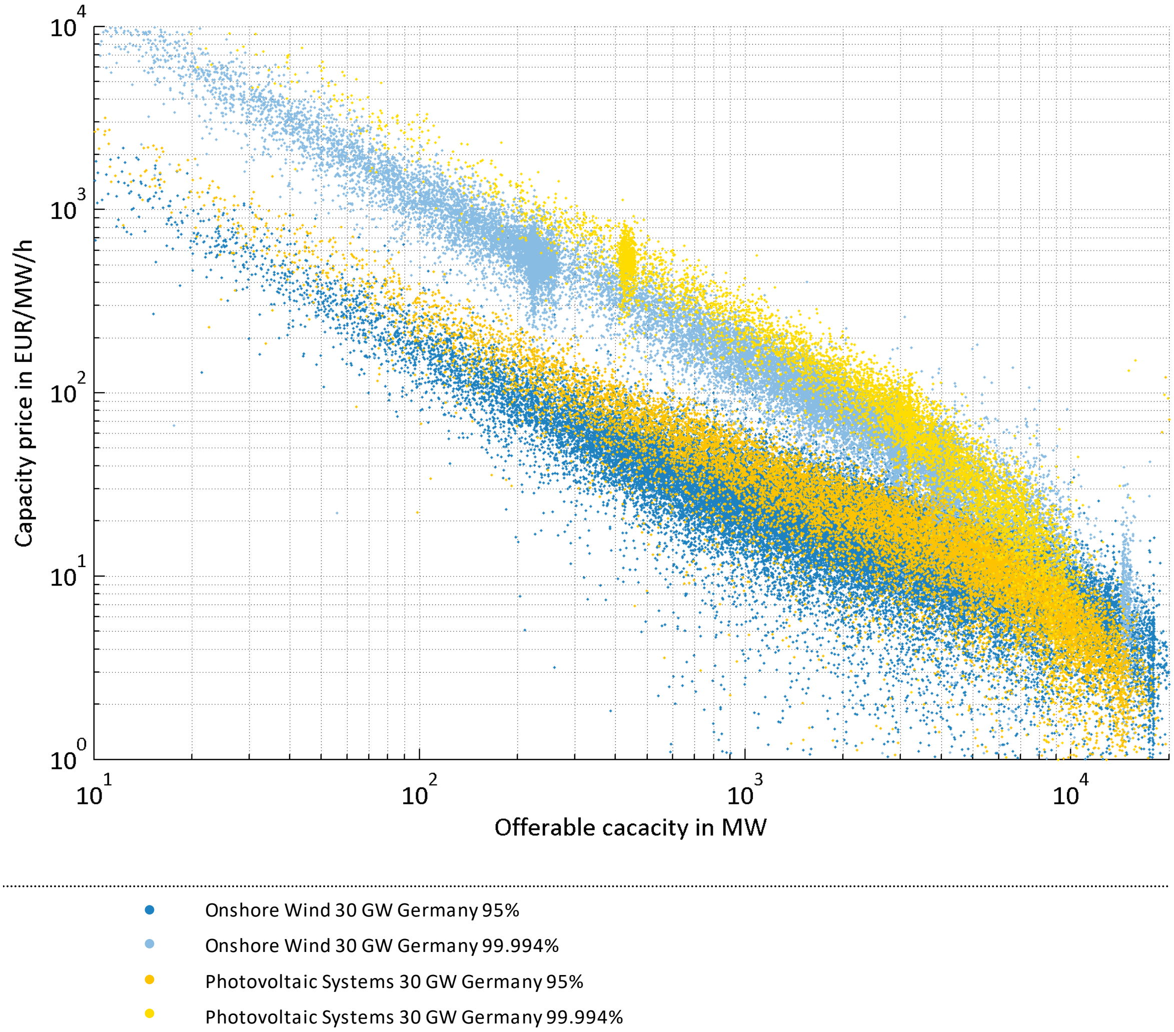
The capacity prices are an availability payment to the market participants. The opportunity costs to be covered by the fluctuating RES generators partly depend on the proof mechanism (see Figure 3-17 and Figure 3-18) and on whether the bids are created for negative or positive reserve markets. For negative reserve markets, with the available active power proof method applied, no additional costs for making the reserve available are generated (Figure 3-18). In case of the positive reserve provision, the opportunity costs only amount to the tendered amount. With the balance control proof method applied additional opportunity costs arise from the curtailment to the schedule for both negative and positive reserve products. These costs are added to the costs that arise with the active power proof method.

Opportunity costs for reserve dispatch are proof method independent

Energy costs for the bids are determined by the opportunity costs of a dispatch of control reserve. The dispatch costs are the same with both possible proof methods. In the case that positive reserve is dispatched from fluctuating RES generators, negative dispatch costs might result from the design of the RES support scheme (EEG). The energy price of the bids depends on the assumed feed-in tariff and the price forecast.

Description of the following price/quantity scatter plot

The prices for the reserve provision depend on the offerable capacity. Figure 5-12 displays the combinations of the capacity and the capacity price for the negative reserve market with the balance control proof method applied. The scattered dots indicate the price/quantity combinations of the 30 GW onshore wind farms pool (blue) and the 30 GW pool of PV systems (yellow) for the product length of one hour and a level of reliability of 95 % (darker colours) and 99.994 % (lighter colours). The price/quantity combinations are a log-log plot, which reveals the functional relationship between the offerable amount and the capacity price. PV systems generate significantly higher capacity prices than wind farms. The optical vicinity may be deceptive due to the double logarithmic scaling.

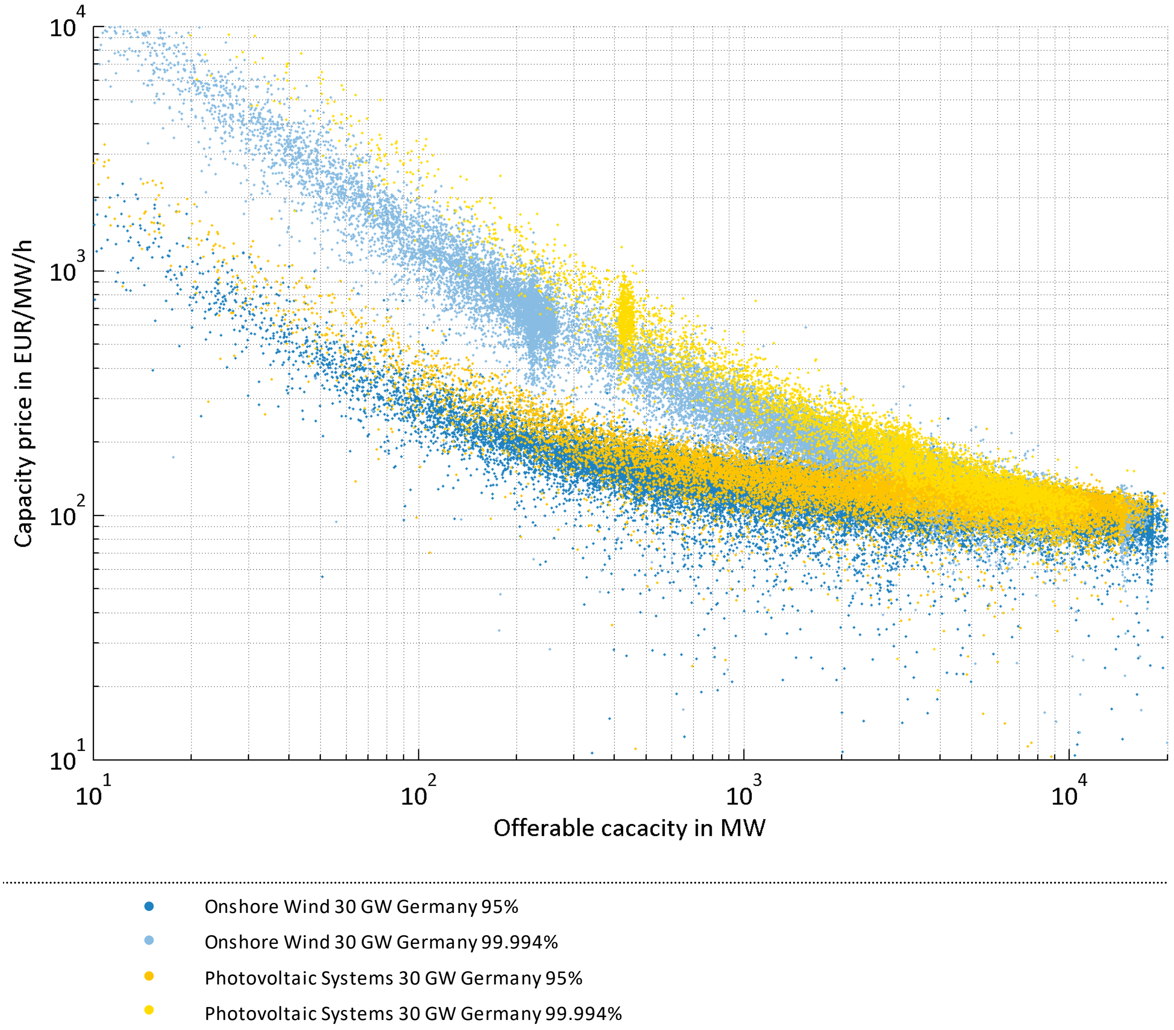


Source: Own analysis

Figure 5-12: Opportunity cost based capacity price bids for different fluctuating RES generators with a level of reliability of 95 % and 99.994 % under the balance control proof mechanism for the product length of one hour for any negative control reserve market and all years

Difference between the proof methods

The capacity costs under the available active power proof method are zero by definition. The subsequent plot Figure 5-13 shows the capacity prices for the positive reserve markets with the balance control proof method applied for a product length of one hour. The price/quantity combinations are again shown as a log-log plot below. The capacity prices under the available active power proof method for positive bids can be obtained by subtracting the capacity prices in Figure 5-12 from the prices in Figure 5-13. The scatter plot for this can be seen in Appendix B-D.



Source: Own analysis

Figure 5-13: Opportunity cost based capacity price bids for different fluctuating RES generators with a level of reliability of 95 % and 99.994 % under the balance control proof mechanism for the product length of one hour for any positive control reserve market and all years

In the double logarithmical scaling one can identify a nearly inverse linear correlation between the capacity and the price. Only bids with prices in the lower section of the plot have a chance of being accepted in the market. These tend to appear when the fluctuating RES generators produce close to or at full load capacity. This also shows the complexity of bid creation. Since log-log plots are not intuitively usable and they cannot easily be used to compare different fluctuating RES generators, indicator based values are used further on. Specifically, capacity weighted annual averages are presented.

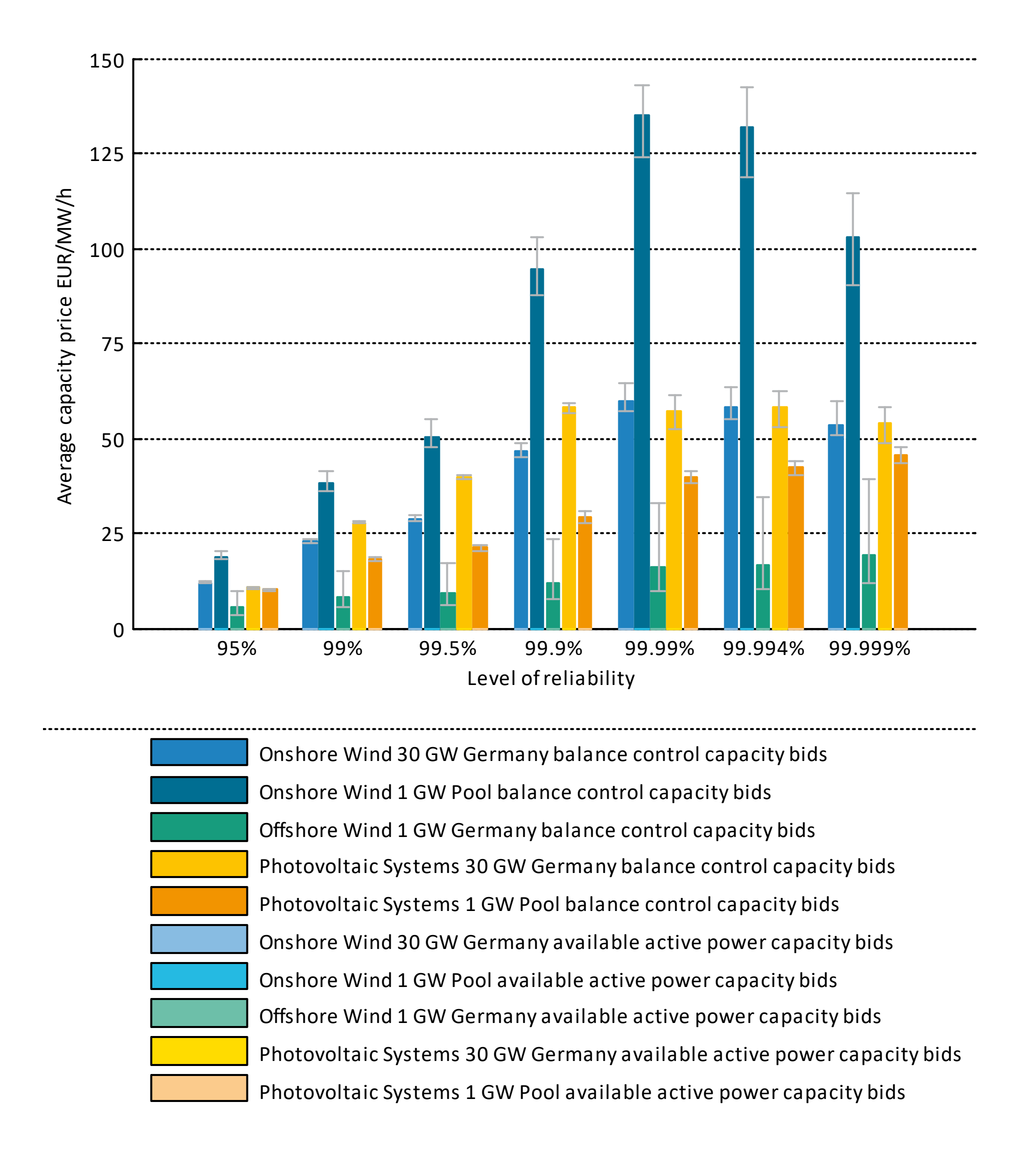
Simplifying complexity of bids for the market by using indicator values

When looking at the graphs from Figure 5-14 onwards, one should keep in mind the underlying complexity of the bids. This is also one of several reasons why the modelling results from REBal are not easily scalable or transferable to other generators. Further challenges arise from the development of the prices in the market. If the assumption of perfect price forecasts were dropped, the bids would most likely look dissimilar and may not have a functional relationship. Despite the simplified presentation in this document, REBal processes each one of these bids individually. On a case-by-case basis, it is decided whether the created bids are accepted in the market or not.

Complexity is kept in the modelling environment REBal

Figure 5-14 shows the annually averaged capacity prices for the balance control mechanism as coloured bars for the negative control reserve market (both secondary and tertiary) for a product length of one hour and different levels of reliability. The capacity prices for the available active power mechanism are zero and indicated as small light coloured stripes at the bottom. The value in the bar represents the average annual value for the data available (see Figure 4-2). The range indicators show the minimum and maximum of the mean average annual values. Additional plots for other product lengths and levels of reliability can be found in Appendix B-D.

Indicator based presentation of capacity price bids for negative control reserve markets

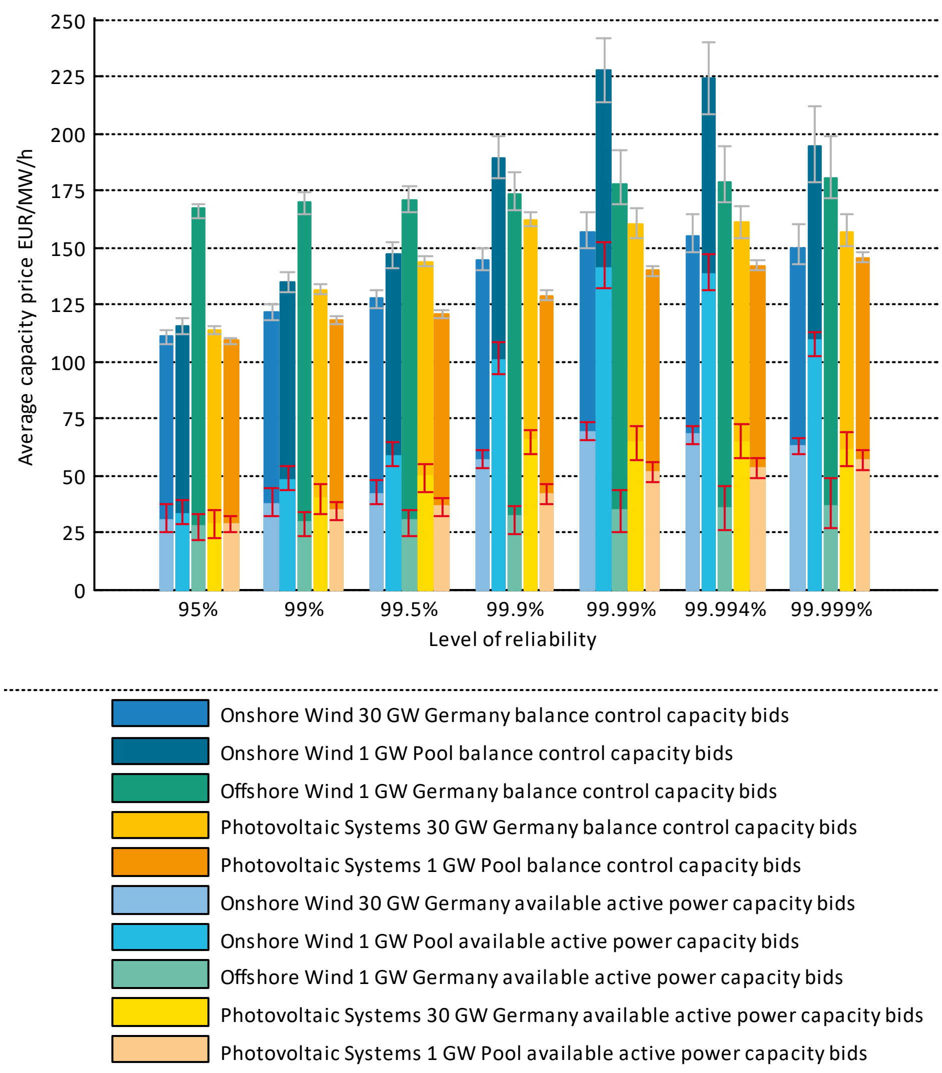


Source: Own analysis

Figure 5-14: Average opportunity cost based capacity price bids for different fluctuating RES generators with a level of reliability of 99.994 % under the balance control (darker colours) and available active power (lighter colours) proof mechanism for the product length of one hour for any negative control reserve market

Indicator based presentation of capacity price bids for positive control reserve markets

Figure 5-15 shows price/quantity combinations for bids for any of the positive control reserve markets. For the prices with the available active power proof method, opportunity costs arise from the previous curtailment of the generators to increase the power output when the control reserve is dispatched. For the balance control proof method, these costs are added to the cost of providing negative control reserve as shown in Figure 5-14. The light coloured values are the capacity prices with the available active power proof method applied. The corresponding range indicators are shown in red.



Source: Own analysis

Figure 5-15: Average opportunity cost based capacity price bids for different fluctuating RES generators with a level of reliability of 99.994 % under the balance control and available active power proof mechanism for the product length of one hour for any positive control reserve market

Analysis of the opportunity cost based capacity price bids

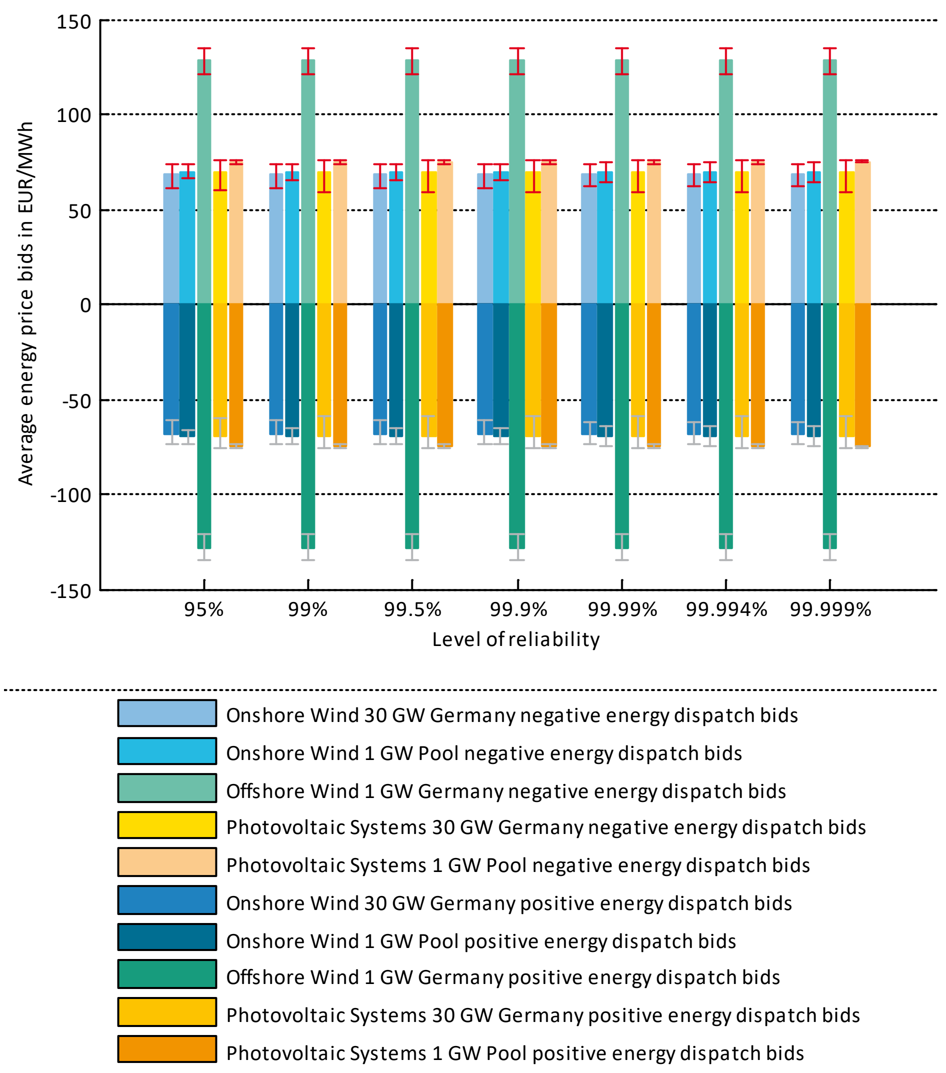
The opportunity cost based capacity prices for the negative reserve market are significantly lower than for the positive reserve market. The lost energy that has to be financially recovered under the balance control proof method leads to high opportunity costs which most likely would prevent fluctuating RES generators from participation in the control reserve markets. For prices in the market, please refer to price information from Figure 3-12 to Figure 3-15. From the relationships shown in Figure 5-12 and Figure 5-13, it is apparent that some capacity bids may enter the merit-order list. However, based on the average value this would not be the case. The market structure might change in the future since the availability of power plants in the spot market also affects the units available in the control reserve market.

Energy price bids for negative control and positive reserve markets

Figure 5-16 shows the energy prices of bids by the fluctuating RES generators for negative and positive control reserve markets. These are independent of the proof method and therefore have equal energy prices in both regimes. Since the energy prices of the bids are mostly governed by the underlying feed-in tariff they do not fluctuate as much as the capacity price bids. The presentation of the individual prices is therefore omitted. The prices shown are for the product length of one hour. The level of reliability does not have an influence on the costs of control reserve dispatch. Throughout the evaluation, energy prices correspond to dispatch prices and dispatch costs.

Analysis of energy price bids for negative control and positive reserve markets

The energy prices show little variation over time within each year and little variation between the years. Neither the product length nor the level of reliability has an influence on the energy price bids. These findings are true as long as the opportunity costs are calculated independently from the capacity price costs. Dispatch of negative control reserve from fluctuating RES generators would create positive dispatch costs for the system, although with the benefit of decreased RES support scheme payments to the generators. The dispatch of positive control reserve generates negative dispatch costs at the cost of increased RES support scheme payments.



Source: Own analysis

Figure 5-16: Average opportunity cost based energy price bids for different fluctuating RES generators for the product length of one hour for any negative and positive control reserve market

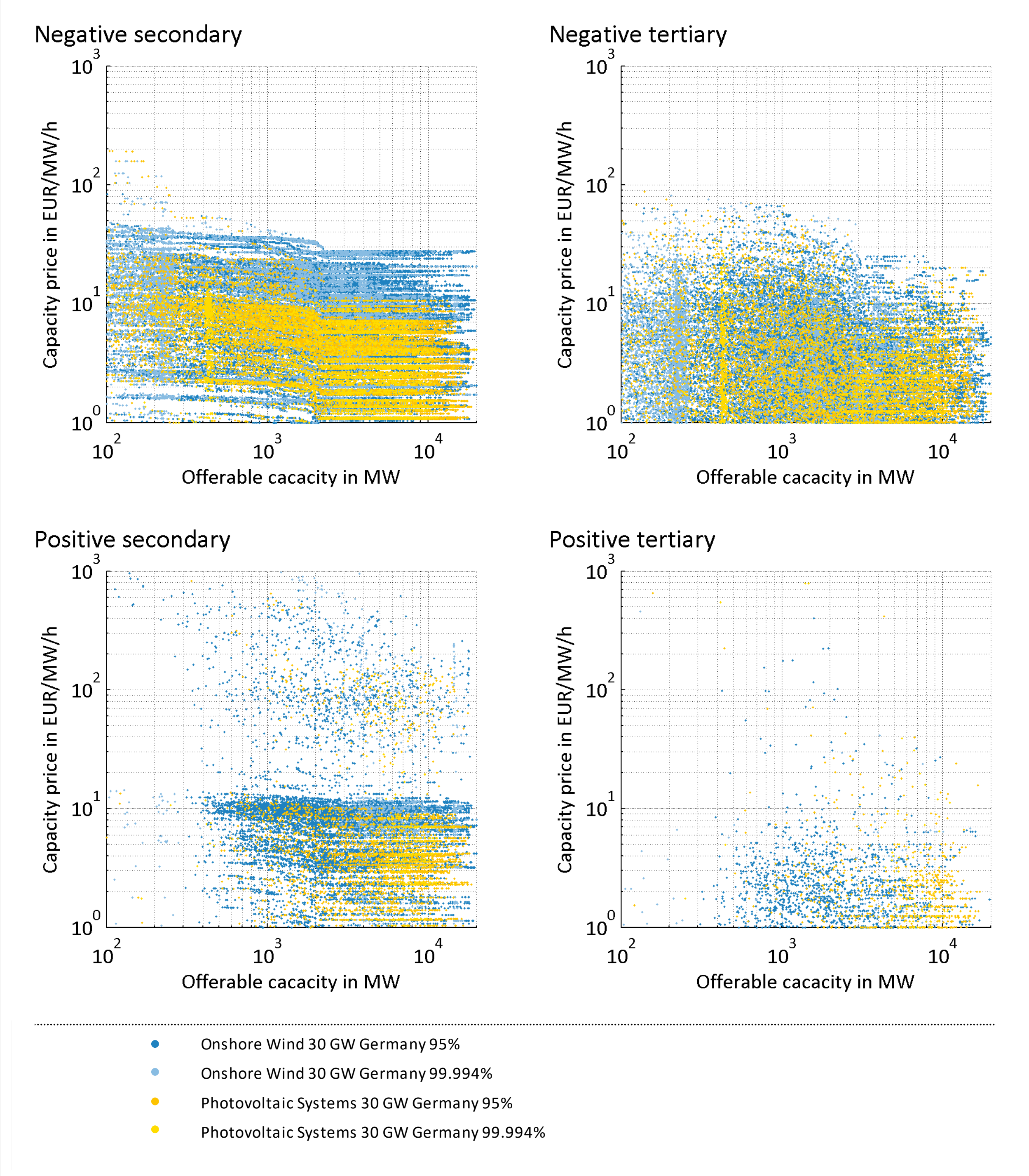
5.3.2 Profit maximizing bids

Introduction to profit maximizing bidding

The profit maximizing bidding approach creates bids for the control reserve market that maximize the additional revenue that could be achieved by the fluctuating RES generators. The methodology is laid out in chapter 4.4.3.2. This approach displays the additional revenue that would have been generated by operators of the fluctuating RES generators. The market price based bidding strategy leads to no or very little reduction in control reserve procurement costs from the system's point of view.

Individual price/quantity combinations for the profit maximizing bidding approach

The market optimizing bids from the price/quantity combinations are plotted in the log-log plot in Figure 5-17 which shows the resulting profit maximizing capacity prices with the available active power proof method applied. Results for the balance control method are located in Appendix B-D.



Source: Own analysis

Figure 5-17: Profit maximizing capacity price bids for different fluctuating RES generators with a level of reliability of 95 % and 99.994 % under the available active power proof mechanism for the product length of one hour for four control reserve market segments and all years

Description of the previous plot

The results presented in Figure 5-17 can be read the same way as in Figure 5-12 and Figure 5-13. The dark blue dots indicate the 30 GW onshore wind farm pool at a reliability of 95 %, whereas the lighter dots indicate a level of reliability of 99.994 %. This is applied similarly to the yellow dots for the 30 GW pool of PV systems. The graph also shows the four considered control reserve market segments, since the prices depend on the market.

Market effects through pool size and generator type

The capacity prices in the market approach are formed by using the capacity price of the last replaced bid in the merit order list (see Figure 4-9). The price of this intersection in the merit-order list is largely determined by the offerable amount for each individual product. A pool of 30 GW would generate more yield than a 1 GW pool simply through the fact that the merit-order list is intersected at a different position, even with a perfectly equal forecast quality. The results additionally depend on the chosen market and the type of RES generator.

Analysis of the profit maximizing capacity bids

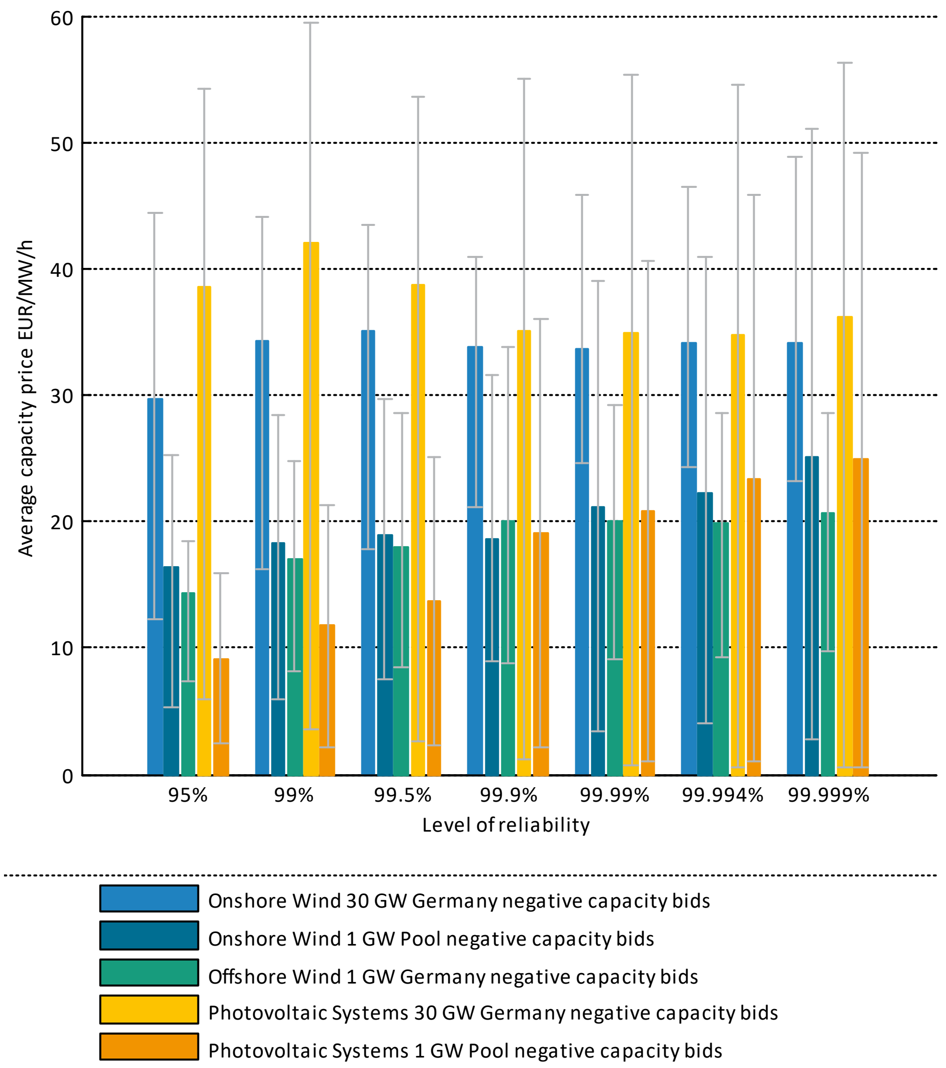
The resulting prices vary between the different fluctuating RES generators due to the fact that their offerable amount differs. The wind farm portfolio tends to realize higher market prices through deeper market penetration. This means that the merit-order list is intersected at a different position, depending on the current potential for delivering control reserve. Prices differ little with regard to the reliability of the underlying forecast. A significant difference could only occur during times when the opportunity costs were higher than the market price. The forecast with a high level of reliability is then at a disadvantage to the lower reliability forecast. Due to highly diverse capacity prices (Figure 5-12 and Figure 5-13), it can be safely concluded that this is not the case very often. One can safely assume that the opportunity costs are clearly either above or below the market prices for all levels of reliability.

Impact of the proof method on the profit maximizing capacity price bids

Comparing the results from Figure 5-17 with those results that have the balance control proof method applied (Appendix B-D), one can see that the balance control proof method will effectively reduce the market participation in the negative control reserve markets and almost completely hinder any participation in the positive reserve markets.

Description of following plots

In Figure 5-18 the annual averages from Figure 5-17 are depicted for all of the investigated pools of fluctuating RES generators. The bars are given in EUR/MW/h. This facilitates comparability, as opposed to EUR/MW. The grey range indicators show the minimum and maximum of the average values spanning all years of each data set.

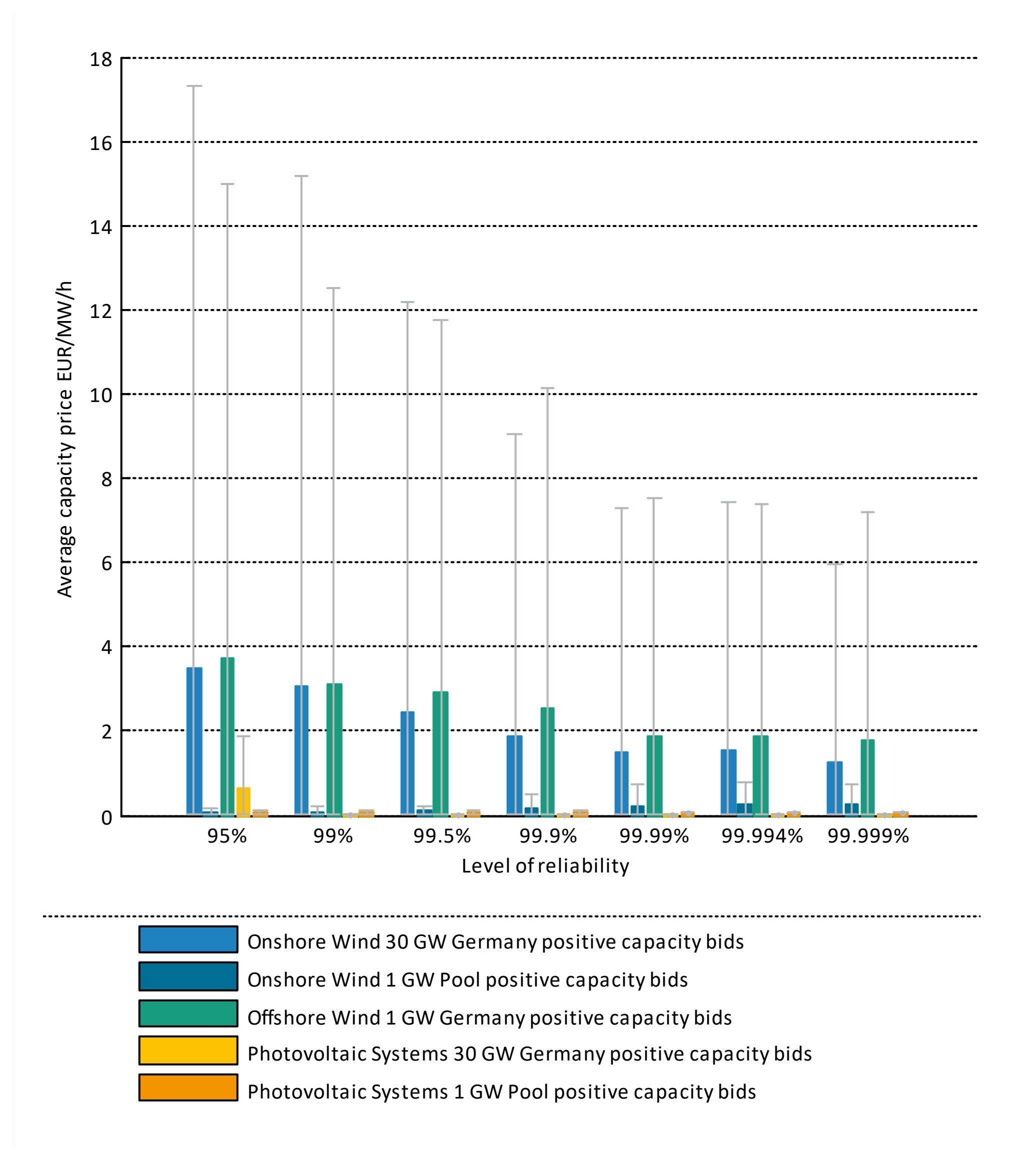


Source: Own analysis

Figure 5-18: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of one hour in the negative secondary control reserve market

High capacity prices in the negative secondary control reserve market

The negative secondary control reserve market yields by far the highest prices of all markets. The pools of 1 GW would be able to generate prices on average above 20 EUR/MW/h at a level of reliability of 99.994 %. The 30 GW pools can even generate average prices above 30 EUR/MW/h. Based on the results shown in Figure 5-12 and Figure 5-14, this would most likely allow the participation of fluctuating RES in the negative control reserve market with the balance control mechanism applied.

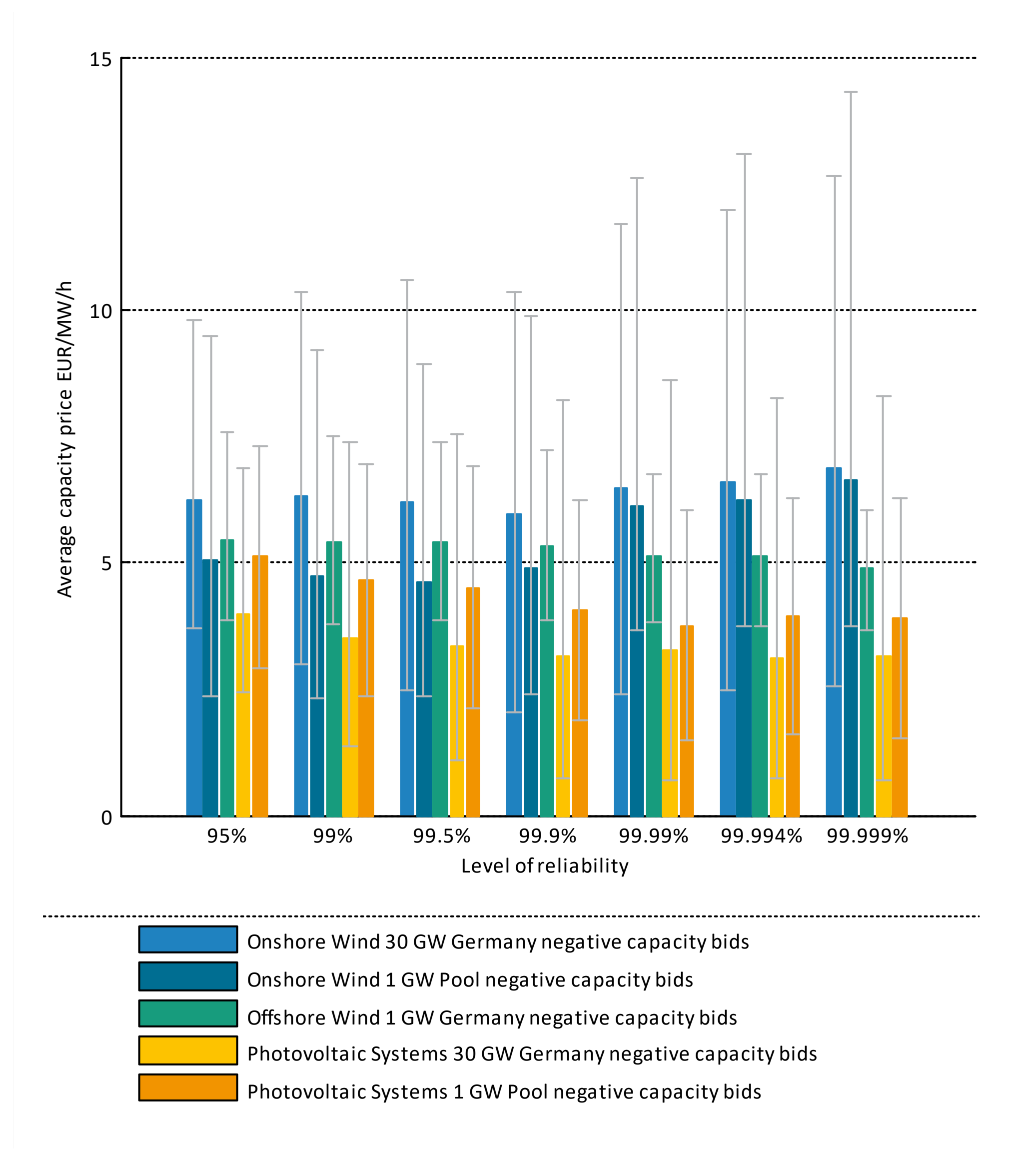


Source: Own analysis

Figure 5-19: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of one hour in the positive secondary control reserve market

The average capacity prices of the fluctuating RES generators participating in the positive secondary control reserve market (Figure 3-13) show very low capacity prices. This indicates that the market penetration cannot be very high. It allows the conclusion that this might only happen with perfect price

Low market value of the capacity bids in the positive secondary control reserve market forecasts. However, the range indicators show very high annual average values, which then in turn would allow participation. It can be concluded that the market potential for fluctuating RES generators is limited and highly dependent on the market price dynamics.



Source: Own analysis

Figure 5-20: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of one hour in the negative tertiary control reserve market

Negative control reserve market most suitable as an entry market

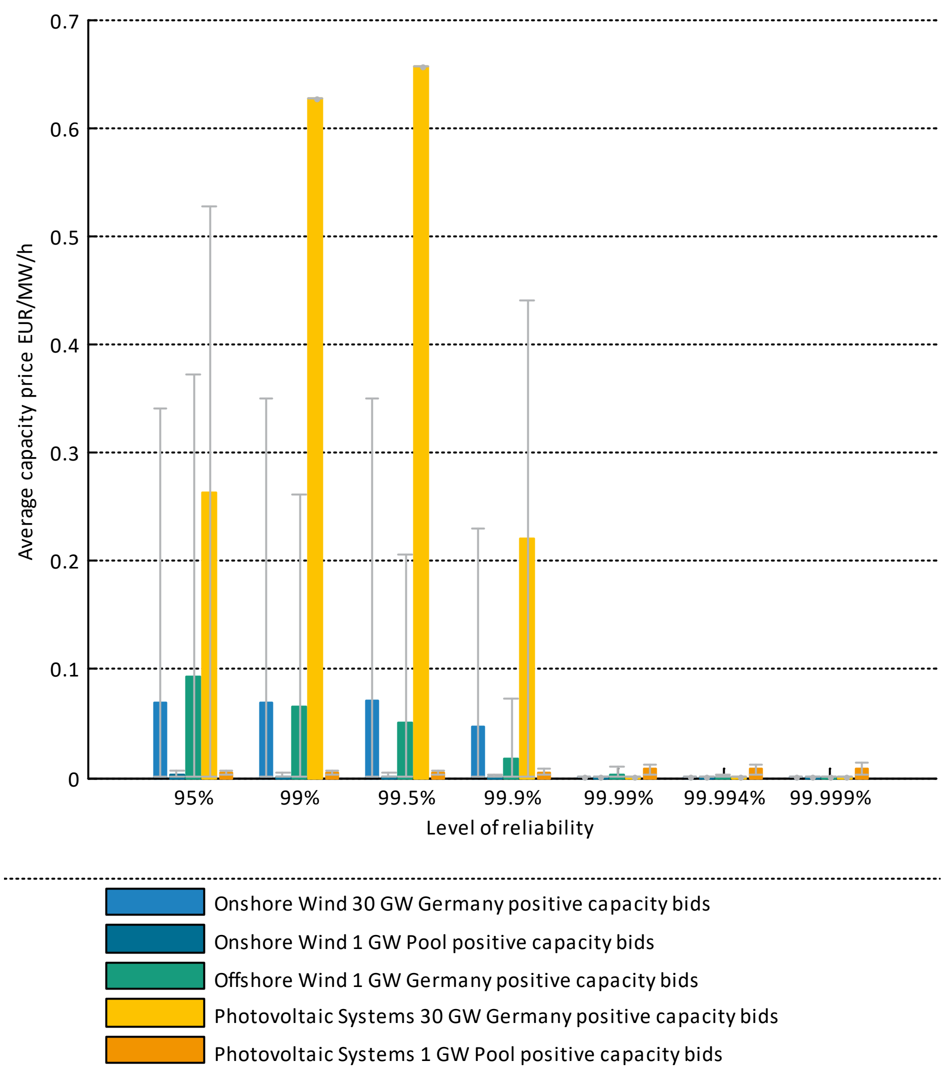
Figure 5-20 illustrates the annual average profit maximizing bids and their annual average extremes (range indicator) in the negative tertiary control reserve market. The resulting prices lead to a medium market penetration. In addition, the prices are mostly unaffected by the level of security. The indicated range of prices draws a much clearer picture and hints at a more consistent behaviour of fluctuating RES in the market. At the same time, the tertiary control reserve market is more competitive than the secondary control reserve market and has significantly lower market entry barriers. This makes it more likely to be implemented first.

Summary on achieved market penetration

The market penetration that can be achieved differs greatly in the four investigated market segments. Smaller pools of fluctuating RES generators can access less market potential, for the aforementioned reasons. The highest market penetration can be achieved in the negative secondary control reserve market. The clear pricing patterns in this market reflect the bids of the fluctuating RES. The negative tertiary control reserve market provides a good opportunity for fluctuating RES generators to participate. The positive secondary control reserve market would be able to absorb fluctuating RES generators to a certain degree. However, forecasts with a higher reliability could possibly prevent their participation in the market. It is also apparent that wind farms have an advantage over PV systems. The smallest opportunity for participation is offered by the positive tertiary control reserve market. A successful contribution by fluctuating RES would only be possible at certain times. If the assumption of the perfect price forecast (see chapter 4.2) was taken away, the market penetration would most likely be very close to zero.

Lowest profitability for fluctuating RES in the positive tertiary control reserve market

Lastly, Figure 5-21 shows the average annual bids for the positive tertiary control reserve market for a product length of one hour. The results in Figure 5-17 allow the conclusion that very few bids can actually enter the market since the opportunity costs are too high. The positive tertiary control reserve market is by far the least beneficial market for fluctuating RES generators.



Source: Own analysis

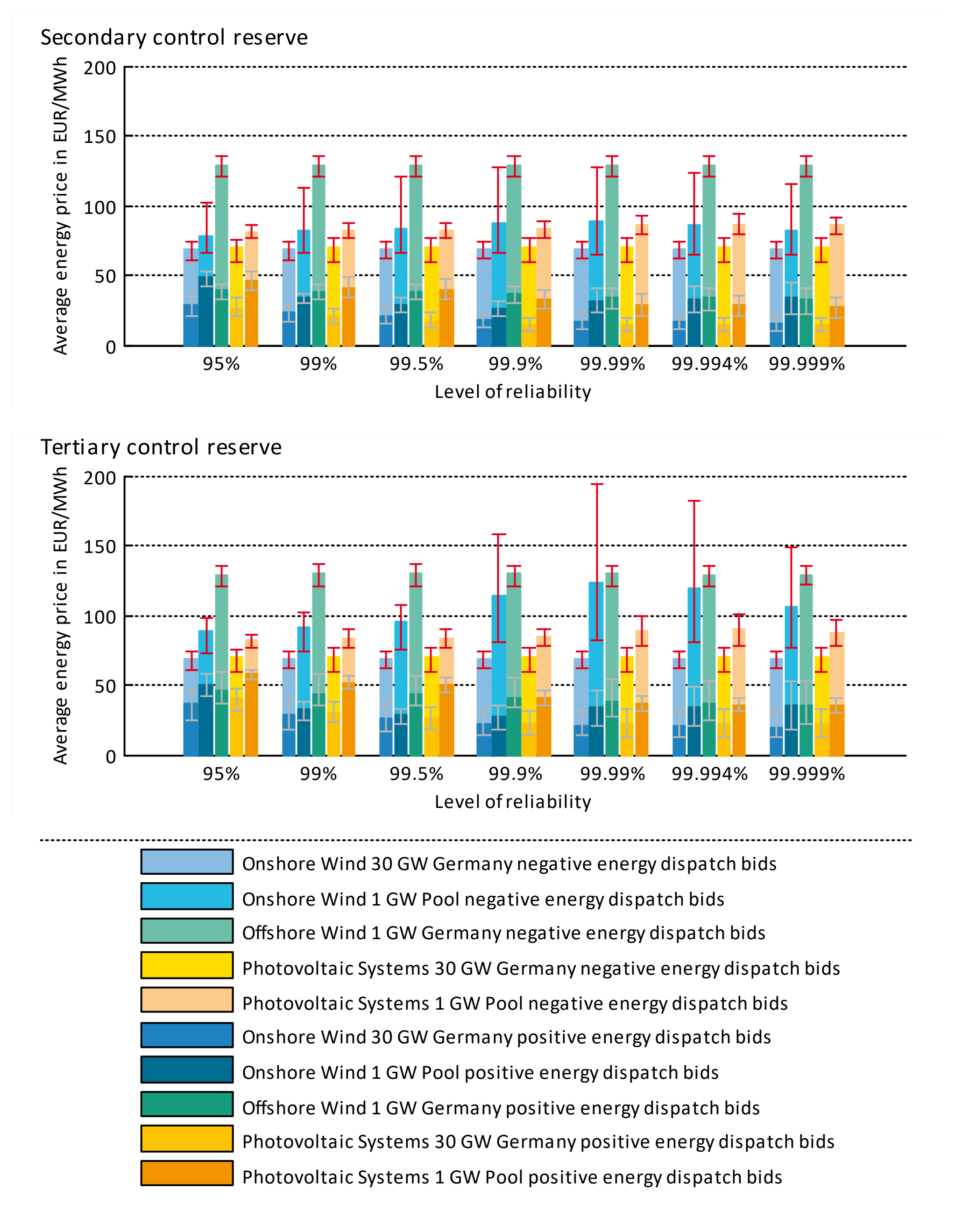
Figure 5-21: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of one hour in the positive tertiary control reserve market

Additional information in the appendix

Since not all dependencies have been shown in this section, additional product lengths for Figure 5-18 to Figure 5-21 are available in Appendix B-D. However, the impact of the product lengths has already been discussed in chapter 5.2. In both the Appendix and the following sections, the product lengths focussed on will be one hour, four hours and twelve hours.

Energy price bids

Figure 5-22 shows the average energy prices of the bids for the negative and positive secondary and tertiary control reserve markets that are derived from the replaced bids in the original merit-order list. The opportunity cost prices are used if they are higher than the market based solution thus ensuring that the bids are economically beneficial for the RES generators.



Source: Own analysis

Figure 5-22: Average profit maximizing energy price bids for different fluctuating RES generators with different levels of reliability for the product length of one hour for the negative and positive secondary and tertiary control reserve markets

Analysis of the energy price bids

The energy price bids for the negative reserve markets largely depend on the opportunity costs. They resemble the findings in Figure 5-16. However, some generator types are capable of catching the high prices that occur in the years

2013 and 2014. The 1 GW onshore wind farm in particular has just about the right pool size to take advantage of the current merit-order list composition.

Conclusion

Different markets have different potentials. Secondary and tertiary negative control reserve markets are especially likely to absorb substantial amounts of control reserve from fluctuating RES generators. The proof method has a major impact on the profitability of offering control reserve to the market. It is very unlikely that a deep market penetration with fluctuating RES generators in the control reserve market will be reached with the balance control proof mechanism. The prices designed in this market step are also an indicator for the levels of accepted capacity, which is discussed in the subsequent chapter.

5.4 Matching of bids in the market and additional revenue for fluctuating RES generators

Introduction to the calculation of the additional revenue for the fluctuating RES generators

This chapter provides information on the calculation of possible additional revenues for the fluctuating RES generators. A full cost calculation of the capacity and energy costs of the control reserve market with the original merit-order lists is performed. Subsequently the bids from the previous section with both bidding approaches (chapter 5.2.2) are placed in the market. Each one of these bids contains a capacity price, an energy price and a quantity. These individual bids are evaluated against the existing prices in the original merit-order lists, as laid out in chapter 4.4.4. In the case that the bid from the fluctuating RES generator is cheaper than the original bid in the merit-order list, it is replaced by the RES generators. The award criterion in the current market design is solely based on the capacity price. The possible participation is performed for all market segments with all possible combinations of bids. The principles are also laid out in Figure 4-10.

Deriving possible additional income from the cost changes due to the participation of fluctuating RES

For each set of bids by the fluctuating RES generators, a cost comparison is carried out. Firstly, the benchmark is calculated with the original merit-order lists, which eventually leads to the costs presented in Figure 3-7. Secondly, with the help of the merit-order lists that contain the bids from the fluctuating RES generators, a full cost calculation of the capacity and energy costs is carried out. The difference between the cost of control reserve with the original merit-order lists and the altered merit-order lists allows assessment of the cost changes. These cost changes depend on the bidding behaviour. The difference between the cost change with the opportunity cost based approach and the cost change with the market-based approach is the possible additional income that could be accessed by the fluctuating RES generators. This is the area marked as B in Figure 4-14. The assessment is carried out based on the difference between the opportunity cost based approach and the profit maximizing approach, with only the available active power mechanism applied. Market results under the balance control are expected to be insignificant, as visible in Figure B-26 in Appendix B-D and later in chapter 6.1.

Figure 5-23 to Figure 5-26 present the additional incomes of the fluctuating RES generators. The four graphs correspond to the negative secondary control reserve (Figure 5-23), the positive secondary control reserve (Figure 5-24), the negative tertiary control reserve (Figure 5-25) and the positive tertiary control reserve (Figure 5-26). These also correspond to the price bids with the different bidding approaches (Figure 5-12 to Figure 5-22) as shown in chapter 5.2.2.

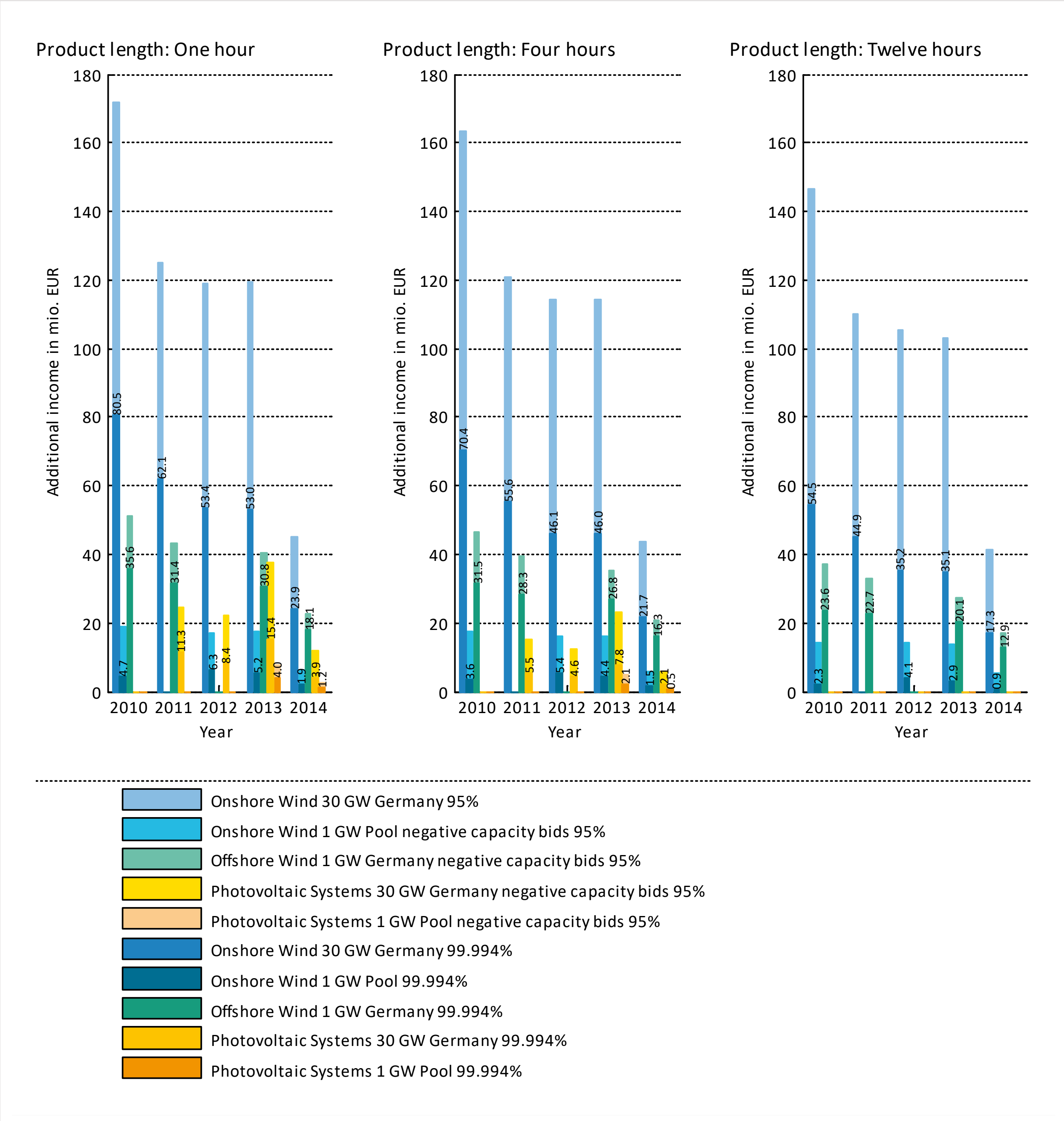
Relation to the previous findings in chapter 5.2.2

Each of the graphs presented in Figure 5-23 to Figure 5-26 shows a different fluctuating RES data set. These cover all years of the assessment period, two different levels of reliability and three different product lengths. Each figure contains three graphs. The left one displays the results with a product length of one hour, the middle one four hours, and the right one a product length of twelve hours. Each single graph gives the years on the x-axis. The bars in the different colours present the results for the five different RES generator pools with colour coding in line with Figure 4-2. Each data set contains two values. The lighter coloured bar indicates the possible additional income with a level of reliability of 95 % whereas the darker coloured bar shows the results with the level of reliability at 99.994 %. The numbers on top of each the darker coloured bars show the possible additional income in million EUR.

Description on the presented cost saving potential

Possible additional income in the negative secondary control reserve market

Figure 5-23 presents the results for the negative secondary control reserve market. The results from this market show that the fluctuating RES generators could generate substantial revenue in this market. The results for the twelve-hour product length and a reliability of 99.994 % are those results that would be achieved in the current market setup.

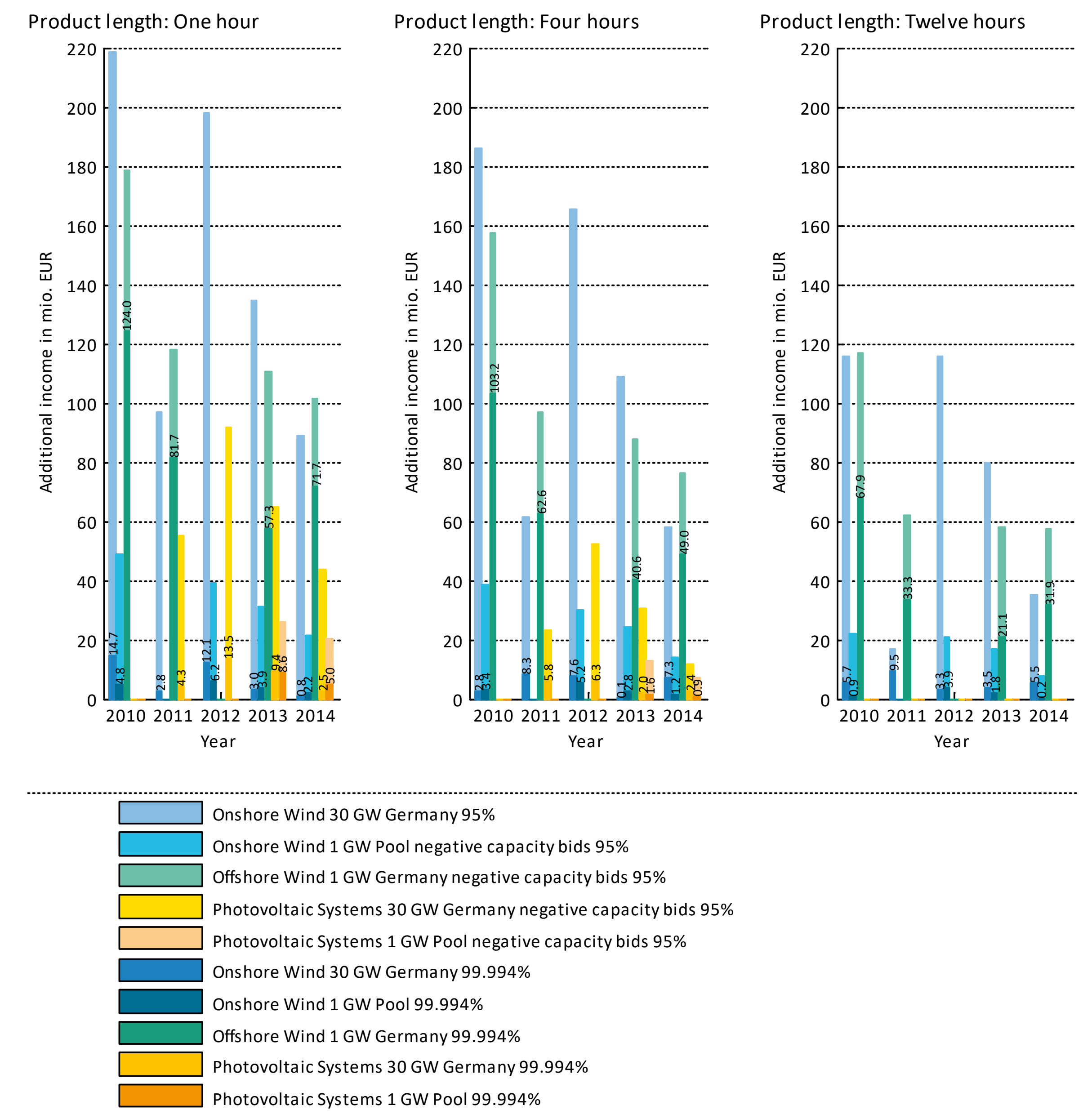


Source: Own analysis

Figure 5-23: Additional possible income for different fluctuating RES generators in the negative secondary control reserve market for the levels of reliability of 95 % (light colours) and 99.994 % (dark colours)

Possible additional income in the positive secondary control reserve market

Figure 5-24 shows the possible additional income for the positive secondary control reserve market. In this market segment, the level of reliability has a very large impact on the potential additional revenues in this market. At the same time, the market entry can be described as the most challenging out of the four assessed market segments.

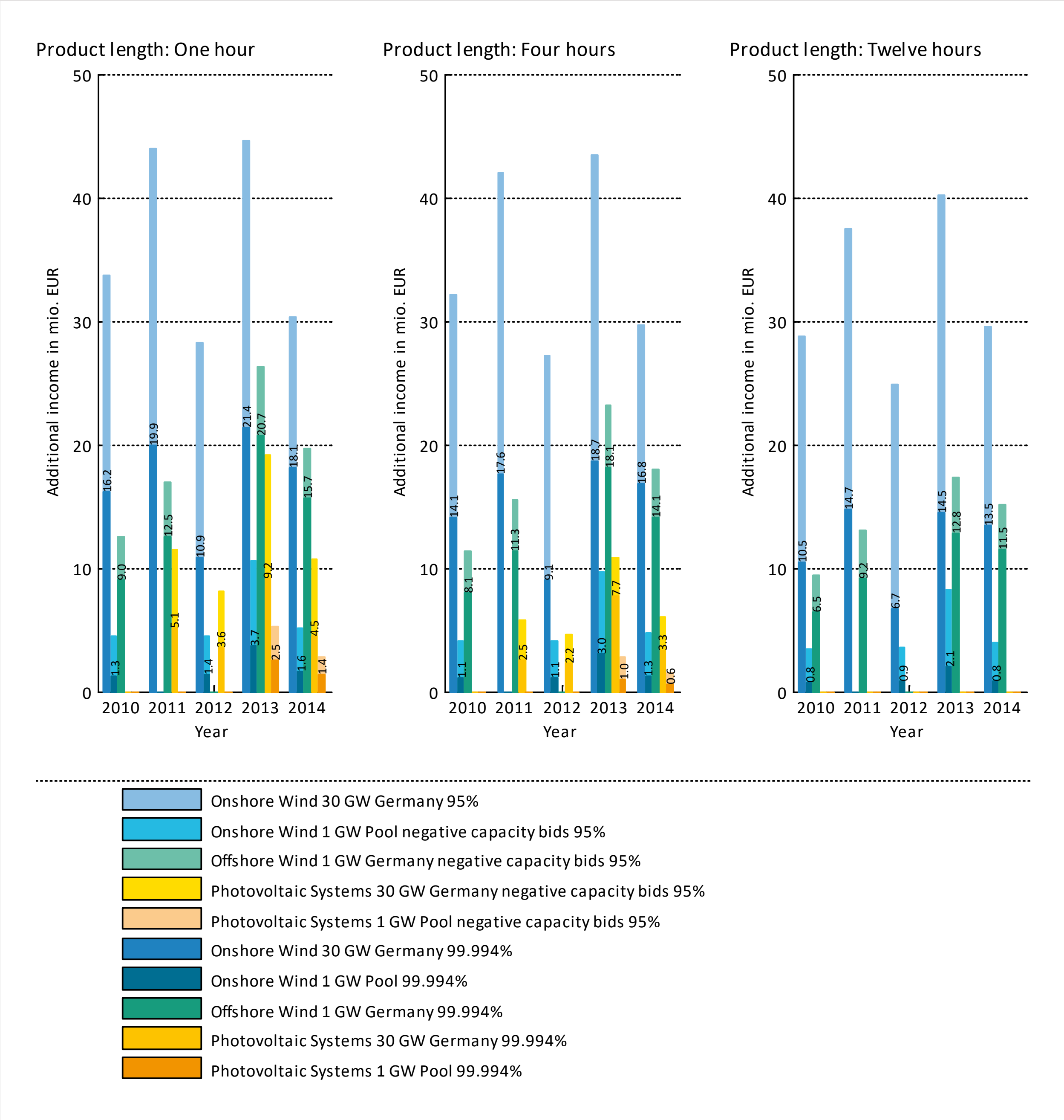


Source: Own analysis

Figure 5-24: Additional possible income for different fluctuating RES generators in the positive secondary control reserve market for the levels of reliability of 95 % (light colours) and 99.994 % (dark colours)

Possible additional income in the negative tertiary control reserve market

The possible additional income in the negative tertiary control reserve market is presented in Figure 5-25. This market represents the most likely option for initial market entry. It combines relatively low technical requirements with a considerable additional income. The results for a product length of four hours with a reliability of 99.994 % could be achieved in the real tertiary control reserve market with its current regulation.

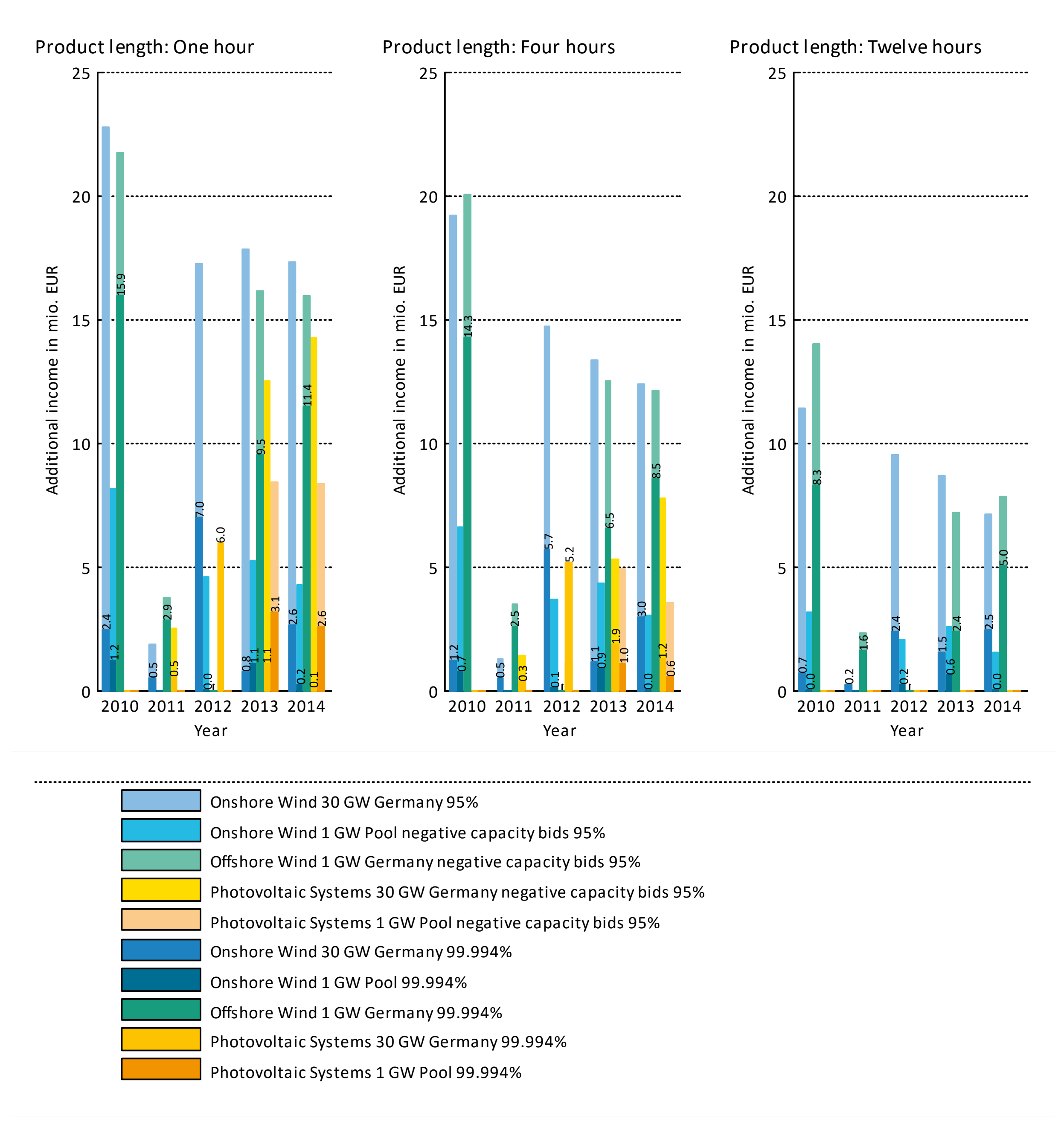


Source: Own analysis

Figure 5-25: Additional possible income for different fluctuating RES generators in the negative tertiary control reserve market for the levels of reliability of 95 % (light colours) and 99.994 % (dark colours)

Lastly, the possible additional income in the positive tertiary control reserve market is presented in Figure 5-26. Confirming the findings in chapter 5.3.2, this market is the least beneficial for fluctuating RES.

Possible additional income in the positive tertiary control reserve market



Source: Own analysis

Figure 5-26: Additional possible income for different fluctuating RES generators in the positive tertiary control reserve market for the levels of reliability of 95 % (light colours) and 99.994 % (dark colours)

The additional income that could be generated by fluctuating RES generators differs largely, depending on different factors. The pool size does not prevent the generators from participating. Nevertheless, the result from the 1 GW

Analysis on the possibilities for additional income pool cannot be scaled linearly to the 30 GW and vice versa. Successful market participation merely depends on the quality of the probabilistic forecast rather than the pool size. The 1 GW pool of PV systems clearly outperforms the 30 GW pool when comparing the numbers on a per GW basis. The better forecast not only offsets the disadvantages of the small pool size, but also generates additional income. The intersection of the merit-order list at a higher price generates a smaller gap between the market price approach and the underlying opportunity costs. The 1 GW pool of wind farms is able to generate significant revenue despite the fact of having the less favourable forecast quality. Offshore wind performs best based on the given forecast, achieving a deep market penetration at its mostly full load oriented generation pattern. However, offshore is also the RES generator that has the most uncertainty about the achievable forecast quality and its technical connection to the mainland grid.

Impact of the level of reliability

Based on the observations one can conclude that the level of reliability has a large influence on the market potential. The effect is more pronounced in the positive markets than in negative markets. The impact of reliability, however, seems to soften over the years due to the price development in the market. The change in market structure, from a capacity price intensive market to a more dispatch cost oriented market, appears to suit the characteristics of fluctuating RES while allowing them to have a stable income. This is especially true for the negative tertiary control reserve market, which is by far the most competitive market.

Impact of the product length

No PV system could generate any revenue with a product length of twelve hours or more. In today's secondary control reserve market, they would not be able to participate at all. Wind farms would also suffer from longer product lengths; however, they would still generate significant revenue in the negative reserve markets.

Identification of trends

In all market segments but the negative tertiary control reserve, a decreasing market potential can be observed. A clear trend between the years 2010 and 2014 is visible for the secondary control reserve markets. In this time, there has been a significant increase in new market players such as virtual power plant (VPP) operators that aggregate decentralized biogas fired combined heat and power (CHP) units.

Focus on negative secondary control reserve market

The negative secondary control reserve market with a level of reliability of 99.994 % and a product length of 12 hours most closely imitates the real secondary control reserve market the most. The real market still has weekly tendering (see assumptions in chapter 4.2). In this market environment, PV systems cannot participate. The 30 GW wind farm pool would have been able to generate up to 54.5 million EUR in 2010 and as much as 17.3 million EUR in 2014. The 1 GW pool of wind farms would have generated between 4.1 million EUR (in 2012) and 0.9 million EUR (in 2014).Where the 30 GW pool has a clearly decreasing trend over the years the 1 GW has no clear direction. The 1 GW pool of offshore wind farms follows the trend of the 30 GW onshore wind farm pool, from 23.6 million EUR in 2010 to 12.9 million EUR in 2014. In total, it can be assumed that the market potential is decreasing over time due to increased competition. The 1 GW pool will follow this trend in general.

Focus on negative tertiary control reserve market

The market with the lowest market entry barrier is the negative tertiary control reserve market. For that reason, it is also the most competitive market in general. Currently a product length of four hours is applied. Together with an expected reliability requirement of 99.994 %, significant revenues can be generated in this market segment. The 30 GW pool of onshore wind farms would have generated between 9.1 million EUR (2012) and 18.7 million EUR (2013). The 1 GW pool of onshore wind farms would have yielded between 1.1 million EUR (2010/2012) and 3.0 million EUR (2013). Offshore wind farms could have generated between 8.1 million EUR (2010) and 18.1 million EUR (2013). The German 30 GW pool of PV systems would also have generated additional income of between 2.2 million EUR (2012) and 7.7 million EUR (2013). The 1 GW pool of individual PV systems would have generated between 0.6 million EUR (2014) and 1.0 million EUR (2013). It can be concluded that the income for any technology peaks in the year 2013 and is at its lowest for most of the pools in 2010 or 2012. This reveals a strong dependency on market prices in general. For the outlook, it will be necessary to relate the economic value to the market development.

Overview of the results

The following table shows the possible additional income in EUR per megawatt per year for all four investigated market segment. The presented results are derived from Figure 5-23 to Figure 5-26 and are given for the four hour product length with a reliability of 99.994 %, as these market conditions are most likely to implemented in the future (Bundesnetzagentur, 2015).

Possible additional income in EUR/MW_{inst}/a	**30 GW onshore wind farm**	**1 GW onshore wind farm**	**1 GW offshore wind farm**	**30 GW PV systems**	**1 GW PV systems**
Secondary negative market	**1600** (720-2300)	**3700** (1500-5400)	**25700** (16300-31500)	**170** (70-260)	**1300** (520-2100)
Secondary positive market	**170** (0-280)	**3200** (1200-5200)	**63900** (40600-103200)	**4100** (2000-6300)	**1300** (910-1600)
Tertiary negative market	**510** (300-620)	**1600** (1100-3000)	**12900** (8100-18100)	**130** (70-260)	**800** (600-1000)
Tertiary positive market	**80** (20-190)	**420** (30-870)	**8000** (2500-14300)	**70** (10-170)	**810** (570-1000)

Source: own analysis

Table 5-1: Possible additional income in EUR/MW_{inst}/a for all market segments and years with a reliability of 99.994 % and a product length of four hours with minimum and maximum values in brackets

Analysis of the results

The results in the previous table show the average additional income of each generator pool in the four market segments assessed. Offshore wind has by far the largest additional income per MW_{inst}. This is due to the feed-in characteristics of offshore wind power plants. Forecasts for offshore wind farms have a high reliability during hours with maximum feed-in as this weather regime is stable and has little forecast errors. The offshore wind farms in total have also more full load hours. The negative secondary and tertiary control reserve markets will see the fluctuating RES first. The additional income in these markets can be generated through competition for the capacity price. This will also be shown in Figure 6-1 and Figure 6-2. The high additional income in the positive secondary control reserve market can only be accessed through price differences of the dispatch cost, which are most likely not sustainable.

A decreasing market potential for fluctuating RES generators can be observed in the negative secondary control reserve market and a stagnating market potential in the negative tertiary control reserve market. Both positive market segments are practically irrelevant in the current market structure, especially if market price forecast uncertainties are accounted for. Though the possible revenues for the RES generators have declined over time, they could still prove that they are competitive in the latest data from 2014. From this, it can be concluded that the fluctuating RES generators will be able to access the market's potential in an increasingly competitive environment. Competition, however, will increase further through the changes induced by the green paper / white paper process of the BMWi (Bundesministerium für Wirtschaft und Energie, 2015b). Conclusions

6 Economic impact of fluctuating RES on the power system level

The bids from the previous chapter are placed into the market environment of the negative and positive secondary and tertiary control reserve markets, using the hindcasting approach described in chapter 4.4. Identifying the change in control reserve procurement costs allows the determination of the gain in welfare due to the introduction of additional market participants, such as the fluctuating RES generators. Also in this chapter, the impact of the proof method on the spot market is shown. At the end of this chapter, the results for a forecasting approach are presented.

Introduction to the micro-economic evaluation of fluctuating RES in the control reserve markets

The system point of view is chosen for the entire chapter. Subsequently only the input data for the 30 GW pool of wind farms and the 30 GW pool of PV systems are used. Only these pools would be able to deliver an insight into the possible impact of fluctuating RES in the control reserve market. The three 1 GW pools would only be able to show a fraction of the entire potential. They are therefore omitted. In reality, both 30 GW pools would consist of several smaller pools competing against each other in the market.

Identification of the cost saving potential and welfare gain is based on the two 30 GW pools

6.1 Determination of the change in costs

The introduction of new market participants leads to a change of the cost structure in the market. It is solely dependent on the capacity price whether a bid is accepted or not. This is called the award criterion. Since the dispatch costs are not part of the criterion, the overall costs can increase, although the capacity costs decrease by the introduction of new market players. This is the case when the dispatch costs increase more than the capacity costs decrease. The changes in control reserve procurement cost are calculated with the bids from the two different bidding approaches in chapter 5.3 according to the methodology in chapter 4.4.5.

Summary of the applied methodology

Interpreting the upcoming graph on cost saving potentials

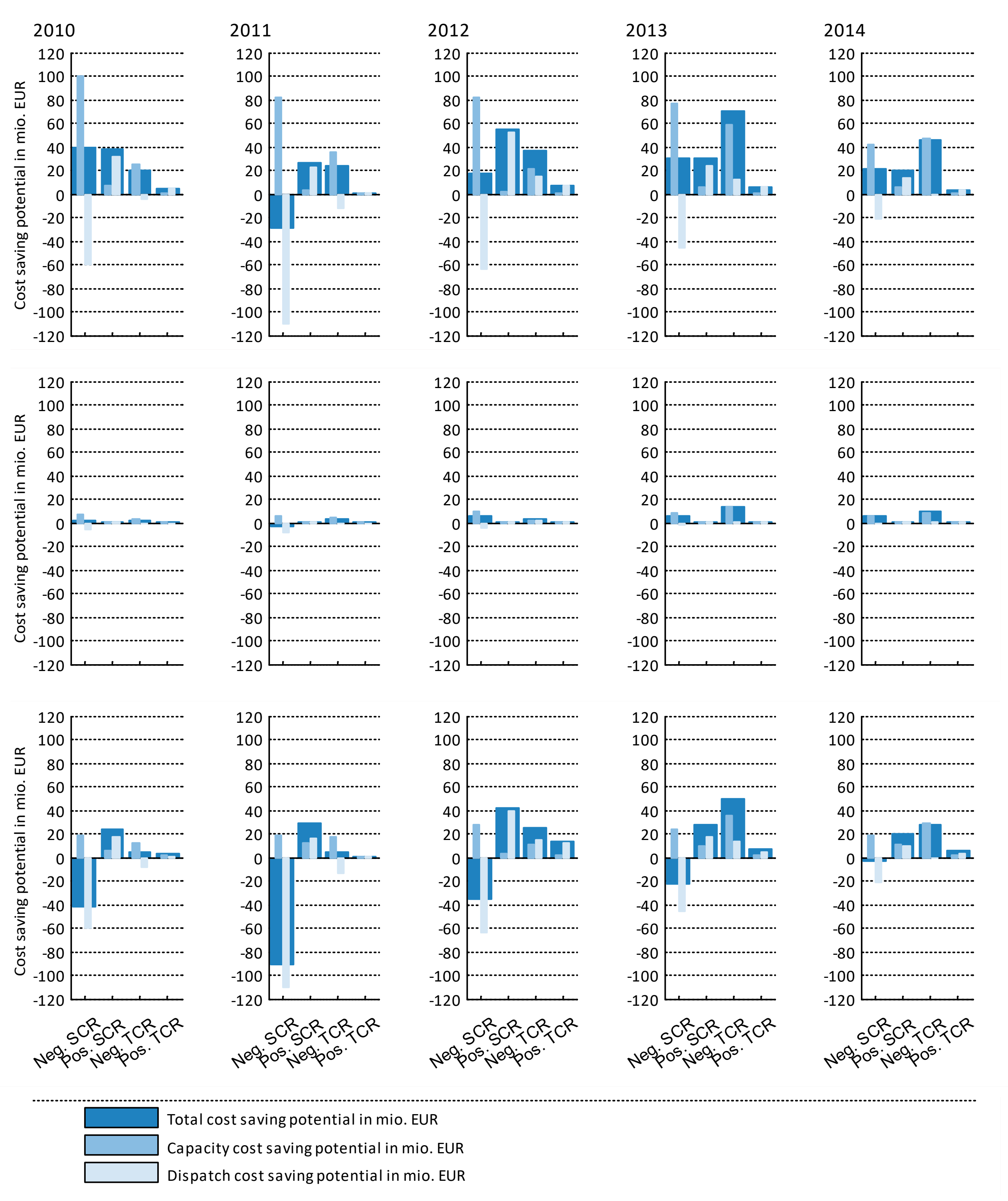
Figure 6-1 shows the cost saving potentials for the German 30 GW wind farm pool participating in negative and positive secondary and tertiary control reserve markets. The cost saving potentials are given in million EUR. The presented numbers include the saving potentials for the capacity costs, the dispatch costs and, as a sum of both, the total cost savings. The upper graph shows the saving potentials with the opportunity cost based bids and the available active power mechanism applied. The middle graph is based on the opportunity cost based approach with the balance control mechanism applied. The lower graph shows the cost saving with the market-based profit maximizing approach. For further reference, it is assumed that the market-based approach has the available active power proof method applied.

Relationship between cost saving potentials and possible additional income

The difference in cost reduction between each one of the first two opportunity cost based approaches (upper and middle graph) and the market based profit maximizing approach (lower graph) equals the possible additional revenue for the fluctuating RES generators, as shown in chapter 5.4; however the additional income under the balance control mechanism is not displayed. The bids presented in chapter 5.3 are used for the calculation of the saving potentials.

Selection of presented values

The figure displays values for the product length of one hour and a level of reliability of 99.994 %. The product length of one hour is chosen since it allows for the best comparison between wind farms and PV systems, without having a predominant effect of the product length on the potentials. The level of reliability is chosen to ensure that the potentials have the same level of reliability as current units in the market. Therefore, it is most likely to be implemented in the future. The years covered by the data set are 2010 to 2014. For results with the product lengths of four hours and twelve hours please refer to Appendix C-A.



Source: Own analysis

Figure 6-1: Capacity, energy and total cost saving potentials of the German 30 GW onshore wind pool in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, for the years 2010 to 2014, and a product length of one hour

Inefficiencies due to the proof method

The differences between the top graph and the middle graph are caused by the difference between the proof methods applied: the available active power proof method and the balance control method. The significantly lower cost saving potentials with the balance control method can be interpreted as the inefficiencies of the proof method, as it fails to generate significant levels of market penetration.

Analysis of the cost saving potentials of wind farms by bidding approach

The previous figure shows the cost saving potential of the 30 GW wind farm pool in all four different market segment. The uppermost graph displays the results with the available active power proof method applied and the opportunity cost based bidding approach. This approach provides the highest saving potentials from the system point of view. Apart from one data set in the year 2011 for the negative secondary control reserve market, all results indicate positive saving potentials from the system's point of view. The same applies for the opportunity cost based approach with the balance control method. In contrast, however, the saving potentials are very low, as they never exceed 10 million EUR. Interestingly, the profit maximizing approach still generates significant amounts of saving potentials. It could have been expected that these would be rather small. The bidding behaviour uses the intersection of the merit-order list for price determination for the wind farms. Replacing large parts of the merit-order list leads to very low prices for the replaced bids. Since all bids then have the same low price, significant saving potentials can be accessed. In a real market environment these saving potentials could partially be accessed by the fluctuating RES generators. The degree of this is highly uncertain due to strategic bidding in the market.

Capacity cost saving potentials

The saving potentials are displayed both as a total and also split into the two contributing cost components. The market award criterion is based on the capacity price. In all of the data sets, a positive saving potential based on the capacity costs is achieved. This means that the fluctuating RES generators were able to reduce the capacity costs. Under the available active power proof method, this would be up to 100 million EUR (year 2010) and never lower than 40 million EUR in the negative secondary market. In the negative tertiary market, the capacity cost saving accounts for up to 60 million EUR and at least 20 million EUR. With the market-based approach, the savings would still be around 20 million EUR annually for the negative secondary market and 10 to 36 million EUR in the negative tertiary market.

The secondary cost components are the dispatch costs. These occur when the contracted generator delivers energy from the control reserve unit to the power system. Since the dispatch price is not part of the award criterion, the market participants are free to bid any price. This has recently led to price hikes of up to 6000 EUR/MWh, and even higher ones in the past. Any new addition to the market that replaces a lower priced position in the merit-order list increases the costs. In the future one can expect regulatory changes on this specific aspect. The dispatch costs will be considered in the tendering process (see green paper / white paper process of the BMWi (Bundesministerium für Wirtschaft und Energie, 2015b)). For the wind farms with relatively expensive dispatch costs due to the RES support scheme payments, this could lead to increasing system costs under the current market design. Wind farms have negative dispatch costs in positive reserve markets and may generate additional cost savings there. In negative reserve markets, negative dispatch cost savings can be observed. Whether the bids generate cost savings or increases depends on the market situation. For any positive reserve market, the wind farms generate additional positive cost saving potentials.

Dispatch cost saving potentials

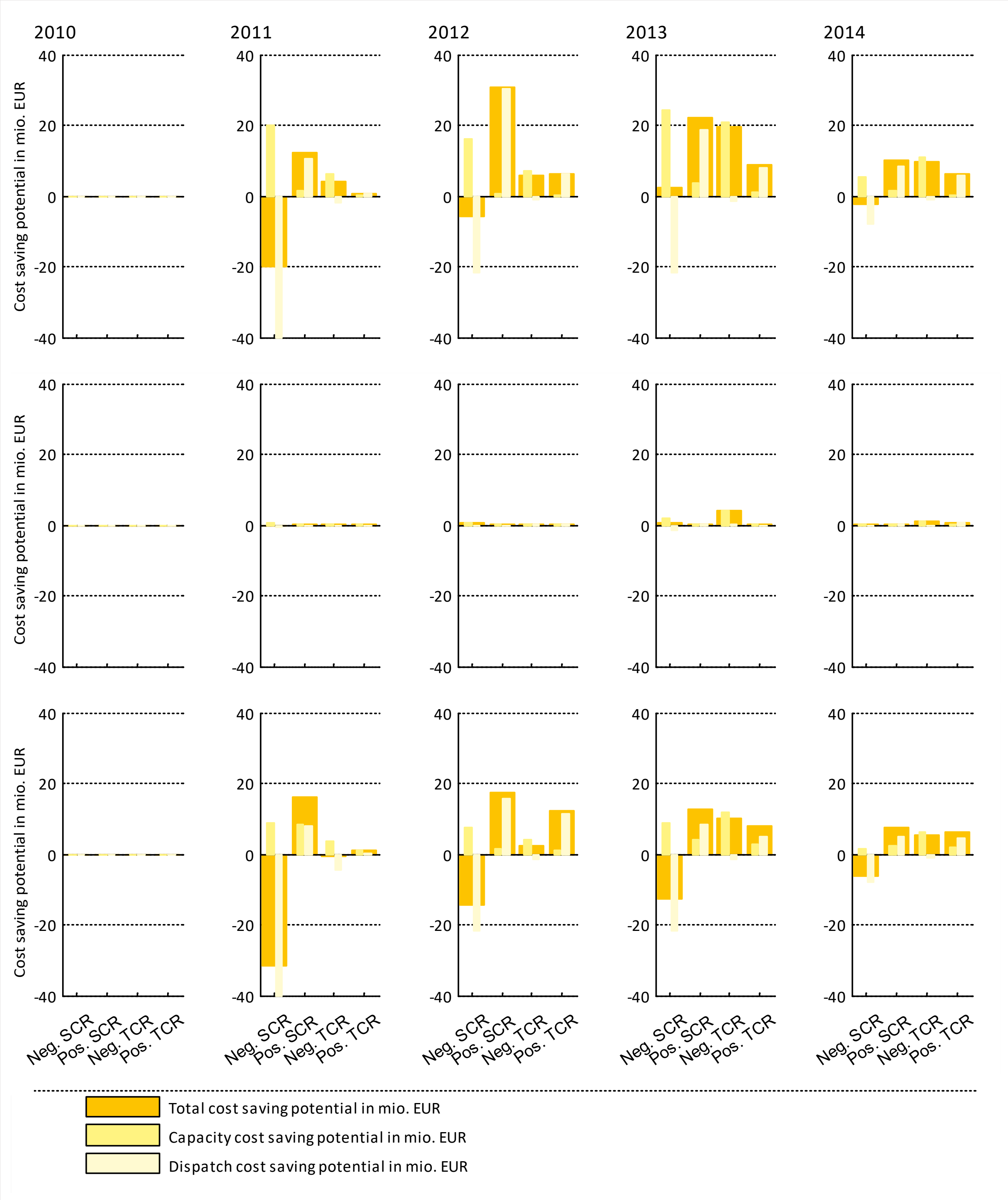
The findings in Figure 6-1 show that the cost saving potentials can be offset by cost increases due to higher dispatch costs. In 2011, the participation of fluctuating RES in the negative secondary control reserve market, with the available active power proof mechanism, would have led to a cost increase. For all years in the market optimizing approach, cost increases in the negative secondary market can be observed. In the negative tertiary market some additional cost savings occur during the years

Cost savings in the capacity costs are partially offset by cost increases in the dispatch costs

The saving potentials for the 30 GW pool of PV systems are shown in Figure 6-2. Results for a product length of four hours are available in Appendix C-A. Longer product lengths do not need to be displayed for PV systems. The cost saving potentials for the 1 GW onshore wind farm pool, the 1 GW German offshore wind farm pool and the 1 GW pool PV systems are not shown here. They have limited significance when the impact at the system level is assessed as these pools would not be able to exploit the entire market

30 GW pool of PV systems and 1 GW pools

potential. For completeness they can be seen in the Appendix C-A for a product length of one hour and a reliability of 99.994 % only.



Source: Own analysis

Figure 6-2: Capacity, energy and total cost saving potentials of the German 30 GW pool of PV systems in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, for the years 2010 to 2014, and a product length of one hour

The 30 G pool of PV systems manages to realize cost saving potentials. Findings can be transferred from the findings for the 30 GW pool of wind farms. The total savings however are significantly lower than for the wind farms. With the available active power proof method, significant cost saving potentials can be achieved whereas the balance control proof method will effectively inhibit successful market participation.

Analysis of the cost saving potentials of PV systems

The total cost saving potentials of PV systems are significantly lower than those of the with wind farms at the same installed capacity. This is due to the lower full load hours and the simultaneity of the feed-in. The highest saving potential, of 30 million EUR, was observed in the secondary positive market in 2012. The savings were realized through significantly lower dispatch costs. A real market participant, however, will exploit the tendering process and monetarize these saving potentials. The lowest saving potential was -20 million EUR (opportunity cost approach) in the negative secondary control reserve market in 2011, once again determined by the dispatch prices.

Total cost saving potentials

Similarly to the wind farm pool, capacity cost saving potentials are realized in all years for the negative secondary and tertiary control reserve markets. In the negative secondary control reserve market, the cost saving potentials reach from 5 million EUR (2014) to over 22 million EUR (2013) based on the opportunity cost based bids. Cost saving potentials with bids from the profit maximizing approach are smaller. In the negative tertiary control reserve market, the capacity cost reductions lie between 5 million EUR (2011) and 21 million EUR (also 2013). The capacity cost saving potentials are offset by an increase in dispatch cost in three of the four yours for the negative secondary market. In the negative tertiary market, no significant dispatch cost changes can be observed. Capacity cost saving potentials in the positive reserve markets are limited to low single digit values. However, significant dispatch cost savings can be realized in those markets; between 9 million EUR and 30 million EUR in case of the positive secondary markets.

Capacity and dispatch cost saving potentials from PV systems

Annual variations

The results for the 30 GW wind farms pool and the pool of PV systems show a large variation of the results throughout the different years. A consistent trend in the data is the decrease in negative dispatch cost reductions in the negative secondary market over the years. It is notable that the negative tertiary market generates consistent results for both wind farms and PV systems for the different years with a slightly upward trend towards 2014. Other than that, the cost saving potentials largely depend on prices in the spot market as well as in the control reserve markets. Spot market prices affect the opportunity costs for the provision of capacity. The spot market prices, however, have decreased significantly in the past.

Conclusion

The participation of wind farms and PV systems in the negative and positive secondary and tertiary control reserve market would not only generate additional income for those generators (see chapter 5.4), but also reduce the overall control reserve procurement costs. Due to the market size, the highest saving potentials can be located in the secondary control reserve market. In some cases, however, the current market design leads to total cost increases. This is mainly due to the fact that dispatch costs are not part of the tendering process. This undesirable behaviour has been observed mostly in the negative secondary market segment. If this mechanism were exploited by the market participants further price increases in dispatch prices could be expected. At the same time, increased competition in the market has led to the diminishing importance of this effect in more recent years. Additionally, the issue will be addressed by future legislation. Without the effect from the dispatch costs, the negative control reserve markets generate more saving potentials than the positive markets by far. In total, the participation of wind farms and PV systems in the control reserve markets generates benefits for the generators and the systems. The cost saving potentials are significant if the regulations are adjusted accordingly.

6.2 Impacts of the proof mechanism on the spot market

Energy losses due to proof mechanism

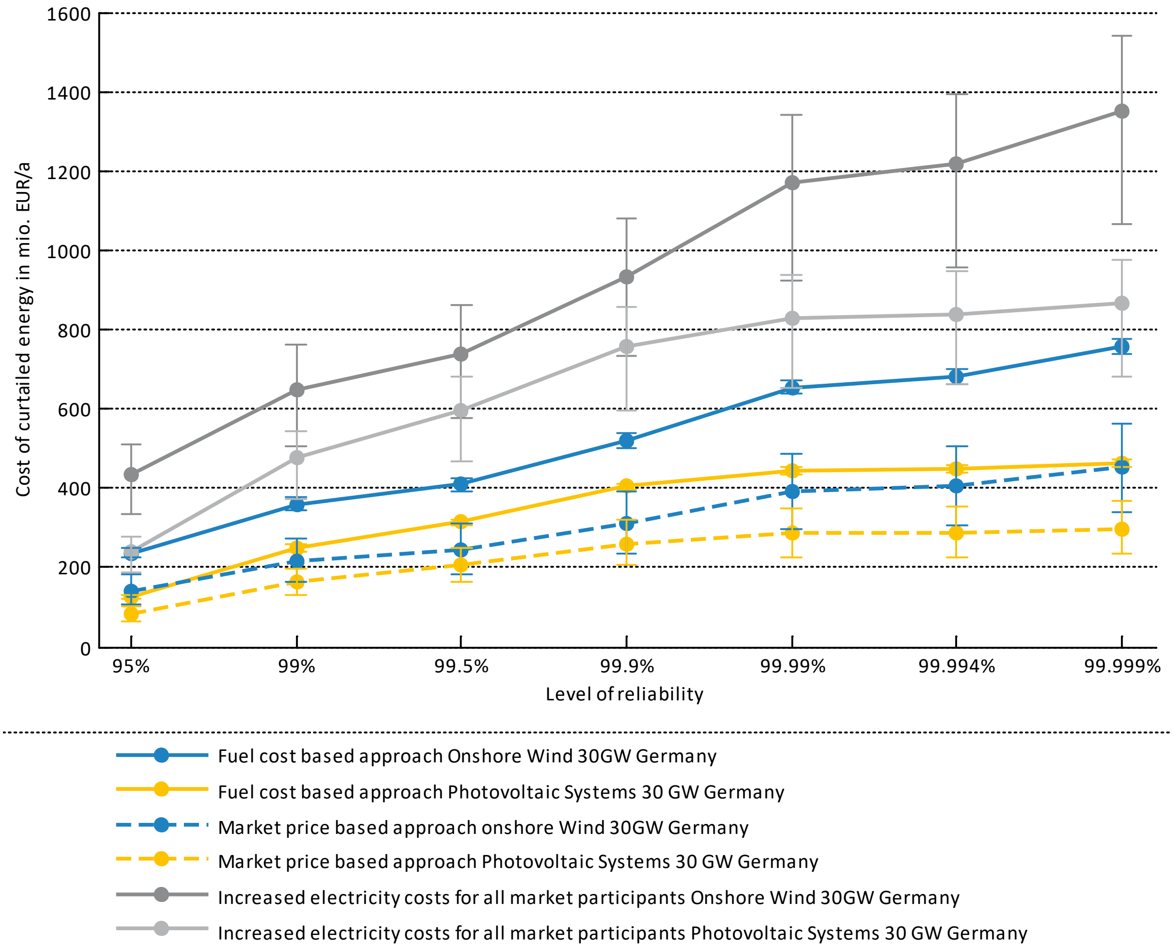
This chapter investigates additional losses that occur with the implementation of the balance control proof method as in 5.2.2. The nature of the balance control proof method requires that wind farms and PV systems are curtailed to a schedule with a guaranteed level of reliability. This curtailment means less feed-in of fluctuating RES. This electricity has to be generated by other (presumably conventional) generation. The energy losses presented in Figure 5-11 are valued with the fuel replacement costs as well as with the day-ahead spot market prices at each point in time according to the methodology in chapter 4.4.6. Additionally, costs due to an increased day-ahead spot market price for all market participants are shown. The results can be seen in Figure 6-3.

Description of the following figure

The lines in Figure 6-3 show the additional costs in the power system for compensating the curtailment of the fluctuating RES generators. The results in blue and yellow represent the additional energy replacement costs of wind farms and PV systems. The grey lines show the cost increment caused by the lower RES penetration in the market and the resulting increase in the market price. The lighter grey line is for the PV systems whereas the darker grey line gives the results for the wind farms. The straight lines show the results for the fuel replacement cost approach. The dashed lines show the additional costs when the curtailed energy is valued with the spot market price.

Remarks on the issue of bid acceptance in the market

The losses are taken from the same time series as presented in chapter 5.2.2. This means that no matching of the bids with market has yet taken place. It is therefore assumed that whenever an offer can be made to the market the according losses have to be covered by other units in the market. For this reason, these results present the upper limit of the additional costs, as not all bids are accepted in the market. However, since the participation of fluctuating RES in the control reserve market is very dependent on the market situation, conclusive results would not be gained by considering this information. Results in reality might be significantly lower than presented here.



Source: Own analysis

Figure 6-3: Cost for the replacement of curtailed energy valued with the spot market prices and the fuel replacement costs, as well as additional cost due to merit-order induced increases in the market price.

Cost increments due to curtailment of fluctuating RES generators under the balance control proof method

The results show that the maximum cost increase caused by the curtailment of fluctuating RES due to the proof mechanism can create significant costs in other markets, such as the spot market. The additional cost for the curtailed wind at a level of reliability of 99.994 % accounts for up to 407 million EUR per year when valued with the market price, and 681 million EUR with the average fuel replacement cost. PV systems would generate maximum additional costs between 288 million EUR for the market price approach and up to 449 million EUR for the fuel costs approach at the same level of reliability. The maximum increase in the market price due to the lack of fluctuating RES generation is 1.52 EUR/MWh for wind farms and 0.93 EUR/MWh for PV systems. The associated costs at a level of reliability of

99.994 % could reach up to 1,218 million EUR for the wind farms and up to 838 million EUR for the PV systems.

Variability of the calculated cost increases

The results show a small annual variability with the fuel cost and a medium variability with the market price approach. This indicates that the results are consistent throughout the years despite cost changes in the market. The costs for the increased market prices for all market participants show a high annual variability. Since the previous results were consistent, this would indicate that the steepness of the merit-order list in the spot market changes over time.

Analysis of the projected increase in costs

The total overall cost increase for the replacement of the curtailed electricity from fluctuating RES generators has the same order of magnitude when valued with the fuel cost and the market prices. However, it is notable that the fuel cost approach delivers higher values than the market price approach. This is controversial since the market prices should reflect the fuel costs including an additional mark-up gain for the generators. This controversy could be explained by the fact that the fuel replacement cost as an average value does not consider merit-order information. If fluctuating RES were curtailed during times with high RES penetration, then the generation technology used in the market would have significantly lower fuel costs than the average figures. The market price reflects the current state of the merit-order and also contains older power plants. These may no longer have to recover their investment costs and could therefore have much lower generation costs. The average fuel cost approach delivers full cost recovery generation costs.

The possible coupling to the spot market decreases the benefits of the balance control approach

The costs presented in this chapter are not taken into account in the next chapter where the social welfare gain is presented. This is simply because the balance control proof method is not economical and would occlude the real potential of wind farms and PV systems in the reserve market. The following chapter will only apply the available active power proof method.

Conclusions

The balance control proof method is prohibitively expensive due to its effects on other markets, such as the spot market. The possible cost increases in the spot market outweigh the additional benefit that could be gained in the control reserve markets. Although the balance control mechanism reduces the need for balancing fluctuating RES, it can be safely assumed that the additional costs for balancing fluctuating RES are lower than the possible cost increase in the spot market, which exceeds the entire market volume of all control reserve markets.

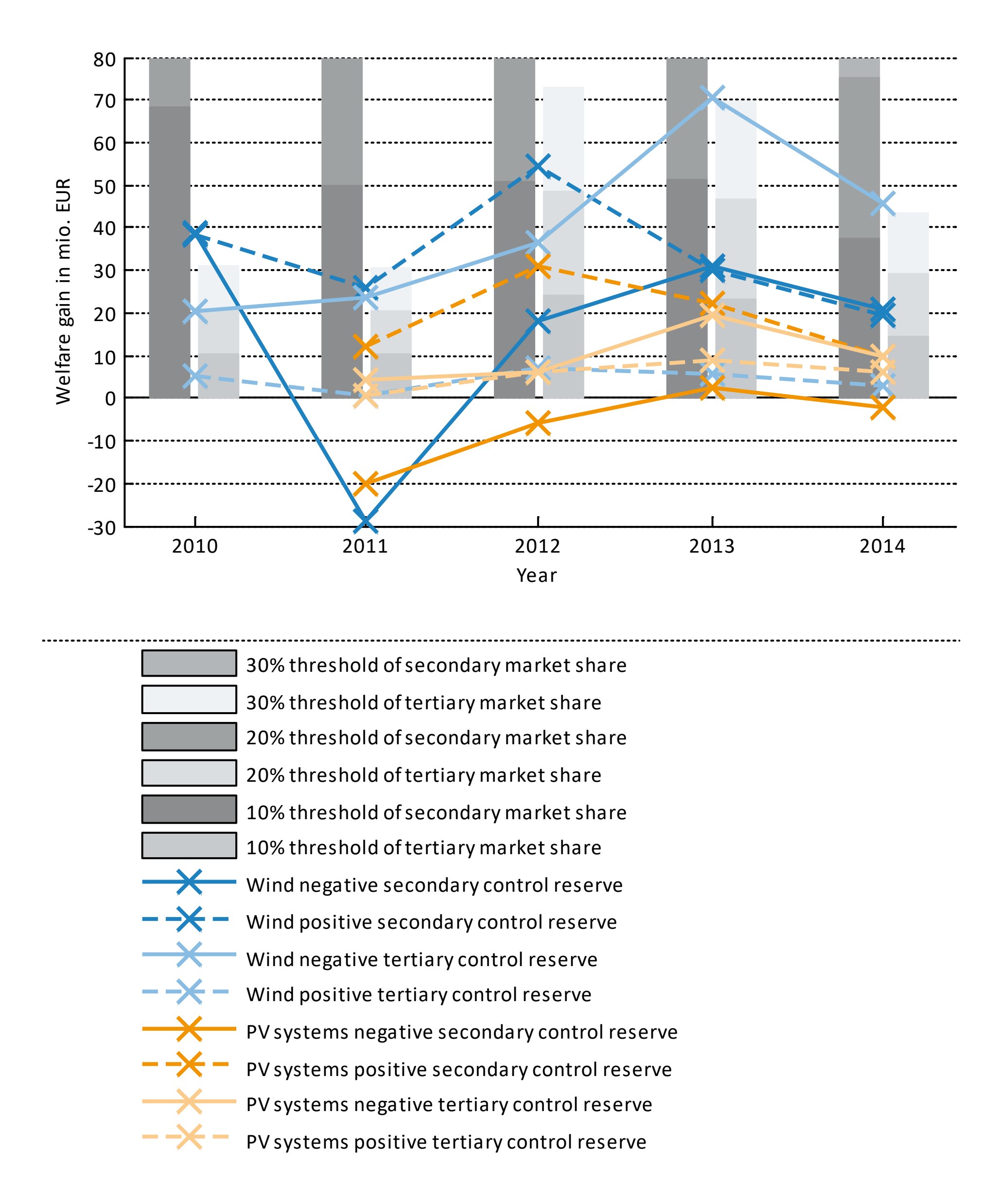
6.3 Social welfare gain

Introduction to social welfare gain from fluctuating RES generators in the control reserve market

The results for welfare gain from the participation of fluctuating RES generators in the control reserve market are calculated according to chapter 4.4.7. The welfare gain, or added value, is calculated from the cost reduction in the opportunity cost approach. The determination of the welfare is also assessed separately based on the cost saving from the capacity costs as well as from the dispatch costs. The welfare gain can also be expressed as the sum of the profit maximizing approach and the possible additional income. The social welfare gain is only displayed for the 30 GW pool of wind farms and the 30 GW pool of PV systems since it is the aim of this chapter to reveal the maximum potentials. Smaller pools that do not cover the entire German fluctuating RES generators fail to deliver in this aspect.

Description of the following graph

Figure 6-4 shows the welfare gain of the 30 GW wind farm pool and the 30 GW pool of PV systems. The welfare gain by the wind farms is presented in blue whereas the PV systems are shown in orange. The darker lines apply for the secondary control reserve market, the lighter, for the tertiary control reserve market. The straight lines show the results for participation in the negative reserve markets. The dashed lines show the welfare gain when fluctuating RES participate in positive control reserve markets. The grey bars in the background show the shares of 10 %, 20 % and 30 % of the entire market volume or the investigated component costs. The darker bars on the left represent the secondary control reserve market, whereas the lighter coloured bars show the market volume of the tertiary control reserve market. Values shown refer to the entire market volume, both negative and positive market segments together. A selection of additional product lengths and levels of reliability can be seen in Appendix D-A.

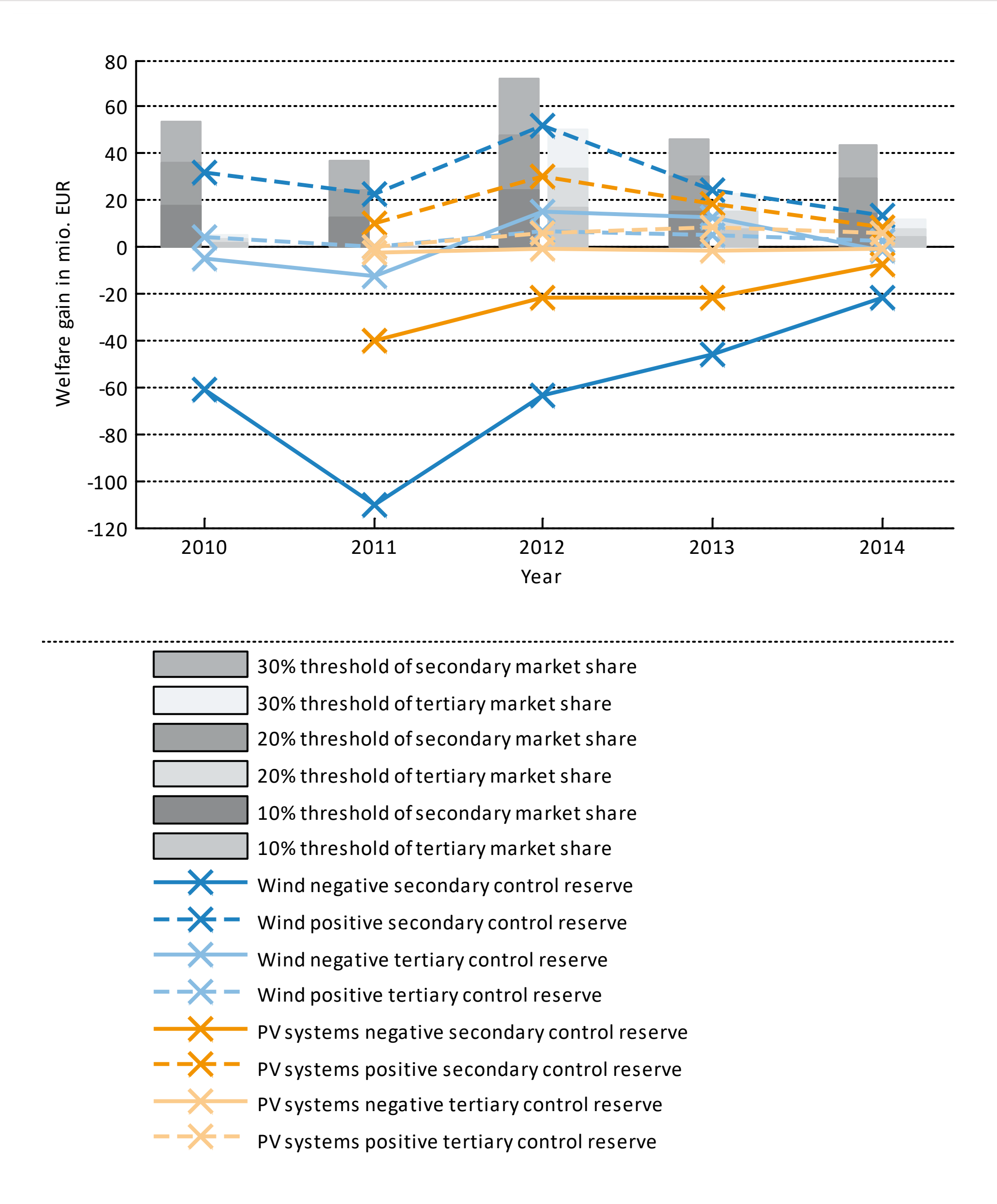


Source: Own analysis

Figure 6-4: Total welfare gain induced by the German 30 GW pool of wind farms and the 30 GW pool of PV systems for a product length of one hour, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market based on the total cost saving potentials

Separation of welfare gain into capacity and dispatch component

The results for the welfare gain reconfirm the previous finding that the participation of fluctuating RES generators in the control reserve market is beneficial for the power system in most cases. This would not be the case for the 30 GW pool of wind farms in the negative secondary reserve market in the year 2011 nor for the PV systems in any year but 2013. It is assumed that this is due to the energy price effects as described in chapter 6.1. In summary, no clear trend can be identified in the previous figure. The price effects require the separation of the welfare gain into a capacity component and a dispatch component. Figure 6-5 illustrates the dispatch cost component.



Source: Own analysis

Figure 6-5: Dispatch component welfare gain based induced by the German 30 GW pool of wind farms and the 30 GW pool of PV systems for a product length of one hour, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market

Figure 6-5 has the same structure as Figure 6-4. The difference is that this figure only presents the dispatch component of the welfare gain. The grey bars show only the dispatch cost component of the market. The illustration of the dispatch component of the welfare gain allows the identification of a trend in the data. The aforementioned increase in dispatch costs leads to a negative welfare gain in the negative secondary market. For wind this peaks at -110 million EUR in 2011; however, it is reduced to about -22 million EUR in 2014. Equally, the 30 GW pool of PV systems follows the same trend with the highest value of -40 million EUR in 2011 decreasing to about -8 million EUR. A cost increase in the negative tertiary market can be observed for wind farms in the years 2010 and 2011 with a maximum of -12 million EUR in 2011. In subsequent years, wind farms generate positive welfare gains in the dispatch component. PV systems fail to deliver added value to market altogether, although the maximum total amount of -2 million EUR is very small.

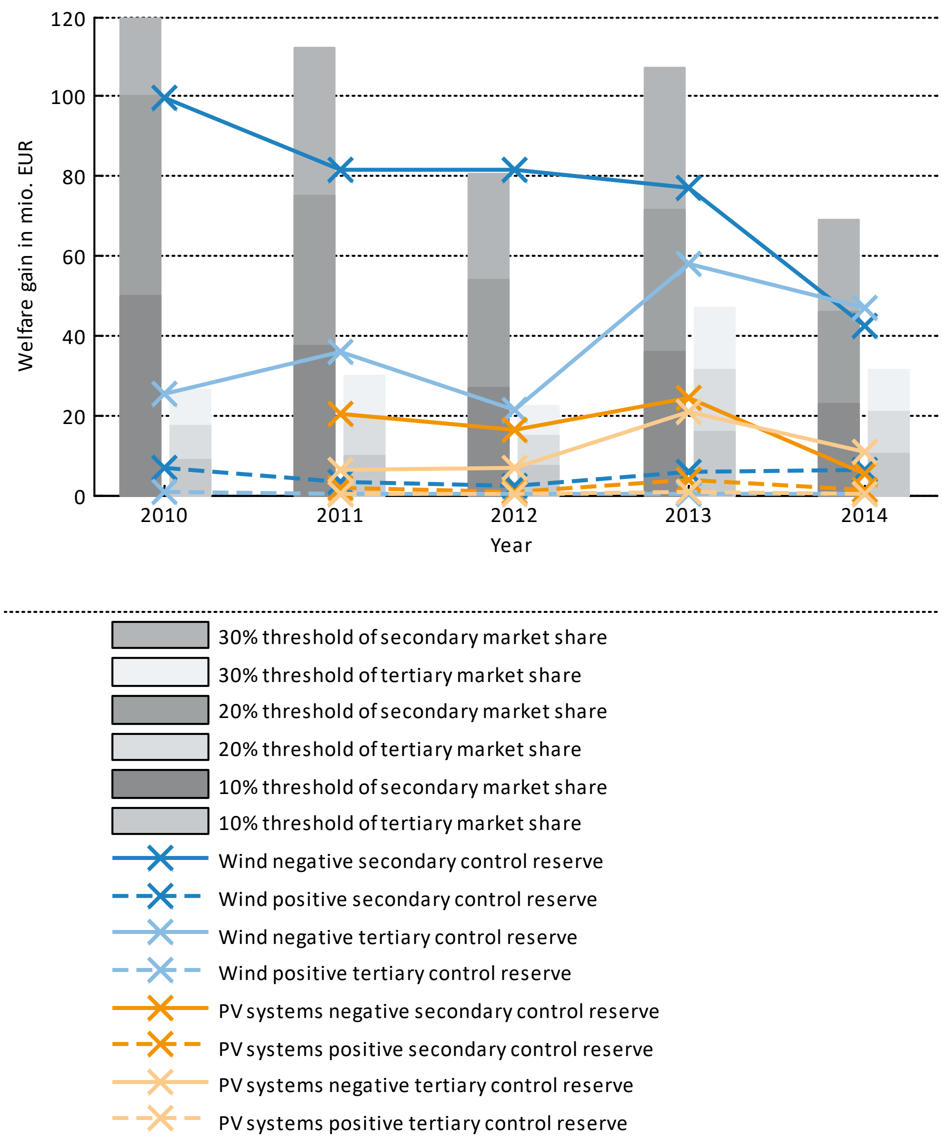
Negative welfare gains of the dispatch component in the negative control reserve markets

The welfare gain of the dispatch component in the positive markets is positive for all years, markets and generators. The positive tertiary market is relatively small, however. PV systems manage to generate an additional value of up to 8 million EUR in 2013, and for wind farms this reaches 7 million EUR in 2012. In the positive secondary market, PV systems generated up to 30 million EUR in 2012, and wind farms up to 52 million EUR in the same year. Both values decrease significantly until 2014 down to 9 million EUR for the PV systems and 13 million EUR for the wind farms.

Positive welfare gains of the dispatch component in the positive control reserve markets

The analysis of the dispatch component of the welfare gain shows that the total value is decreasing. The dispatch costs will have less impact over time in the future. Apart from wind farms in the negative secondary market in 2014 fluctuating RES did not generate additional value of more than 15 million EUR in absolute values. The trend will carry on and accelerate with new regulations, fostering competition in the market. The second component is the added value in the capacity market, as shown in Figure 6-6, applying the same structure as Figure 6-5 and Figure 6-4 for the capacity component.

Fluctuating RES deliver a declining added value to the cost component of the welfare gain



Source: Own analysis

Figure 6-6: Capacity component welfare gain induced by the German 30 GW pool of wind farms and the 30 GW pool of PV systems for a product length of one hour, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market

Positive welfare gains in the capacity component for all market segments

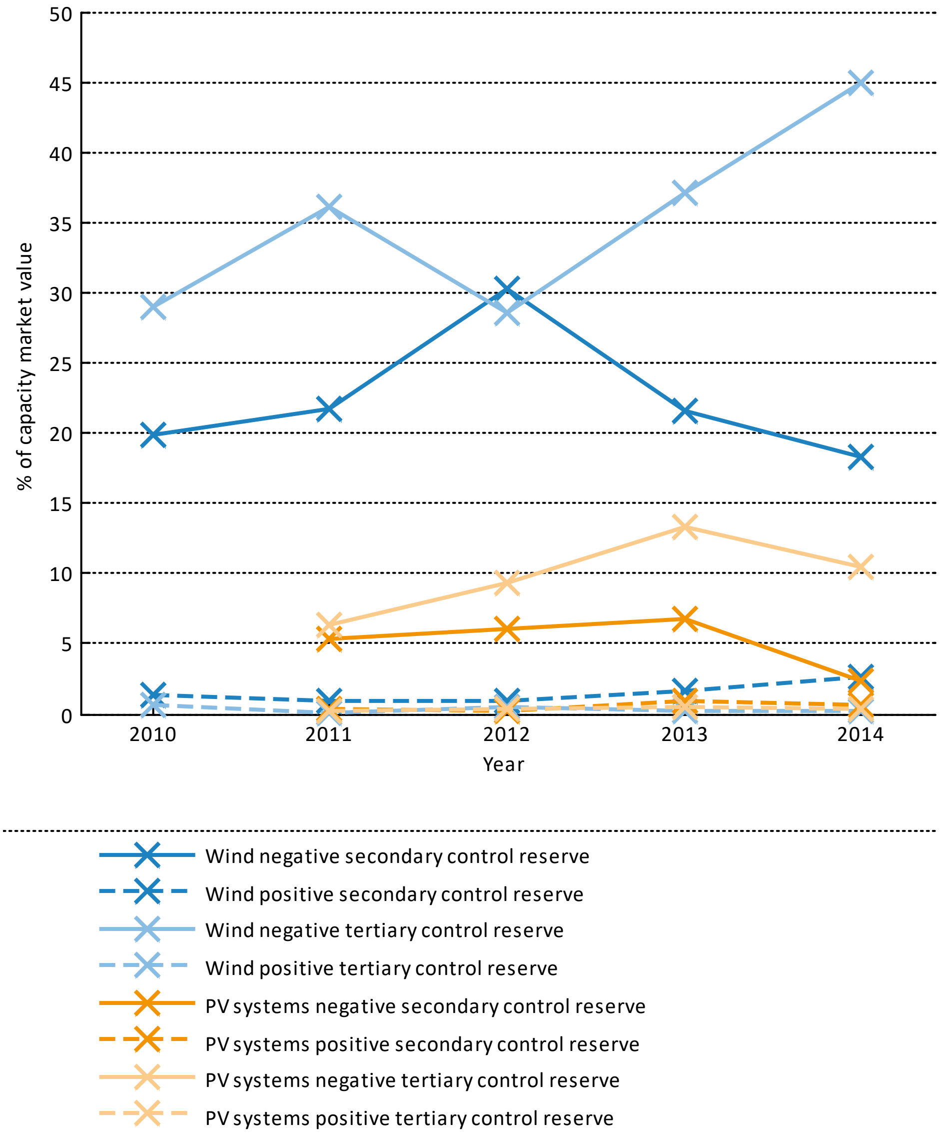
The results in Figure 6-6 show a declining welfare gain from 100 million EUR (2010) to 42 million EUR (2014) in the negative secondary market that roughly correlates with the decrease in capacity cost in that market segment. The welfare gain in the negative tertiary market segment, however, has an increasing trend from 25 million EUR in 2010 to 47 million EUR in 2014 peaking at 58 million EUR in 2013. At the same time, the increase correlates with the total capacity cost in the tertiary market. PV systems follow the same trend in both market segments, peaking at 24 million EUR in the negative secondary market and 21 million EUR in the negative tertiary market. The added value of wind in the positive reserve markets is limited. For the positive secondary market, it stagnates between 3 million EUR and 6 million EUR and is consistently less than 1 million EUR in the positive tertiary control reserve market. Once again the PV systems follow the trend of overall lower values. The added value in the negative secondary market is between less than 1 million EUR and up to 4 million EUR depending on the year, and is less than 1 million EUR in the positive tertiary control reserve market.

Added value dependent on the market size

The observed results show a large dependency on the entire market volume. For the representation of the cost component, a dependency on the corresponding cost component of the market was identifiable. The dependency varies significantly throughout the years, however, possibly due to strategic bidding in the market and therefore occludes the real price. It can be concluded that a significant welfare gain can be achieved in the negative reserve markets with only marginal gains in the positive markets. Additionally the added value largely depends on the market volume.

Displaying the relation the welfare gain and the total market size

The possible influence of the market volume on the added value from fluctuating RES generators is taken into account in Figure 6-7, which shows the ratio between the added value and the total market costs. The values expressed as percentages are the cost reduction potentials as a share of the entire market size. A given percentage value for bids placed in the negative tertiary control reserve markets is set in relation to the entire market volume of the negative and positive tertiary control reserve market. The market volume is equal to the control reserve costs given in Figure 3-7. Figure 6-7 resembles the previous figures apart from the fact that the grey bars with market information are omitted.



Source: Own analysis

Figure 6-7: Ratio between the capacity component welfare gain and the capacity cost market value based on capacity cost reductions only induced by the German 30 GW pool of wind farms and the 30 GW pool of PV systems for a product length of one hour, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market

High market share in the negative market segments and very small market shares in the positive market segments

Fluctuating RES generators achieve significant market shares in the negative reserve markets. Wind farms in the negative secondary market generate a welfare gain based on the market size, of between 18 % and 30 % at a level of reliability of 99.994 %. In the negative tertiary market, this would be between 29 % and 45 %. PV systems would achieve 2-8 % in the negative secondary market and between 6 % and 13 % in the negative tertiary market. In both positive reserve markets, the added value does not exceed 3 % of the market volume with slightly higher shares in the secondary market. This confirms that the economics for fluctuating RES are far more suitable to participate in the negative control reserve markets.

Conclusions and consideration on must-run units

Being able to replace large amounts of conventional generators in the market fosters the transformation of the power system. In a system with increasingly dynamic residual load requirements, conventional generators often do not operate at their maximum capacity. Each conventional generator in the power system that provides control reserve is therefore a potential must-run unit and causes uneconomic dispatch. Fluctuating RES generators providing control reserve therefore can have a positive impact on the spot market. In conclusion, significant welfare gains can be achieved by the introduction of fluctuating RES generators into the markets. High market shares can be achieved in the negative reserve markets.

6.4 Forecast of welfare gain in 2020 and 2030

Methodology on the welfare gain for 2020 and 2030

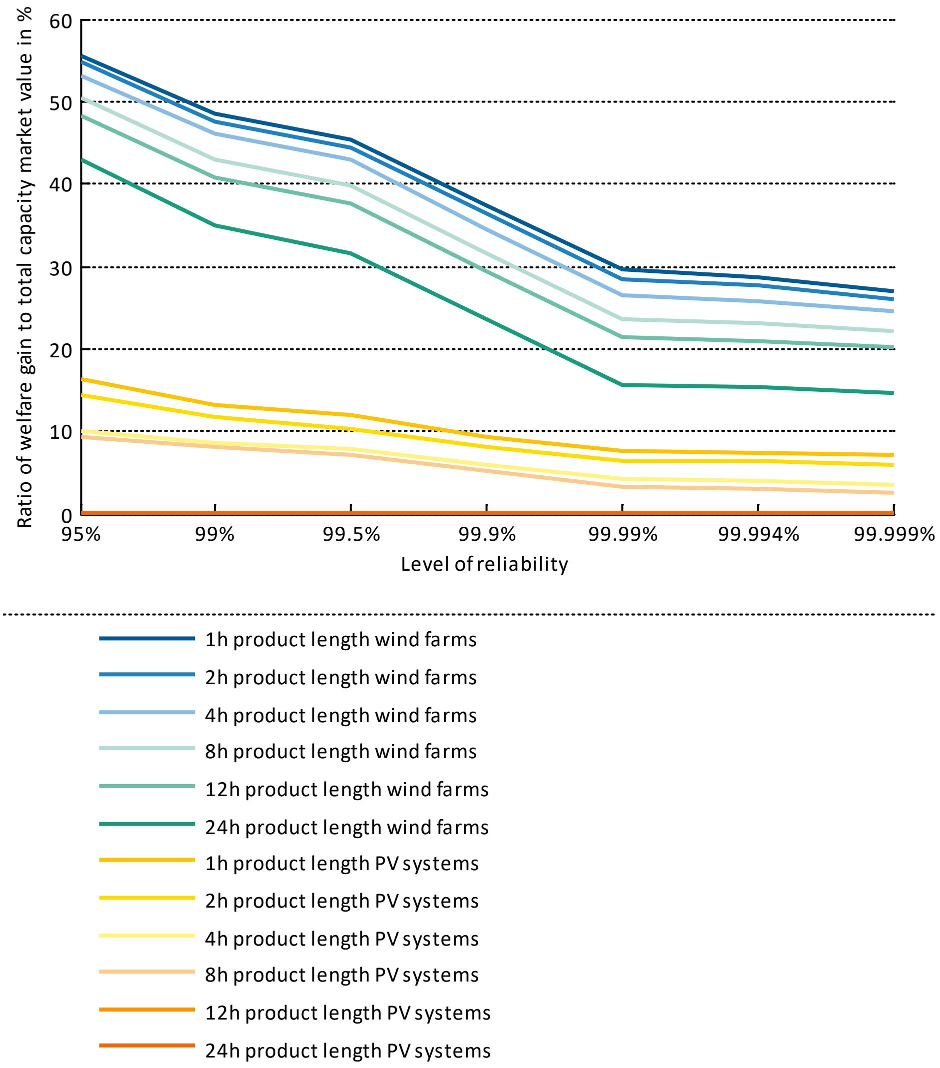
Based on all previous findings, this chapter aims to forecast the welfare gain in the years 2020 and 2030. This is carried out with the methodology from chapter 4.4.8. The presented methodology is highly dependent on the results shown in chapter 6.3. The methodology builds on the finding that the welfare gain is proportional to the market volume.

Steps for forecasting the welfare gain in 2020 and 2030

Based on the presented methodology three steps are necessary. The first step identifies the average ratio between the capacity cost based welfare gain and the total volume of the capacity market, which includes the capacity components of the entire secondary and tertiary control reserve markets. Since the welfare gain correlates with the market volume, it is forecasted in the second step. Finally, the ratios gained from the first step are applied to the forecasted market volume.

Identifying average ratios of welfare gain in 2010 to 2014

The first step evaluates the ratios between the capacity cost based welfare gain and the total capacity market volume of the control reserve market. The average ratio is the mean value of the ratios in the secondary and tertiary market control reserve capacity market components. The two markets are evaluated together, since they are interchangeable for fluctuating RES generators under the forthcoming market changes (see (Bundesnetzagentur, 2015)). The ratios are the average values over all years of the average value of the two markets, as laid out in equation (4-44). The individual shares for each year and market segment are presented in Figure 6-7 and Figure D-41 to Figure D-44 in Appendix D-B. The annual average ratios of both markets are shown in Figure 6-8 below.



Source: Own analysis

Figure 6-8: Average annual ratios between welfare gain and the joint capacity market volume for different levels of reliability and product lengths

Annual average welfare gain ratios for wind farms and PV systems

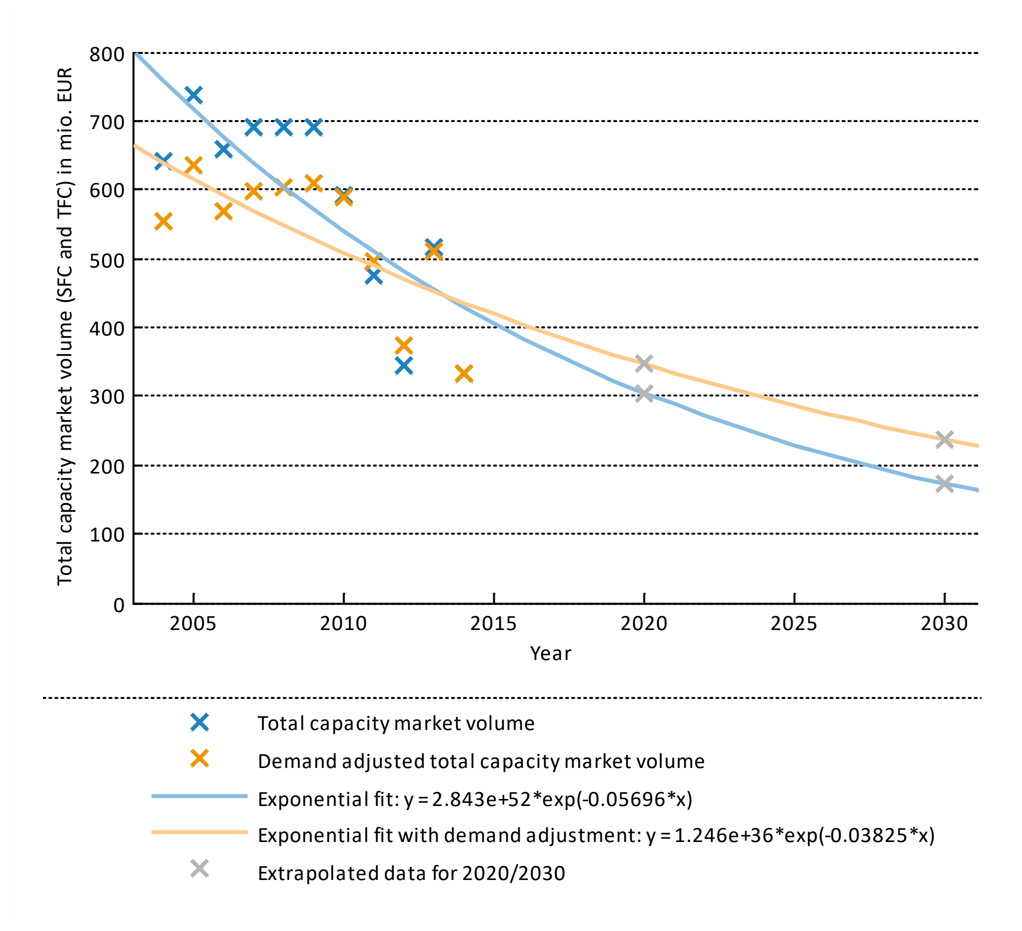
The average of the ratios for wind with a level of reliability of 99.994% and a product length of one hour is 28.7 %. With a product length of four hours this falls to 25.8 %. The ratios of PV systems are significantly lower. At the same level of reliability we see 7.5 % with a product length of one hour, and 4.1 % with a product length of four hours. In general, one can observe diminishing ratios of welfare gain with increasing product lengths and increasing levels of reliability. Once again, it is emphasized that the level of reliability of 99.994 % and the product length of one hour is guaranteeing the security of the bids whilst maximizing the output at the same time. The product length of one hour is most suitable for comparing wind farms and PV systems. Changing the product length from one hour to four hours, diminishes the PV systems potential by 45.3 %, while it is reduced by only 10.1 % for the wind farms. For 2020 and 2030, it can also be assumed that the product length is shortened to one hour, as already indicated by the Federal Network Agency.

Forecasting the market volume for 2020 and 2030

The previous step identified that the ratio between the welfare gain and the market volume of the capacity costs of the secondary and tertiary control reserve market capacity component is approximately constant while maintaining the same installed capacity. Knowing the market volume in the future allows identification of the welfare gains by fluctuating RES generators. This finding requires the extrapolation of the market volume to 2020 and 2030 in the second step. The methodology is presented in chapter 4.4.8. The proposed methodology identifies the exponential function as a suitable function family. The function is fitted to the previous market volumes, as shown in Figure 6-9.

Adjustment of market volume to the demand

The market volumes are the sum of the capacity components of the secondary and tertiary control reserve markets. These values are depicted as blue crosses in Figure 6-9. Fitting equation (4-45) to these values yields the coefficients $a = 2.843e^{52}$ and $b = -0.05696$, resulting in the blue curve. The goodness of the fit is relatively low with $R^2 = 0.6324$. Since the demand has changed in the past, the impact on the market volume has to be accounted for. Control reserve demand is presented in Figure 3-10. Past market volumes are derated in proportion to their annual average control reserve demand in both markets and scaled to the demand for the year 2014. This adjusts the market volumes in the past. For the years 2004 to 2009 in particular the market volume is reduced, by up to 101.7 million EUR in 2006. In 2011 and 2012 the demand was lower than in 2014, and the market volume is increased accordingly. These demand adjustments reduce the steepness of the fitted exponential function. The new coefficients are $a = 1.246e^{36}$ and $b = -0.03825$, forming the orange curve. The goodness of fit is reduced to $R^2 = 0.5006$.



Source: Own analysis

Figure 6-9: Extrapolation of joint capacity market volume for the years 2020 and 2030 based on the observed market size between 2004 and 2014 using an exponential fit

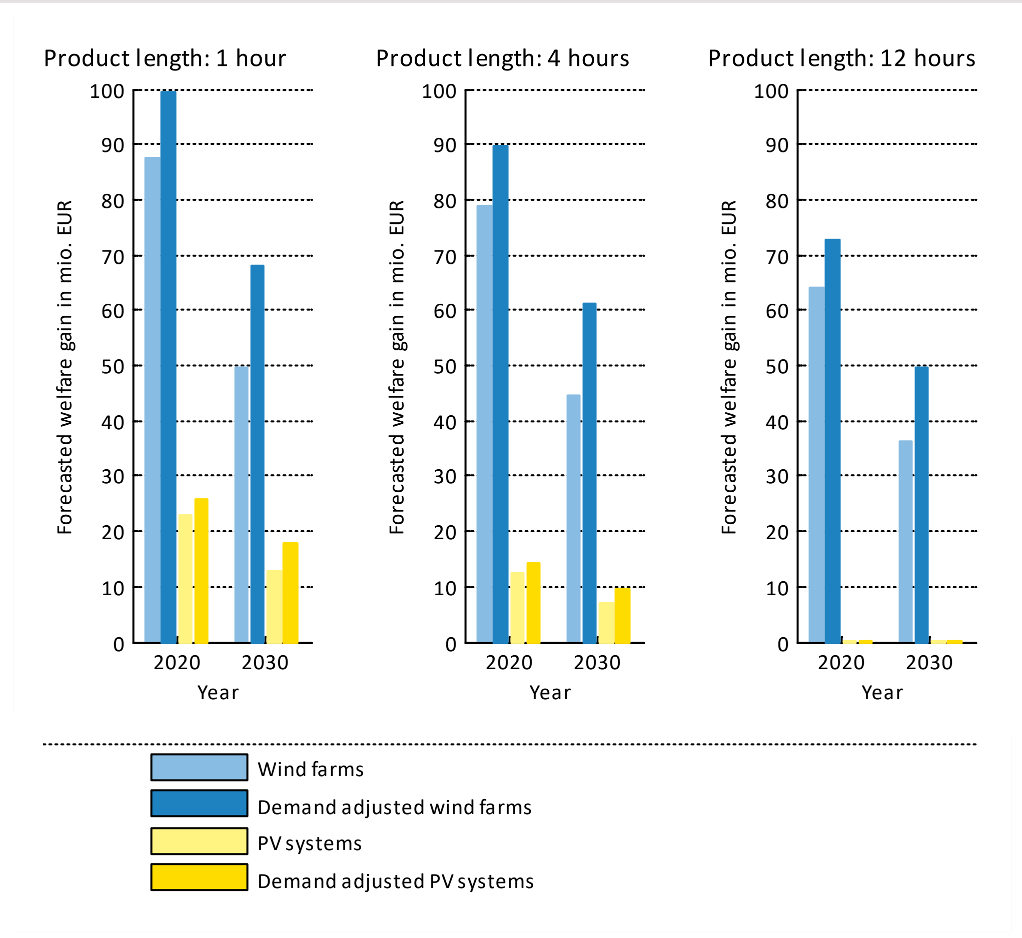
Forecasted total capacity market volumes (SCR and TCR)

The resulting market volumes for the years 2020 and 2030 are indicated in Figure 6-9 with grey crosses. For the exponential fit with no demand adjustments, the market volume would be 304.9 million EUR in 2020 and 172.5 million EUR in 2030. With the control reserve demand based adjustments the market volume would reach 346.5 million EUR in 2020, and

236.4 million EUR in 2030. The market forecast for 2020 would therefore be higher than the lowest value of 332.2 million EUR, observed in 2014. Since market volume information is derived from the exponential extrapolation only, it would be desirable to validate this with a different methodology, as e.g. in Lorenz and Gerbaulet (2015). This becomes increasingly important for larger time horizons, especially for the year 2030 and beyond.

In the third and final step, the average ratios of the welfare gain are applied to the forecasted market volume information. The forecasts for the welfare gain from fluctuating RES generators are calculated. The results for a level of reliability of 99.994 % and the various product lengths of one hour, four hours and twelve hours can be seen in Figure 6-10 below. The same plot with level of reliability of 95 % can be found in Figure D-50 in Appendix D-C.

Forecast of the welfare gain



Source: Own analysis

Figure 6-10: Forecast of welfare gain by the fluctuating RES generators in the control reserve market for the years 2020 and 2030 at a level of reliability of 99.994 %

Forecasted welfare gain by fluctuating RES generators in 2020 and 2030

The figure above shows the potential welfare gains in 2020 and in 2030. The yellow colours refer to the data on the 30 GW pool of PV systems. The blue bars indicate the results for the 30 GW wind farm pool. The lighter colours are for the market volume forecast without demand adjustment, while the darker colours include the demand adjustment. In the case of the wind farms with the demand adjusted forecast for 2020, the welfare gain is 100.0 million EUR with a product length of one hour and 90.0 million EUR with a product length of four hours. The PV systems would create 26.0 and 14.2 million EUR respectively. The results for the year 2030 are 31.8 % lower than in 2020.

Discussion of results

In both cases the capacity is assumed to be 30 GW, equal to the values in the assessment period. However, an increase in capacity is expected. This would potentially increase the welfare gain further. At the same time, the welfare gain could have been overestimated, due to the fact that the average has been used and applied to the entire market volume, whereas previously it was stated that the capacity could have been exhausted in one market segment already. Although this might be true in some hours of the year, the fluctuating RES provide enough reliable capacity to provide both services simultaneously, judging by the forecasts presented before.

Conclusions

The forecast of the welfare gain for the years 2020 and 2030 revealed significant potentials. However, the results should be verified by different modelling approaches, such as fundamental models. If the welfare gain were monetized by the wind farms and PV systems, additional income could be generated. For 2020, wind farms could generate approximately 3300 EUR/MW_{inst}, and PV systems up to 850 EUR/MW_{inst}, applying a level of security of 99.994 % and a product length of one hour. The forecasts of the welfare gain show the economic significance of a possible control reserve provision for the system and the contributing fluctuating RES generators.

7 Final assessment of the hypothesis and conclusions

Context of the study and relevance to policy makers and market participants

The study set out to explore the economics of a control reserve provision by fluctuating renewable energy sources. The very specific feed-in characteristics require additional steps to bring these generators to a market that requires reliable delivery. The high importance of this topic becomes apparent through the current consideration in the green/white paper process (Bundesministerium für Wirtschaft und Energie, 2015b), and the announcement of market participants (Döring, Sachs, & Thomas, 2014) as well as the frequent changes in the market design (Bundesnetzagentur, 2011c, 2011d, 2011e, 2015). Discussions in this area often lack reliable scientific data (Bucksteeg et al., 2014); decisions on regulatory changes often depend on the aggregated opinions of the stakeholders rather than scientific evidence (Bundesnetzagentur, 2015). This is underlined by the undoubtedly beneficial consultation periods before major market design changes. Since the technical capabilities of fluctuating RES to provide control reserve have been proven previously, this study is seeking to shed light on the economics of the topic. This is the next step towards a business model and market implementation.

Research question

Derived from the research hypothesis the research question is stated again:

> **How can stochastic units, such as wind farms and PV systems, provide control reserve to the power system competitively without altering the level of reliability whilst decreasing system costs?**

Beneficiaries of the research results

Answering the research question enables policy makers, researchers and market participants to know the value of their actions. The policy makers can adjust legislation towards a more fluctuating RES oriented market design. Researchers can match the numbers from this thesis with their results gained from unit commitment and agent-based models. This would lead to an exchange in scientific ideas. Market participants can estimate the value of their assets and judge whether they have a valid business model to prepare their market entrance.

7.1 Main findings

Answers to the research question

The research results have shown that they can answer the research question. The requirements to enable fluctuating RES generators to provide control reserve to the market have been identified. The results also indicate that having the wrong market regulations in place may lead to undesirable results and a potential increase in costs. The keywords of the findings are highlighted.

Providing reliability is possible

With the application of **probabilistic forecasts,** it is possible for fluctuating RES generators to provide control reserve with a **very high level of reliability**. If the real level of reliability of the existing market participants was disclosed by the grid operators, the forecast could be tuned to this exact value. This would guarantee that the reserve provided by fluctuating RES generators were no less than equally reliable as the reserve provided by conventional generation.

Large shares of renewables can provide large shares of control reserve

Fluctuating RES generators can achieve a **deep market penetration**. Wind farms have an advantage over PV systems since they have more full load hours and no diurnal periodicity, hence low simultaneity of their feed in. At **times of high fluctuating RES penetration,** wind farms and PV systems can contribute **large shares of the control reserve demands**, and therefore relieve other generators from their duty. The degree of market penetration can vary substantially, depending on the market, the product specifications and other influencing factors.

Regulatory environment is paramount for successful market participation

The impact of many issues of market regulation is captured and the effects on the fluctuating generators are quantified. By the variation of the product length, the level of reliability and other parameters, the **impact of different market regulations** is determined. For each different type of generator, numerous results were obtained. For example, if the product lengths are too long, PV systems would not be able to provide control reserve, although certain shares of their feed-in can be forecasted very reliably, whilst bearing in mind the daily and seasonal periodicity. Current secondary control reserve markets would be inaccessible for this reason alone, setting aside the other market entrance barriers. For the highest potential, the product length and the gate closure time should be as short as possible without discriminating against existing market participants. The level of reliability should be as high as necessary to fulfil the criteria but as low as possible to increase the potentials.

Range of bidding approaches captures the possible additional income

The **economics** of possible **participation** of fluctuating RES generators have been assessed extensively. This thesis has demonstrated a way to create market compliant bids with the required level of reliability, as appropriate for the control reserve market. Different bidding approaches have been modelled specifically to capture the entire range of possible market outcomes. The real market outcome will lie in-between the two approaches. The achievable market penetration differs largely between different bidding approaches and the market regulations. For all of the bids a market entry simulation has been performed to address the income possibilities of fluctuating RES generators in those markets. The results show that significant additional revenue can be generated in the negative secondary and tertiary control reserve markets.

Significant additional income for fluctuating RES generators

Wind farms in particular have a good ability to **generate additional income** in the market. With a falling trend over the years studied, a 30 GW pool was able to generate at least 17 million EUR and up to 54 million EUR in the negative secondary market, applying close-to-reality market conditions. **PV systems'** additional income is one **order of magnitude inferior**. Wind farms have proven to be adaptable to changes in the most dynamic and competitive of all market segments, the negative tertiary market. The additional revenue over the years varied from 10 million EUR to 19 million EUR with a much more stable outlook into the future. Additional income opportunities in the positive reserve market mostly arise from the dispatch of control reserve. Forthcoming regulatory changes, which are due to inefficiencies in the past, will decrease this potential significantly.

High welfare gains through wind farms in the negative reserve markets

In a hindcasting approach, the bids from the fluctuating RES generators have been used to generate **possible cost saving potentials** for the system. Derived from these results the **welfare gain** is determined. If the dispatch component were considered negative, welfare gains would be possible. Since these inefficiencies will be solved by regulatory changes, the welfare gain **based only on the capacity component** is considered, which leads to solely positive welfare gains in all market segments. The **welfare gains expressed as a share of the market volume** averages 24 % in the negative secondary market and 37 % in the negative tertiary market. The share in the negative secondary market is mostly constant whereas the share in the negative tertiary market is increased. The share of PV systems is significantly lower, at only 5 % in the secondary and 10 % in the tertiary market. However, both technologies might complement each other well. The welfare gain in positive markets does not exceed low single digit percentage values. The results are used to provide an outlook of the welfare gain for the years 2020 and 2030.

Differentiation from publications of other authors

The forecast in the future based on the welfare gains is in opposition to the approach of Papaefthymiou et al. (2015), which uses forecasted price data. The approach via the welfare gain is far more robust since control reserve market prices tend to be highly erratic, due to the strategic bidding in the market. Similar findings were made on the bidding characteristics of the wind farms. For onshore wind farms the difference is an order of magnitude inferior. According to the approach of Papaefthymiou offshore wind farms could generate an additional 5,000 - 8,000 EUR/MW_{inst}. The results in this study suggest that the additional income is between 8000 EUR/MW_{inst} and 18000/MW_{inst}. The results from this study confirm the findings in (Papaefthymiou et al., 2015, p. 5). It has to be noted however, that the paper of Papaefthymiou builds upon the methodology presented in this work and its preceding publications. Matching results with an alternative methodology would increase the confidence in the results further. The study by Consentec (2011, p. 29) comes to a similar conclusion on the same issues of potentially increasing dispatch costs, although in this case for dispatchable RES generators.

The presented results show that fluctuating RES generators can deliver control reserve reliably, and confirm which regulations need to be addressed to enable the provision of control reserve with an increasing share of fluctuating RES in the grid. It is proven not only that a valid business model for the generators exists, but also that the costs for the procurement of control reserve can be reduced. The work has provided an insight into the economics of fluctuating RES in the control reserve markets and the dependencies on the regulatory framework. The research hypothesis can therefore be accepted.

Closing the research question

7.2 Suggestions for action

Based on the results, the control reserve market should be developed further to allow fluctuating RES generators to participate. Some of the suggestions are already in the discussion (Bundesministerium für Wirtschaft und Energie, 2015b; Bundesnetzagentur, 2015), some may go beyond the scope of it.

Regulatory changes

1. Carry out the daily tendering for all control reserve types. This reduces the effects on the spot markets (must-run), increases competition and allows the dynamic dimensioning of the reserves for the next day (Jost et al., 2014). Abandon week-daily tendering as the market participants move towards a 24/7-operation.

2. Investigate the possibility of shortening the lead-time of the market. The current regulation of tendering the control reserve market before the spot market reduces the dispatch efficiency in the spot market without increasing the efficiency in the control reserve market. Consider control reserve market gate closure time after the publishing of the results in the spot market and the announcement of the schedules by the balance responsible party.

3. Reduce the product lengths in the control reserve markets to no more than four hours. If PV systems were to deliver control reserve, the product length would not be more than two hours. Explore the

possibility of product lengths of one hour and the implications on system operation and conventional generators.

4. Define a level of reliability for the market participants. The current reliability of 100 % is unrealistic for any market participant and occludes the associated risks.

5. Include the dispatch price in the tendering process to avoid the occurrence of very high dispatch prices. At the same time, this will increase the competition in the market and subsequently lead to decreasing costs.

6. Allow the available active power proof method for fluctuating RES generators and other stochastic units in the power system. The control reserve market is not suitable to improve the balancing discipline of the balance responsible parties. Use the balancing energy price mechanism instead.

7.3 Recommendation for future research

Future research

New potential research questions have arisen in this study. Some of the initial questions might not have been answered to exhaustion.

1. Investigation of the effects of co-optimization for the control reserve markets and spot markets simultaneously. Just (2011) stated that the increase in complexity does not lead to a high increase in efficiency. Alternatively investigate the efficiency gains when the co-optimization is performed stochastically. Results in Brauns et al. (2014, p. 58) show that high gains can be achieved when fluctuating RES and dispatchable generation are pooled. Investigate the changes on bidding prices and feed them back to the REBal model.

2. Explore the impact of alternate methodologies to calculate the probabilistic forecast. Many of the presented results are dependent on the probabilistic forecasts. When parametric methodologies are used, the issue of fat-tailed distributions needs to be investigated, since

extreme values might not fit the chosen approach. The selected method for this work does not have this problem since it is a non-parametric methodology. Necessarily, one would need to assess and optimize different forecast methods for their suitability in the control reserve provision.

3. Investigate the bidding behaviour of real market participants in detail. This would allow modelling and forecasting the economic results more precisely. Combine the bidding of different fluctuating RES generators to address the simultaneity issues.

4. Iterate more portfolio sizes to identify the functional relationship between the pool size and the welfare gain.

5. Place the bids in all market segments simultaneously, starting with the most profitable one and then using spare capacity in the next-best market segment and so on.

6. Explore the possibility of determining the welfare gain in the future in more detail, using a different methodology. This could incorporate the use of fundamental models to generate prices in the future.

7. Determine how the control reserve markets can be described best. These markets are partially driven by the fundamentals in the market and partially by strategic bidding behaviour. Determining the extent of the strategic behaviour, allows estimation of the level of uncertainty in future predictions of the market outcome and the welfare gain.

8. Increase the overall potential for the delivery of control reserve by identifying recurring or foreseeable patterns that have a large negative influence on the forecast levels. Probabilistic forecasts with very high levels of reliability are influenced by the extreme values. If the reliability of a forecast over a year is 99.99 %, then the time where the forecasted data exceeds the feed-in shall not be more than 52 minutes per year. Increasing the forecast reliability to 99.999 % changes this number to 5 minutes. For this reason, it might be

favourable to remove certain times from the data. One class of influencing events for wind turbines is storms, which repeatedly introduce large forecast errors (Dobschinski, Wessel, Lange, Bremen, & Saint-Drenan, 2008). If data for a predicted storm event were omitted the forecast accuracy could be increased (Dobschinski et al., 2010, p. 11).

9. Investigate the risk of offshore wind farms lacking n-1 security for their connection.

7.4 Conclusion

The distinctive production patterns of onshore wind farms, offshore wind farms and PV systems relate to their ability to provide a control reserve that is based on the availability of the resources. The "gaps" in-between can be filled with other renewable or non-renewable generation, such as biomass, hydro-storages and conventional generation. Economically this makes sense since these units are providing electricity when the resources are not available.

Fluctuating RES generators should be admitted to the market since they can deliver added value to the market and beyond. The ability to provide all necessary ancillary services from fluctuating RES generators is paramount for a power system with high shares of renewables. An energy system with a high level of RES penetration will not only have the demand for electricity at the right time in the year but also the need for ancillary services. Therefore, it is desirable that fluctuating RES generators are enabled to provide control reserve when they are supplying a large share of the energy to the power system.

The participation of fluctuating RES implicitly demands fair competition, with a regulatory framework that facilitates the market participation of as many units as possible. Fair market conditions, wind farms and PV systems are a part of the solution for a secure and stable energy system in the future. In summary, the safe and secure operation of the grid can be achieved with renewables at competitive costs.

References

50Hertz Transmission GmbH. (2015). Bilanzkreisabrechnung. Retrieved from http://www.50hertz.com/de/Maerkte/Regelenergie/Bilanzkreisabrechnung

50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH. (2011a). Informationen zur internationelen Erweiterung des Netzregelverbundes um die Regelzone Dänemark-West.

50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH. (2011b). Netzregelverbund. Retrieved from https://www.regelleistung.net/regelleistungWeb/static/netzregelverbund.jsp

50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH. (2012a). Ausschreibungen. Retrieved from https://www.regelleistung.net/regelleistungWeb/publicAusschreibungen/PublicAusschreibungenController.jpf

50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH. (2012b). *Modell zur Berechnung des regelzonenübergreifenden einheitlichen Bilanzausgleichsenergiepreises (reBAP) unter Beachtung des Beschlusses BK6-12- 024 der Bundesnetzagentur vom 25.10.2012.*

50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH. (2014). Prequalification procedure for the provision and activation of control reserve. Retrieved from https://www.regelleistung.net/ext/static/prequalification

50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH. (2015a). Bestimmung des Bedarfs an Primärregelleistung. Retrieved from https://www.regelleistung.net/ip/action/dimensionierung

50Hertz Transmission GmbH, Amprion, TenneT TSO GmbH, & TransnetBW GmbH. (2015b). Leitfaden zur Präqualifikation von Windenergieanlagen zur Erbringung von Minutenreserveleistung im Rahmen einer Pilotphase. Retrieved from https://www.regelleistung.net/ext/download/pqWindkraft

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. Mindestanforderungen an die Informationstechnik des Anbieters für die Erbringung von Sekundärregelleistung. Retrieved from https://www.regelleistung.net/ip/action/static/prequalSrl

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. (2012). Gemeinsame Ausschreibung Primärregelleistung auf regelleistung.net. Retrieved from https://www.regelleistung.net/ext/static/prl

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. (2013). *Netzentwicklungsplan Strom 2013 (NEP2013), Teil 1: Zweiter Entwurf*. Berlin, Pulheim, Bayreuth, Stuttgart.

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. (2015a). Musterprotokoll zum Nachweis der Erbringung von positiver Minutenreserveleistung am Beispiel einer 30 MW - Präqualifikation. Retrieved from https://www.regelleistung.net/ip/action/static/prequal

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. (2015b). Musterprotokoll zum Nachweis der Erbringung von positiver Primärregelleistung. Retrieved from https://www.regelleistung.net/ip/action/static/prequal

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. (2015c). Musterprotokoll zum Nachweis der Erbringung von positiver Sekundärregelleistung. Retrieved from https://www.regelleistung.net/ip/action/static/prequal

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. (2015). Präqualifizierte Anbieter je Regelenergieart. Retrieved from https://www.regelleistung.net/ip/action/static/provider

50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, & TransnetBW GmbH. (2015d). Tender overview. Retrieved from https://www.regelleistung.net/ip/action/ausschreibung/public?language=en

50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH, & TenneT TSO GmbH. (2013). Ausschreibungen - Daten zur Regelenergie. Retrieved from www.regelleistung.net/ip/action/ausschreibung/public

50Hertz Transmission GmbH, Amprion GmbH, TransnetBW GmbH, & TenneT TSO GmbH. (2015). regelleistung.net: Internetplattform zur Ausschreibung von Regelleistung der deutschen Übertragungsnetzbetreiber. Retrieved from www.regelleistung.net

ACER. (2012). *Framework Guidelines on Electricity Balancing*. Retrieved from http://www.acer.europa.eu/Electricity/FG_and_network_codes/Pages/Balancing.aspx

AEE. (2015). Stürmischer Dezember steigert Windstromeinspeisung. Retrieved from http://www.unendlich-viel-energie.de/erneuerbare-energie/wind/offshore/offshore-windenergie-ueberschreitet-2014-die-gigawattmarke?utm_source=Newsletter&utm_medium=newsletter&utm_campaign=renews_jan15

Aho, J., Buckspan, A., Laks, J., Jeong, Y., Dunne, F., Pao, L.,. . . Johnson, K. (2012). Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control: To be presented at the 2012 American Control Conference Montreal, Canada June 27-29, 2012.

Al-Awaad, A. (2009). *Beitrag von Windenergieanlagen zu den Systemdienstleistungen in Hoch- und Höchstspannungsnetzen: Dissertation an der Universität Wuppertal.*

Almeida, R. G. de, & Lopes, J. A. P. (2007). Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation: Power Systems, IEEE Transactions on. *Power Systems, IEEE Transactions on*, *22*(3), 944–950.

Anaya-Lara, O., Hughes, F. M., Jenkins, N., & Strbac, G. (2006). Contribution of DFIG-based wind farms to power system short-term frequency regulation: Generation, Transmission and Distribution, IEE Proceedings-. *Generation, Transmission and Distribution, IEE Proceedings-*, *153*(2), 164–170.

Andersen, A., Strom, S., Tang, J., Davidsen, T., & Dupont, N. (2012). Proactive participation of wind turbines in the electricity markets: Proceedings of EWEA Annual Event 2012, 16 - 19 April 2012, Copenhagen.

Azpiri, I., Combarros, C., Pére, C. J., Veguillas, R., López, M., Lorenzo, M.,. . . Saiz, E. (2013). TWENTIES Deliverable nº 9.1 DEMO 1: Test results, with their technical impact and validation, regarding the secondary frequency control demonstration & voltage control demonstration. Retrieved from http://www.twenties-project.eu/system/files/Deliverable%209_1%20Final.pdf

Bessa, R. J., Miranda, V., Botterud, A., Zhou, Z., & Wang, J. (2012). Time-adaptive quantile-copula for wind power probabilistic forecasting. *Renewable Energy*, *40*(1), 29–39. doi:10.1016/j.renene.2011.08.015

Bevrani, H., Ghosh, A., & Ledwich, G. (2010). Renewable energy sources and frequency regulation: survey and new perspectives: Renewable Power Generation, IET. *Renewable Power Generation, IET*, *4*(5), 438–457.

Beyer, H. G., Heilscher, G., & Bofinger, S. (2004). A robust model for the MPP performance of different types of PV-modules applied for the performance check of grid connected systems: Proceedings Eurosun 2004, Freiburg, Germany.

Bhatt, P., Roy, R., & Ghoshal, S. P. (2011). Dynamic participation of doubly fed induction generator in automatic generation control. *Renewable Energy*, *36*(4), 1203–1213. Retrieved from http://www.sciencedirect.com/science/article/pii/S0960148110003873

Bhatt, R., & Chowdhury, B. (2011). Grid frequency and voltage support using PV systems with energy storage. In *North American Power Symposium (NAPS), 2011 : North American Power Symposium (NAPS), 2011 : North American Power Symposium (NAPS), 2011* (pp. 1–6). doi:10.1109/NAPS.2011.6025112

BM Intermittent Gen WG. (2010). BM Uni Data from Intermittent Generation - final: WORKING GROUP REPORT.

Boadway, R., & Bruce, N. (2011). *Welfare economics* ([Nachdr.]). Oxford: Blackwell.

Bowman, A. W., & Azzalini, A. (1997). *Applied smoothing techniques for data analysis: The kernel approach with S-Plus illustrations*. Oxford, New York: Clarendon Press; Oxford University Press.

Braun, M. (2009). *Provision of ancillary services by distributed generators. Technological and economic perspective* (Dissertation). Universität Kassel, Kassel. Retrieved from http://www.uni-kassel.de/upress/online/OpenAccess/978-3-89958-638-1.OpenAccess.pdf

Brauns, S., Jansen, M., Jost, D., Siefert, M., Speckmann, M., & Widdel, M. (2014). *Regelenergie durch Windkraftanlagen - Abschlussbericht*. Kassel.

Bucksteeg, M., Niesen, L., Himmes, P., Schober, D., Weber, C., Baumgart, B.,. . . Bittner, M. (2014). *Marktdesign für zukunftsfähige Elektrizitätsmärkte unter besonderer Berücksichtigung der vermehrten Einspeisung von erneuerbaren Energien – DESIRE –: DESIRE Endbericht*. Duisburg, Essen, Aachen. Retrieved from Universität Duisburg-Essen; Trianel GmbH; BET Büro für Energiewirtschaft und technische Planung GmbH website: http://www.bet-aachen.de/fileadmin/redaktion/PDF/Studien_und_Gutachten/DESIRE_Endbericht__141024_FINAL_Lang.pdf

Bundeskartellamt. (2011). *Sektoruntersuchung Stromerzeugung und -großhandel: Abschlussbericht gemäß § 32e GWB – Januar 2011*. Bonn. Retrieved from Bundeskartellamt website: http://www.bundeskartellamt.de/SharedDocs/Publikation/DE/Sektoruntersuchungen/Sektoruntersuchung%20Stromerzeugung%20Stromgrosshandel%20-%20Abschlussbericht.pdf?__blob=publicationFile&v=3

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. (2014). Kombikraftwerk 2: Sicherer Stromnetzbetrieb bei 100% Erneuerbaren Energien in Zukunft möglich. Retrieved from http://www.kombikraftwerk.de/

Bundesministerium für Wirtschaft und Energie. (2014). *Green Paper: An electric power market for the energy transition*. Berlin. Retrieved from Bundesministerium für Wirtschaft und Energie website: http://www.bmwi.de/EN/Topics/Energy/Electricity-Market-of-the-Future/green-paper,did=679748.html

Bundesministerium für Wirtschaft und Energie. (2015a). BMWi - Zahlen und Fakten. Retrieved from http://www.bmwi.de/DE/Themen/Energie/Strommarkt-der-Zukunft/zahlen-fakten

Bundesministerium für Wirtschaft und Energie. (2015b). *Ein Strommarkt für die Energiewende: Ergebnispapier des Bundesministerium für Wirtschaft und Energie (Weißbuch)*. Berlin. Retrieved from http://www.bmwi.de/DE/Mediathek/publikationen,did=718200.html

Bundesnetzagentur. (2006). *Monitoringbericht 2006: Bericht nach § 63 Abs. 4 i.V.m. § 35 EnWG*. Bonn, Berlin. Retrieved from Bundesnetzagentur website: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/DatenaustauschUndMonitoring/Monitoring/Monitoringbericht2006.pdf?__blob=publicationFile&v=2

Bundesnetzagentur. (2007). *Monitoringbericht 2007: Bericht gemäß § 63 Abs. 4 EnWG i.V.m. § 35 EnWG*. Bonn. Retrieved from Bundesnetzagentur website: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/DatenaustauschUndMonitoring/Monitoring/Monitoringbericht2007.pdf?__blob=publicationFile&v=2

Bundesnetzagentur. (2008a). *BK6-08-006 Festlegung des Ausschreibungsverfahrens für Verlustenergie und des Verfahrens zur Bestimmung der Netzverluste.*

Bundesnetzagentur. (2008b). *Monitoringbericht 2008*. Bonn. Retrieved from Bundesnetzagentur website: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/DatenaustauschUndMonitoring/Monitoring/Monitoringbericht2008.pdf?__blob=publicationFile&v=2

Bundesnetzagentur. (2009a). *Anhang 1 und 2 zu BK6-07-002 Festlegung von Marktregeln für die Durchführung der Bilanzkreisabrechnung Strom: Anhang 1 und 2 zu MaBiS*. Retrieved from Bundesnetzagentur - Beschlusskammer 6 website: http://www.bundesnetzagentur.de/DE/Service-Funktionen/Beschlusskammern/1BK-Geschaeftszeichen-Datenbank/BK6-GZ/2007/2007_001bis099/BK6-07-002/BK6-07-002_Anlagen1und2zumBeschluss10062009_bf.pdf?__blob=publicationFile&v=3

Bundesnetzagentur. (2009b). *Anhang 3 zu BK6-07-002 Festlegung von Marktregeln für die Durchführung der Bilanzkreisabrechnung Strom: Anhang 3 zu MaBiS*. Retrieved from Bundesnetzagentur - Beschlusskammer 6 website: http://www.bundesnetzagentur.de/DE/Service-Funktionen/Beschlusskammern/1BK-Geschaeftszeichen-Datenbank/BK6-GZ/2007/2007_001bis099/BK6-07-002/BK6-07-002_Anlage3Beschluss10062009_bf.pdf?__blob=publicationFile&v=3

Bundesnetzagentur. (2009c). *BK6-07-002 Festlegung von Marktregeln für die Durchführung der Bilanzkreisabrechnung Strom: MaBiS*. Retrieved from Bundesnetzagentur - Beschlusskammer 6 website: http://www.bundesnetzagentur.de/cln_1421/DE/Service-Funktionen/Beschlusskammern/1BK-Geschaeftszeichen-Datenbank/BK6-GZ/2007/2007_001bis099/BK6-07-002/BK6-07-002_Beschluss_BKV.html?nn=269602

Bundesnetzagentur. (2009d). *Monitoringbericht 2009: Monitoringbericht gemäß § 63 Abs. 4 EnWG i.V.m. § 35 EnWG*. Bonn. Retrieved from Bundesnetzagentur website: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/DatenaustauschUndMonitoring/Monitoring/Monitoringbericht2009.pdf?__blob=publicationFile&v=2

Bundesnetzagentur. (2010). *Monitoringbericht 2010: Monitoringbericht gemäß § 63 Abs. 4 EnWG i.V.m. § 35 EnWG*. Bonn. Retrieved from Bundesnetzagentur website: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/DatenaustauschUndMonitoring/Monitoring/Monitoringbericht2010.pdf?__blob=publicationFile&v=1

Bundesnetzagentur. (2011a). *Bilanzkreisvertrag - Anlage zum Beschluss BK6-06-013.*

Bundesnetzagentur. (2011b). *BK6-07-002 Festlegung von Marktregeln für die Durchführung der Bilanzkreisabrechnung Strom - Konsolidierte Lesefassung gemäß der letzten Änderung durch den Beschluss BK6-11-150 vom 28.10.2011: MaBiS*. Retrieved from Bundesnetzagentur - Beschlusskammer 6 website: http://www.bundesnetzagentur.de/DE/Service-Funktionen/Beschlusskammern/Beschlusskammer6/BK6_31_GPKE_und_GeLiGas/Mitteilung_Nr_31/Anlagen/Konsolidierte_Lesefassung_MaBiS.pdf?__blob=publicationFile&v=2

Bundesnetzagentur. (2011c). *Festlegung zu Verfahren und Ausschreibung von Regelenergie in Gestalt der Minutenreserve: BK6-10-099.*

Bundesnetzagentur. (2011d). *Festlegung zu Verfahren zu Ausschreibung von Regelenergie in Gestalt der Primärregelleistung: BK6-10-097.*

Bundesnetzagentur. (2011e). *Festlegung zu Verfahren zur Ausschreibung von Regelenergie in Gestalt der Sekundärregelung: BK6-10-098.*

Bundesnetzagentur. (2012a). Beschluss in dem Verwaltungsverfahren wegen der Weiterentwicklung des Ausgleichsenergiepreis-Abrechnungssystems: Az: BK6-12-024.

Bundesnetzagentur. (2012b). *Monitoringbericht 2011: Monitoringbericht gemäß §63 Abs. 4 EnWG i.V.m. § 35 EnWG*. Bonn.

Bundesnetzagentur. (2013). *BK6-06-013 - Festlegung zur Vereinheitlichung der Bilanzkreisverträge.*

Bundesnetzagentur. (2015). *Festlegungsverfahren zur Weiterentwicklung der Ausschreibungsbedingungen und Veröffentlichungspflichten für Sekundärregelung und Minutenreserve: Konsultation von Eckpunkten*. § 29 EnWG, § 27 Abs. 1 Nr. 2 und Abs. 2 StromNZV. Bonn. Retrieved from Bundesnetzagentur - Beschlusskammer 6 website: http://www.bundesnetzagentur.de/DE/Service-Funktionen/Beschlusskammern/1BK-Geschaeftszeichen-Datenbank/BK6-GZ/2015/2015_0001bis0999/BK6-15-158/BK6-15-158_Eckpunktepapier_vom_23_11_2015.pdf?__blob=publicationFile&v=2

Bundesnetzagentur, & Bundeskartellamt. (2013). Monitoringbericht 2012: Monitoringbericht gemäß § 63 Abs. 3 i.V.m. § 35 EnWG und § 48 Abs. 3 i.V.m. § 53 Abs. 3 GWB.

Bundesnetzagentur, & Bundeskartellamt. (2014). *Monitoringbericht 2014: Monitoringbericht gemäß § 63 Abs. 3 i. V. m. § 35 EnWG und § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWB*. Bonn.

Bundesnetzagentur, & Bundeskartellamt. (2015). *Monitoringbericht 2015: Monitoringbericht gemäß § 63 Abs. 3 i. V. m. § 35 EnWG und § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWBStand: 10. November 2015*. Bonn. Retrieved from Bundesnetzagentur; Bundeskartellamt website: http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2015/Monitoringbericht_2015_BA.pdf?__blob=publicationFile&v=2

Bundesnetzagentur, B. (2014). *Monitoringbericht 2013: gemäß § 63 Abs. 3 i. V. m. § 35 EnWG und § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWB*. Bonn.

Bundesregierung. (2010). *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung.*

Verordnung zu abschaltbaren Lasten. Bundesgesetzblatt 2998 (Bundesregierung 2012).

Stromnetzzugangsverordnung, Bundesregierung 2014.

Bündgen, F. (2012). *Regelleistung durch Photovoltaik* (Diploma-Thesis). Technische Hochschule Mittelhessen, Gießen.

Chattopadhyay, D., & Baldick, R. (2002). Unit commitment with probabilistic reserve. In *Winter Meeting of the Power Engineering Society* (pp. 280–285). doi:10.1109/PESW.2002.984999

Chaudhuri, D., Chaudhuri, B. B., & Murthy, C. A. (1996). A data driven procedure for density estimation with some applications. *Pattern Recognition*, *29*(10), 1719–1736. doi:10.1016/0031-3203(96)00028-3

Chowdhury, B. H., & Ma, H. T. (2008). Frequency regulation with wind power plants: Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE. *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 1–5.

Cleveland, W. S. (1979). Robust Locally Weighted Regression and Smoothing Scatterplots. *Journal of the American Statistical Association*, *74*(368), 829–836. doi:10.1080/01621459.1979.10481038

Cleveland, W. S., & Devlin, S. J. (1988). Locally Weighted Regression: An Approach to Regression Analysis by Local Fitting. *Journal of the American Statistical Association*, *83*(403), 596. doi:10.2307/2289282

Consentec. (2008). Gutachten zur Höhe des Regelenergiebedarfs: Im Auftrag der BNetzA.

Consentec. (2010). *Gutachten zur Dimensionierung des Regelleistungsbedarfs unter dem NRV: Untersuchung im Auftrag der BNetzA.*

Consentec. (2011). *Auswirkungen der Teilnahme von EEG-Anlagen aus der festen Einspeisvergütung auf die Regelenergiemärkte: Gutachten im Auftrag der BNetzA*. Aachen, Bonn.

Consentec. (2014). *Beschreibung von Regelleistungskonzepten und Regelleistungsmarkt: Studie im Auftrag der deutschen Übertragungsnetzbetreiber*. Aachen.

Consentec, r2b, & FGH. (2011). Optimierung und Umstrukturierung der EEG-Förderung zur verbesserten Netz- und Marktintegration Erneuerbarer Energien: Studie im Auftrag des BMWi.

Conzelmann, G., Boyd, G., Koritarov, V., & Veselka, T. (2005). Multi-agent power market simulation using EMCAS. In *IEEE Power Engineering Society General Meeting, 2005* (pp. 917–922). doi:10.1109/PES.2005.1489271

Cramton, P. (2009). Single Clearing Price in Electricity Markets. Retrieved from http://www.cramton.umd.edu/papers2005-2009/baldick-single-price-auction.pdf

Cramton, P., & Stoft, S. (2007). Why We Need to Stick with Uniform-Price Auctions in Electricity Markets. *The Electricity Journal*, *20*(1), 26–37. doi:10.1016/j.tej.2006.11.011

Dany, G. (2001). Power reserve in interconnected systems with high wind power production: Power Tech Proceedings, 2001 IEEE Porto. *Power Tech Proceedings, 2001 IEEE Porto*, *4*, 6 pp. vol.4.

David, A. K., & Fushuan Wen (2000). Strategic bidding in competitive electricity markets: a literature survey. In *2000 Power Engineering Society Summer Meeting* (pp. 2168–2173). doi:10.1109/PESS.2000.866982

DECC. (2013). *Electricity Generation Costs*. Retrieved from Department of Energy and Climate Change website: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/269888/131217_Electricity_Generation_costs_report_December_2013_Final.pdf

den Ouden, B., & Jean Verseille (2011, June). *CWE Market Coupling Flow-Based Forum*, Amterdam. Retrieved from https://www.epexspot.com/document/13241/Flow-Based_Forum-%20June-presentation.pdf

dena, Molly, J. P., Neddermann, B., Schorer, T., Callies, D., Knorr, K.,. . . Sievers, J. (2010). *dena-Netzstudie II: Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015 - 2020 mit Ausblick 2025*. Berlin.

Dentcheva, D., Gollmer, R., Möller, A., Römisch, W., & Schultz, R. (1996). *Solving the Unit Commitment Problem in Power Generation by Primal and Dual Methods*. Berlin. Retrieved from HU Berlin website: http://edoc.hu-berlin.de/series/mathematik-preprints/1996-25/PDF/25.pdf

Energiewirtschaftsgesetz *Bundesgesetzeblatt*, Deutscher Bundestag 2011.

Erneuerbare-Energien-Gesetz *Bundesgesetzeblatt* 1066, Deutscher Bundestag 2014.

Dobschinski, J., Pascalis, E. de, Wessel, A., Bremen, L. von, Lange, B., Rohrig, K., & Saint-Drenan, Y.-M. (2010). The potential of advanced shortest-term forecasts and dynamic prediction intervalls for reducing the wind power induced reserve requirements. *European Wind Energy Conference and Exhibition*.

Dobschinski, J. (2016). *Vorhersage der Prognosegüte verschieden großer Windpark-Portfolios*. Publication Pending.

Dobschinski, J., Wessel, A., Lange, B., Bremen, L. von, & Saint-Drenan, Y.-M. (2008). Estimation of wind power prediction intervals using stochastic methods and artificial intelligence ensembles: DEWEK 2008, 9th German Wind Energy Conference. Proceedings. 26 - 28 November 2008, Bremen, Germany.

ENERTRAG AG; Trianel GmbH; GESY Green Energy Systems GmbH. (2014). *ENERTRAG, GESY und Trianel gehen Kooperation ein: Systemstabilität durch Regelenergie aus Windkraft*. Aachen. Retrieved from http://www.trianel.com/de/pressearchiv/details/article//enertrag-gesy-und-trianel-geh.html

DTU. (2012). PossPOW: Possible Power of Offshore Wind power plants. Retrieved from http://www.posspow.dtu.dk/

Durante, F., Westerhellweg, A., & Jimenez, B. (2012). Comparison of a Mesoscale Model with FINO Measurements in the German Bight and the Baltic Sea. In DEWI (Ed.), *DEWI Magazin* (No. 40).

eex. (2015a). eex - Infoproducts: Transparency data of wind power plants and PV systems. Retrieved from infoproducts.eex.com

eex. (2015b). eex - Transparency in electricity markets. Retrieved from www.transparency.eex.com

eex. (2015c). Transparency in Energy Markets - Actual Solar Power Generation (chart). Retrieved from http://www.eex-transparency.com/homepage/power/germany/production/usage/actual-solar-power-generation-

eex. (2015d). Transparency in Energy Markets - Actual Wind Power Generation (chart). Retrieved from http://www.eex-transparency.com/homepage/power/germany/production/usage/actual-wind-power-generation

eex. (2015e). Transparency in Energy Markets - Expected Solar Power Generation (chart). Retrieved from http://www.eex-transparency.com/homepage/power/germany/production/usage/expected-solar-power-generation-/expected-solar-power-generation-chart-eex. (2015f). Transparency in Energy Markets - Expected Wind Power Generation (chart). Retrieved from http://www.eex-transparency.com/homepage/power/germany/production/usage/expected-wind-power-generation-

Ehsani, A., Ranjbar, A. M., & Fotuhi-Firuzabad, M. (2009). A proposed model for co-optimization of energy and reserve in competitive electricity markets. *Applied Mathematical Modelling*, *33*(1), 92–109. doi:10.1016/j.apm.2007.10.026

EirGrid. (2009). EirGrid - Grid Code Version 3.4: Modifications approved October 16th 2009.

Eisen, S., Sørensen, P., Donovan, M., & Hansen, K. (2007). Real Time Estimation of Possible Power for Wind Plant Control. In N. Cutululis & P. Sørensen (Eds.): *Vol. 1624. Risø R, Report, Proceedings, Nordic Wind Power Conference, Risø National Laboratory, 1 - 2 November 2007.* Roskilde: Risø National Laboratory.

Ela, E., Kirby, B., Lannoye, E., Milligan, M., Flynn, D., Zavadil, B., & O'Malley, M. (2010). Evolution of operating reserve determination in wind power integration studies: Power and Energy Society General Meeting, 2010 IEEE. *Power and Energy Society General Meeting, 2010 IEEE*, 1–8.

Ela, E., Milligan, M., & Kirby, B. (2011). Operating Reserves and Variable Generation: Technical Report.

Elberg, C., Growitsch, C., Höffler, F., Richter, J., & Wambach, A. (2012). *Untersuchungen zu einem zukunftsfähigen Strommarktdesign: im Auftrag des Bundesministeriums für Wirtschaft und Technologie (BMWi)*. Köln, Berlin. Retrieved from Energiewirtschaftliches Institut an der Universität zu Köln (EWI) website: http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/endbericht-untersuchungen-zu-einem-zukunftsfaehigen-strommarktdesign.pdf

Elkraft. (2004). *Regulation TF3.2.6 Wind turbines connected to grids with voltages below 100 kV: Technical regulations for the propertiesand the control of wind turbines*. Official english translation. Retrieved from https://selvbetjening.preprod.energinet.dk/NR/rdonlyres/E976C1E0-BBD7-431B-ADAE-E69E02C06EA3/0/Windturbinesconnectedtogridswithvoltagesbelow100kV2004.pdf

Elkraft, & Eltra. (2004). *Regulation TF 3.2.5 Wind Turbines Connected to Grids with Voltages above 100 kV: Technical regulation for the properties and the regulation of wind turbines*. Retrieved from https://selvbetjening.preprod.energinet.dk/NR/rdonlyres/E4E7A0BA-884F-4E63-A2F0-98EB5BD8D4B4/0/WindTurbinesConnectedtoGridswithVoltageabove100kV.pdf

Energie&Management. (2015a). E&M-Direktvermarkter und Ihre Portfolios 2014. Retrieved from http://www.energie-und-management.de/uploads/media/Screenshot_Direktvermarkter.jpg

Energie&Management. (2015b). Energie und Management online. Retrieved from http://www.energie-und-management.de

Energie&Management. (2016). Die Direktvermarkter und ihre Portfolios 2015. Retrieved from http://www.energy2market.de/fileadmin/e2m/user_upload/Bilder/Downloads/EM_2016_03_Direktvermarktung.pdf

Energinet.dk. Download of market data. Retrieved from http://www.energinet.dk/en/el/engrosmarked/udtraek-af-markedsdata/Sider/default.aspx

Energy Brainpool. (2015). Fundamentalmodell Power2Sim - Energy Brainpool: Fundamentales Energiemarktmodell zur Simulation von Strompreisen. Retrieved from http://www.energybrainpool.com/analyse/fundamentalmodell-power2sim.html

EnergyMap. (2015). EnergyMap - Auf dem Weg zu 100% EE - Der Datenbestand. Retrieved from http://www.energymap.info/download.html

ENTSO-E. (2012). Regional Groups. Retrieved from https://www.entsoe.eu/system-operations/regional-groups/

ENTSO-E. (2013a). 2013 Survey on Ancillary Services Procurement and Electricity Balancing Market Design: Ancillary Services Working Group (WGAS). Retrieved from https://www.entsoe.eu/publications/position-papers/position-papers-archive/Pages/Position%20Papers/2013%20Survey-on-Ancillary-Services-Procurement-and-Electricity-Balancing-Market-Design-.aspx

ENTSO-E. (2013b). ENTSO-E Network Code on Load-Frequency Control and Reserves.

ENTSO-E. (2014). ENTSO-E Network code on Electricity Balancing: Version 3.0. Retrieved from https://www.entsoe.eu/Documents/Network%20codes%20documents/NC%20EB/140806_NCEB_Resubmission_to_ACER_v.03.PDF

ENTSO-E. (2015). Hourly load values for a specific country for a sprecific month. Retrieved from https://www.entsoe.eu/db-query/consumption/mhlv-a-specific-country-for-a-specific-month

EPEX SPOT SE. (2011). *15-minute contracts succesfully launched on German intraday market: EPEX SPOT helps to integrate renewable energy into the power system*. Paris. Retrieved from https://www.epexspot.com/document/14763/2011-12-15_15%20minute_contracts_launch.pdf

EPEX SPOT SE. (2014a). CWE FB MC project. Retrieved from http://static.epexspot.com/document/28430/Social%20Welfare%20Report_02-07%202014.pdf

EPEX SPOT SE. (2014b). EPEXDIB Digital Information Board: Prices, Volumes and statistics: The markets' core figures at a glance. Retrieved from http://www.epexspot.com/dib/

EPEX SPOT SE. (2014c). Trading. Retrieved from http://www.epexspot.com/en/product-info/Trading

EPEX SPOT SE. (2014d). *Successful launch of 15-Minute Intraday Call Auction in Germany*. Paris, Leipzig. Retrieved from https://www.epexspot.com/en/press-media/press/details/press/_Successful_launch_of_15-Minute_Intraday_Call_Auction_in_Germany

EPEX SPOT SE. (2015a). EPEX SPOT SE: Day-Ahead Auction. Retrieved from http://www.epexspot.com/en/market-data/dayaheadauction

EPEX SPOT SE. (2015b). EPEX SPOT SE: Intraday Auction. Retrieved from http://www.epexspot.com/en/market-data/intradayauction

EPEX SPOT SE. (2015c). EPEX SPOT SE: Intraday Continuous. Retrieved from http://www.epexspot.com/en/market-data/intradaycontinuous

EPEX SPOT SE. (2015d). EPEX SPOT SE: Welcome. Retrieved from http://www.epexspot.com/en/

EPEX SPOT SE. (2015e). FTP-Server Marktinformationsdaten. Retrieved from https://mis.eex.com/

EPEX SPOT SE. (2016). EPEX Spot Operational Rules. Retrieved from http://www.epexspot.com/en/extras/download-center

EPEX SPOT SE; European Commodity Clearing. (2015). *EPEX SPOT and ECC to reduce Intraday lead time on all markets: Trading up to 30 minutes before delivery – Austrian lead time decreases by 45 minutes*. Paris, Leipzig, Bern, Vienna.

Erlich, I., & Wilch, M. (2010). Primary frequency control by wind turbines: Power and Energy Society General Meeting, 2010 IEEE. *Power and Energy Society General Meeting, 2010 IEEE*, 1–8.

Ernst, B., Reyer, F., & Vanzetta, J. (2009). Wind power and photovoltaic prediction tools for balancing and grid operation: Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium. *Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium*, 1–9.

European Commission. (2009). TWENTIES Project: Transmission system operation with large penetration of wind and other renewable electricity sources in networks by means of innovative tools and and integrated energy solutions. Retrieved from http://www.twenties-project.eu

European Commission. (2010). REserviceS Project: Wind and solar PV: powerful and economic service providers for managing the future European electricity system. Retrieved from http://www.reservices-project.eu/

Directive 2009/28/EC of the European Parliament and of the Council. Official Journal of the European Union pp. 16-47 (European Parliament; European Council 2009).

Directive 96/92/EC of the European Parliament and the Council. Official Journal of the European Communities 20 (European Parliament and the Council 19.12.1996).

Faiella, M., Hennig, T., Cutululis, N., & van Hulle, F. (2013). *Capabilities and costs for ancillary services provision by wind power plants: Deliverable D 3.1.*

Ferrero, R. W., Shahidehpour, S. M., & Ramesh, V. C. (1997). Transaction analysis in deregulated power systems using game theory. *IEEE Transactions on Power Systems*, *12*(3), 1340–1347. doi:10.1109/59.630479

FGH, Consentec, & IAEW. (2012). Studie zur Ermittlung der technischen Mindesterzeugung des konventionellen Kraftwerksparks zur Gewährleistung der Systemstabilität in den deutschen Übertragungsnetzen bei hoher Einspeisung aus erneuerbaren Energien: Abschlussbericht. Retrieved from http://www.50hertz.com/Portals/3/Content/Dokumente/Presse/Publikationen/Studien/Studie-Mindesterzeugung-4TSO-20120120.pdf

FNN. (2009). TransmissionCode 2007: Anhang D2 Teil 2: Anforderungen für die Umsetzung des SRL-Poolkonzepts zwischen ÜNB und Anbietern.

Focken, U., & Schaller, M. (2011). Solutions for Optimal Trading of Wind Energy: Evaluation results and highlights for the demo case at EWE. *Workshop - "Towards Smart Integration of Wind Generation", Paris, France*.

Foley, A. M., Leahy, P. G., Marvuglia, A., & McKeogh, E. J. (2012). Current methods and advances in forecasting of wind power generation. *Renewable Energy*, *37*(1), 1–8. doi:10.1016/j.renene.2011.05.033

Forrest, S., & MacGill, I. (2013). Assessing the impact of wind generation on wholesale prices and generator dispatch in the Australian National Electricity Market. *Energy Policy*, *59*, 120–132. doi:10.1016/j.enpol.2013.02.026

Fraunhofer IWES. (2011). Begleitstudie zum Vorschlags für einen Anhang zum Transmission Code zur Präqualifikation von Windparks für die Erbringung von Minutenreserve: Studie im Auftrag der Firma Westkapital.

Fraunhofer IWES. (2015). Wind Monitor: Einspeisevergütung. Retrieved from http://windmonitor.iwes.fraunhofer.de/windmonitor_de/4_Offshore/6_foerderbedingungen/1_einspeiseverguetung/

Fraunhofer IWES, Amprion GmbH, 50Hertz Transmission GmbH, Enerparc AG, TenneT TSO GmbH, Energiequelle GmbH, & VGB PowerTech e.V. (2014). Regelenergie durch Wind und PV: ReWP. STROMNETZE Forschungsinitiative der Bundesregierung. Retrieved from http://www.energiesystemtechnik.iwes.fraunhofer.de/de/projekte/suche/laufende/rewp.html

Fraunhofer IWES, LichtBlick SE, & Volkswagen AG. (2012). Intelligente Netzanbindung von Elektrofahrzeugen zur Erbringung von Systemdienstleistungen: INEES. Retrieved from http://www.energiesystemtechnik.iwes.fraunhofer.de/de/projekte/suche/laufende/inees.html

Frunt, J., Kechroud, A., Kling, W. L., & Myrzik, J. M. A. (2009). Participation of distributed generation in balance Management. In *2009 IEEE Bucharest PowerTech (POWERTECH)* (pp. 1–6). doi:10.1109/PTC.2009.5281990

Frunt, J. (2011). *Analysis of balancing requirements in future sustainable and reliable power systems: Doctoral Thesis at the university of Eindhoven*. Enschede.

Gesino, A. J. (2011). *Power reserve provision with wind farms: Grid integration of wind power*. Kassel: Kassel University Press.

Giebel, G., Brownsword, R., Kariniotakis, G. N., Denhards, M., & Draxl, C. (2011). *Deliverable D-1.2 - The State-Of-The-Art in Short-Term Prediction of Wind Power: A Literature Overview, 2nd Edition* (No. 2). Roskilde. Retrieved from http://orbit.dtu.dk/fedora/objects/orbit:83397/datastreams/file_5277161/content

Glotzbach, T. (2010). Ein Beitrag zur mathematischen Charakterisierung von Photovoltaik-Dünnschichttechnologien auf Basis realer I/U-Kennlinien: Dissertation an der Uni Kassel.

Gottelt, F., Ziems, C., Meinke, S., Haase, T., Nocke, J., Weber, H., & HAssel, E. (2009). Auswirkungen von fluktuierenden Windenergieeinspeisung auf das regel- und thermodynamische Betriebsverhalten konventionleler Kratwerke in Deutscfhland-Bestandsaufnahme und Ableitung zukünftier Anforderungen. *Forschungsprojekt des VGB PowerTech e.V.*

Growitsch, C., Höffler, F., & Wissner, M. (2010). Marktmachtanalyse für den deutschen Regelenergiemarkt. *WIK - Diskussionsbeitrag, Bad Honnef*.

Growitsch, C., Rammerstorfer, M., & Weber, C. Redesigning the balancing power market in Germany - a critical assessment. In *2008 5th International Conference on the European Electricity Market (EEM 2008)* (pp. 1–6). doi:10.1109/EEM.2008.4579025

Grünwald, R., Ragwitz, M., Sensfuß, F., & Winkler, J. (2015). *Regenerative Energieträger zur Sicherung der Grundlast in der Stromversorgung: Endbericht zum Monitoring*. Berlin, Karlsruhe. Retrieved from TAB - Büro für Technikfolgen-Abschätzung beim deutschen Bundestag website: http://www.tab-beim-bundestag.de/de/untersuchungen/u140.html

Guerci, E., & Rastegar, M. A. (2013). Comparing system-marginal-price versus pay-as-bid auctions in a realistic electricity market scenario. In A. Teglio, S. Alfarano, E. Camacho-Cuena, & M. Ginés-Vilar (Eds.), *Lecture Notes in Economics and Mathematical Systems. Managing Market Complexity* (Vol. 662, pp. 141–153). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-31301-1_12

Hamon, C., & Söder, L. (2011). Review paper on wind power impact on operation of reserves: Energy Market (EEM), 2011 8th International Conference on the European. *Energy Market (EEM), 2011 8th International Conference on the European*, 895–903.

Haucap, J., Heimeshoff, U., & Jovanovic, D. (2012). *Competition in Germany's Minute Reserve Power Market: An Econometric Analysis: Discussion Paper* (No. 75). Düsseldorf. Retrieved from Düsseldorf Institute for Competition Economics website: http://www.dice.hhu.de/fileadmin/redaktion/Fakultaeten/Wirtschaftswissenschaftliche_Fakultaet/DICE/Discussion_Paper/075_Haucap_Heimeshoff_Jovanovic.pdf

Heath, B., Hill, R., & Ciarallo, F. (2009). A Survey of Agent-Based Modeling Practices (January 1998 to July 2008). *Journal of Artificial Societies and Social Simulation*. Retrieved from http://jasss.soc.surrey.ac.uk/12/4/9.html

Heiberger, R. M., & Neuwirth, E. (2009). Polynomial Regression. In R. M. Heiberger & E. Neuwirth (Eds.), *Use R! R through Excel. A spreadsheet interface for statistics, data analysis, and graphics* (pp. 269–284). Dordrecht, New York: Springer. doi:10.1007/978-1-4419-0052-4_11

Heim, S., & Goetz, G. (2013). *Do pay-as-bid auctions favor collusion?: Evidence from Germany's market for reserve power*. Joint Discussion Paper Series in Economics No. 24-2013 (No. 24-2013). Aachen, Gießen, Göttingen, Kassel, Marburg, Siegen. Retrieved from https://www.uni-giessen.de/faculties/f02/faculty/professorships/economics/goetz/do-pay-as-bid-auctions-favor-collusion-evidence-from-germanys-market-for-reserve-power

Hennig, T., Löwer, L., Faiella, L. M., Stock, S., Jansen, M., Hofmann, L., & Rohrig, K. (2014). Ancillary Services Analysis of an Offshore Wind Farm Cluster – Technical Integration Steps of a Simulation Tool. *Energy Procedia*, *53*, 114–123. doi:10.1016/j.egypro.2014.07.220

Hirth, L. (2013). The market value of variable renewables. *Energy Economics*, *38*, 218–236. doi:10.1016/j.eneco.2013.02.004

Hirth, L., & Ziegenhagen, I. (2015). Balancing power and variable renewables: Three links. *Renewable and Sustainable Energy Reviews*, *50*, 1035–1051. doi:10.1016/j.rser.2015.04.180

Hochloff, P., Baier, A., Ferner, F., Lesch, K., & Schlögl, F. (2010). Optimized storage operation in virtual power plants in the electricity market: 5th International Renewable Energy Storage Conference (IRES 2050), 22- 24 November 2010.

Hochloff, P., & Schreiber, M. (2012). Biogasanlagen und Speicher zur Integration erneuerbarer Energien: Beitrag auf dem 17. Kasseler Symposium 2012.

Hodge, B.-M. S., Lew, D., Milligan, M., Holttinen, H., Sillanpäa, S., Gómez-Lázaro, E. S. R.,. . . Dobschinski, J. (2012). Wind Power Forecasting Error Distributions: An International Comparison: Preprint - To be presented at The 11th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants Conference, Lisbon, Portugal, November 13–15, 2012.

Holttinen, H., Milligan, M., Ela, E., Menemenlis, N., Dobschinski, J., Bessa, R. J.,. . . Detlefson, N. (2011). Methodologies to Determine Operating Reserves due to Increased Wind Power. *IEEE PES Transactions on Sustainable Energy*.

Holttinen, H., Meibom, P., Orths, A., van Hulle, F., Lange, B., O'Malley, M.,. . . Ela, E. (2009). *Design and operation of power systems with large amounts of wind power: Final report, Phase one 2006 - 08*. IEA Wind Task 25. Espoo.

Holttinen, H., Miettinen, J., & Samuli, S. (2013). *Wind power forecasting accuracy and uncertainty in Finland*. Espoo. Retrieved from VTT website: http://www.vtt.fi/inf/pdf/technology/2013/T95.pdf

Hui Wu, & Gooi, H. B. (1999). Optimal scheduling of spinning reserve with ramp constraints. In *IEEE Power Engineering Society. 1999 Winter Meeting (Cat. No.99CH36233)* (p. 785-790 vol.2). doi:10.1109/PESW.1999.747264

Jansen, M. (2011). *Bewertung von Mechanismen zur Bepreisung von Ausgleichsenergie hinsichtlich der Systemintegration von Windenergie* (Masterthesis). Universität Flensburg / Fachhochschule Flensburg, Flensburg.

Jansen, M., Hochloff, P., Schreiber, M., Oehsen, A. von, & Peñaloza, B. (2013). TWENTIES Deliverable nº 16.4: Report on the portability of VPP concepts to Germany - Economic Impact Assessment.

Jansen, M., Schneider, D., Siefert, M., & Widdel, M. (2014). Regelenergie durch Windkraftanlagen: Proceedings of 13th Symposium Energieinnovation, 12. - 14. February 2014, Graz.

Jansen, M., & Speckmann, M. (2013a). Participation of photovoltaic systems in control reserve markets. In *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)* (p. 245). doi:10.1049/cp.2013.0631

Jansen, M., & Speckmann, M. (2013b). Wind turbine participation on Control Reserve Markets: Proceedings of EWEA Annual Event, 4 - 7 February 2013, Vienna. In European Wind Energy Association (EWEA) (Ed.), *European Wind Energy Conference & Exhibition 2013.* Red Hook, NY: Curran.

Jansen, M., Speckmann, M., & Baier, A. (2012). Impact of frequency control supply by wind turbines on balancing costs: Proceedings of EWEA Annual Event, 16 - 19 April 2012, Copenhagen.

Jansen, M., Speckmann, M., Harpe, A. von, & Hahler, M. (2013). Pool of Photovoltaic Systems delivering Control Reserve - Large scale PV systems in the German RES market scheme: Proceedings of 3rd International Workshop on Integration of Solar Power into Power Systems, 21 - 22 October 2013, London.

Jansen, M., Speckmann, M., Schneider, D., & Siefert, M. (2013). Macro Economic Evaluation of Proof Methods for the delivery of Balancing Reserve by Wind Farms - A holistic approach considering different cost effects: Proceedings of 12th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 22 - 24 October 2013, London.

Jansen, M., Speckmann, M., & Schwinn, R. (2012). Impact of control reserve provision of wind farms on regulating power costs and balancing energy prices: Proceedings of 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 13 - 15 November 2012, Lisbon.

Jansen, M. (2014). *Optimierung der Marktbedingungen für Die Regelleistungserbringung Durch Erneuerbare Energien: Kurzstudie im Auftrag des Bunderverbandes Erneuerbare Energie. e.V. und der Hannover Messe*. Kassel, Berlin. Retrieved from Fraunhofer IWES website: http://www.bee-ev.de/_downloads/publikationen/studien/2014/20140407_BEE_OptimierungderMarktbedingungenfrRegelleistungserbringungfuerErneuerbareEnergien.pdf

Jansen, M. (2016). Economics of control reserve provision by fluctuating renewable energy sources (forthcoming). In *EEM 13th International Conference on the European Energy Market. EEM15 : Porto, 6-9 Juni 2016.* Piscataway, NJ: IEEE.

Jiang Wu, Xiaohong Guan, Feng Gao, & Guoji Sun (2008). Social welfare maximization auction for electricity markets with elastic demand. In *2008 7th World Congress on Intelligent Control and Automation* (pp. 7157–7162). doi:10.1109/WCICA.2008.4594029

Johansson, P.-O. (1997). *An introduction to modern welfare economics* (Reprinted.). Cambridge: Cambridge Univ. Press.

Jónsson, T., Morales Gonzalez, J., Zogno, M., Madsen, H., & Otterson, S. (2011). Allocation and Deployment of Spinning Reserves.

Jost, D., Braun, A., & Fritz, R. (2014). Sizing control reserves with a new dynamic method considering wind and photovoltaic power forecasts. In U. Betancourt & T. Ackermann (Eds.), *Proceedings / 13th Wind Integration Workshop, International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 11 - 13 November 2014, Berlin, Germany.* Langen: Energynautics.

Jost, D., Braun, A., & Fritz, R. (2015). Dynamic Dimensioning of Frequency Restoration Reserve Capacity based on Quantile Regression. In *EEM 12th International Conference on the European Energy Market. EEM15 : Lisbon, 19-22 May 2015.* Piscataway, NJ: IEEE.

Jost, D., Braun, A., Fritz, R., Drusenbaum, C., & Rohrig, K. *Dynamische Bestimmung des Regelleistungsbedarfs: Abschlussbericht.*

Juban, J., Siebert, N., & Kariniotakis, G. N. (2007). Probabilistic Short-term Wind Power Forecasting for the Optimal Management of Wind Generation. In *2007 IEEE Power Tech* (pp. 683–688). doi:10.1109/PCT.2007.4538398

Juban, J., Fugon, L., & Kariniotakis, G. (2007). Probabilistic short-term wind power forecasting based on kernel density estimators.

Just, S. (2011). *Appropriate contract durations in the German markets for on-line reserve capacity*. EWL Working Paper No. 02/10. Duisburg, Essen. Retrieved from University of Duisburg-Essen website: https://www.wiwi.uni-due.de/fileadmin/fileupload/BWL-ENERGIE/Arbeitspapiere/RePEc/pdf/wp1002_Just_ContractDurations_2010_08_16.pdf

Just, S., & Weber, C. (2008). Pricing of reserves: Valuing system reserve capacity against spot prices in electricity markets: Technological Change and the Environment. *Energy Economics*, *30*(6), 3198–3221. doi:10.1016/j.eneco.2008.05.004

Kakimoto, N., Takayama, S., Satoh, H., & Nakamura, K. (2009). Power Modulation of Photovoltaic Generator for Frequency Control of Power System: Energy Conversion, IEEE Transactions on. *Energy Conversion, IEEE Transactions on*, *24*(4), 943–949. doi:10.1109/TEC.2009.2026616

Kalantzis, F. G., & Milonas, N. T. (2013). Analyzing the impact of futures trading on spot price volatility: Evidence from the spot electricity market in France and Germany. *Energy Economics*, *36*, 454–463. doi:10.1016/j.eneco.2012.09.017

Kapetanovic, T., Buchholz, B. M., Buchholz, B., & Buehner, V. (2008). Provision of ancillary services by dispersed generation and demand side response – needs, barriers and solutions. *e & i Elektrotechnik und Informationstechnik*, *125*(12), 452–459. doi:10.1007/s00502-008-0599-8

Kempton, W., & Tomić, J. (2005). Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *Journal of Power Sources*, *144*(1), 268–279. doi:10.1016/j.jpowsour.2004.12.025

Ketterer, J. C. (2014). The impact of wind power generation on the electricity price in Germany. *Energy Economics*, *44*, 270–280. doi:10.1016/j.eneco.2014.04.003

Khorasani, J., & Rajabi Mashhadi, H. (2012). Bidding analysis in joint energy and spinning reserve markets based on pay-as-bid pricing. *IET Generation, Transmission & Distribution*, *6*(1), 79. doi:10.1049/iet-gtd.2011.0317

Kian, A., & Keyhani, A. (2001). Stochastic price modeling of electricity in deregulated energy markets. In *Hawaii International Conference on System Sciences. HICSS-34* (p. 7). doi:10.1109/HICSS.2001.926292

Kindler, D. (2011). 20 Months of Wind Data from the FINO3 Meteorological Mast. In GL Garrad Hassan (Ed.), *FINO Conference 2011.* Retrieved from http://www.gl-garradhassan.com/FINO_2011_Session3_04_Kindler.pdf

Kirby, B., Milligan, M., & Ela, E. (2010). Providing Minute-to-Minute Regulation from Wind Plants: Preprint.

Knorr, K., Zimmermann, B., Kirchner, D., Speckmann, M., Spieckermann, R., Widdel, M.,. . . Ritter, P. (2014). *Kombikraftwerk 2 - Abschlussbericht*. Kassel, Hannover. Retrieved from http://www.kombikraftwerk.de/

Konstantin, P. (2009). *Praxisbuch Energiewirtschaft: Energieumwandlung, -transport und -beschaffung im liberalisierten Strommarkt* (2. bearbeitete und aktualisierte Auflage). Berlin Heidelberg: Springer.

Köpke, R. (2014). Windmüller fahren auf Direktvermarktung ab: E&M powernews. Retrieved from http://www.energie-und-management.de/?id=84&no_cache=1&terminID=103442

Koritarov, V. (2004). Real-world market representation with agents. *IEEE Power and Energy Magazine*, *2*(4), 39–46. doi:10.1109/MPAE.2004.1310872

Kost, C., Mayer, J., Thomsen, J., Hartmann, N., Senkpiel, C., Phillips, S.,. . . Schlegl, T. (2013). *Stromgestehungskosten Erneuerbare Energien: Version November 2013*. Freiburg. Retrieved from Fraunhofer ISE website: https://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-stromgestehungskosten-erneuerbare-energien.pdf

Kristan, M., Leonardis, A., & Skočaj, D. (2011). Multivariate online kernel density estimation with Gaussian kernels. *Pattern Recognition*, *44*(10-11), 2630–2642. doi:10.1016/j.patcog.2011.03.019

Kumar David, A., & Fushuan Wen. (2001). Market power in electricity supply. *IEEE Transactions on Energy Conversion*, *16*(4), 352–360. doi:10.1109/60.969475

Kurscheid, E. (2009). Zur Bereitstellung positiver Minutenreserve durch dezentrale KWK-Anlagen: Doktorarbeit an der TU Chemnitz.

Lange, A., Rostankowski, A., Richts, C., Holzhammer, U., Gerhardt, N., Klobasa, M.,. . . Lehnert, W. (2014). *Regelleistungsbereitstellung von Erneuerbaren Energien in der Direktvermarktung: Auswirkungen, Potenziale und Weiterentwicklung*. im Rahmen des Projektes Laufende Evaluierung der Direktvermarktung von Strom aus erneuerbaren Energien. Berlin.

Lange, B., Rohrig, K., Dobschinski, J., Wessel, A., Saint-Drenan, Y.-M., & Felder, M. (2011). Prognosen der zeitlich-räumlichen Variabilität von Erneuerbaren. *Transformationsforschung für ein nachhaltiges Energiesystem - Beiträge zur FVEE*, 93–101.

Li, T., & Shahidehpour, M. (2005). Price-Based Unit Commitment: A Case of Lagrangian Relaxation Versus Mixed Integer Programming. *IEEE Transactions on Power Systems*, *20*(4), 2015–2025. doi:10.1109/TPWRS.2005.857391

LichtBlick SE. (2014). *Entwicklung und Bereitstellung von Sekundärregelleistung durch intelligente Steuerung von ZuhauseKraftwerken - Abschlussbericht*. Retrieved from https://www.lichtblick.de/pdf/info/schwarmenergie/BMWI0325393Abschlussbericht.pdf

LichtBlick SE. (2015). *Medienmitteilung: SchwarmStrom für einen stabilen Puls im Stromnetz: LichtBlick liefert Regelenergie aus Mini-Kraftwerken*. Hambrug. Retrieved from http://www.lichtblick.de/medien/news/?detail=327&type=press

Liebau, B. (2012). *Der deutsche Strommarkt: Marktdesign und Anbieterverhalten* (1. Aufl.). *MV Wissenschaft: Vol. 5*. Münster: Verl.-Haus Monsenstein und Vannerdat.

London Economics. (2013). *The Value of Lost Load (VoLL) for Electricity in Great Britain: Final report for OFGEM and DECC*. Retrieved from London Economics; Ofgem; DECC website: https://www.ofgem.gov.uk/ofgem-publications/82293/london-economics-value-lost-load-electricity-gb.pdf

Lorenz, C., & Gerbaulet, C. (2015). *Entwicklung des Regelleistungsmarktes in Deutschland bis 2025: Strommarkttreffen 14.08.2015*. Berlin. Retrieved from TU Berlin, Workgroup for Infrastructure Policy; DIW Berlin, Department of Energy, Transportation, Environment website: http://www.strommarkttreffen.org/2015-8-Lorenz-Regelleistung.pdf

Macal, C. M., & North, M. J. (2010). Tutorial on agent-based modelling and simulation. *Journal of Simulation*, *4*(3), 151–162. doi:10.1057/jos.2010.3

Margaris, I. D., Papathanassiou, S. A., Hatziargyriou, N. D., Hansen, A. D., & Sørensen, P. (2012). Frequency Control in Autonomous Power Systems With High Wind Power Penetration: Sustainable Energy, IEEE Transactions on. *Sustainable Energy, IEEE Transactions on*, *3*(2), 189–199. doi:10.1109/TSTE.2011.2174660

Matos, M. A., & Bessa, R. J. (2011). Setting the Operating Reserve Using Probabilistic Wind Power Forecasts: Power Systems, IEEE Transactions on. *Power Systems, IEEE Transactions on*, *26*(2), 594–603.

Maurer, C., Krahl, S., & Weber, H. (2009). Dimensioning of secondary and tertiary control reserve by probabilistic methods. *European Transactions on Electrical Power*, *19*(4), 544–552. doi:10.1002/etep.326

Michetti, E. (2012). European Energy Markets Transparency Report - 2012 EDITION. Retrieved from http://cadmus.eui.eu/bitstream/handle/1814/24516/ETA_Report.pdf?sequence=1

Morales, J. M., Conejo, A. J., & Perez-Ruiz, J. (2010). Short-Term Trading for a Wind Power Producer. *IEEE Transactions on Power Systems*, *25*(1), 554–564. doi:10.1109/TPWRS.2009.2036810

Morren, J., Haan, S. de, Kling, W. L., & Ferreira, J. A. (2006). Wind Turbines Emulating Inertia and Supporting Primary Frequency Control. *IEEE Transactions on Power Systems*, *21*(1), 433–434. doi:10.1109/TPWRS.2005.861956

Müller, L. (2011, November). *Kooperation bei der Regelenergie - Einführung des Netzregelverbund und weitere Perspektiven: Vortrag auf IQPC Konferenz "Zukunftsperspektiven für den Regelenergiemarkt Strom"*, Berlin.

Müller, M., Sensfuß, F., & Wietschel, M. (2007). Simulation of current pricing-tendencies in the German electricity market for private consumption. *Energy Policy*, *35*(8), 4283–4294. doi:10.1016/j.enpol.2007.02.032

National Grid Electricity Transmission plc. (2012). THE GRID CODE: Issue 4 Revision 11. 16th March 2012. Retrieved from http://www.nationalgrid.com/NR/rdonlyres/67374C36-1635-42E8-A2B8-B7B8B9AF2408/52340/Z_CompleteGridCode_I4R11.pdf

Nicolosi, M. (2010). Wind power integration and power system flexibility–An empirical analysis of extreme events in Germany under the new negative price regime. *Energy Policy*, *38*(11), 7257–7268. doi:10.1016/j.enpol.2010.08.002

Nitsch J., Pregger, T., Naegler, T., Heide D., Luca de Tena, D., Trieb, F., Scholz, Y.,. . . Wenzel, B. (2012). EE-Langfristszenarien 2011: Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. Schlussbericht BMU - FKZ 03MAP146.

North, M., Conzelmann, G., Koritarov, V., North, Macal, Charles, Thimmaouram, P., & Veselka, T. (2002). *E-Laboratories: Agent-based moldeling of Electricity MarketsMARKETS*. For submission to 2002 American Power Conference. Argonne, IL. Retrieved from Center for Energy, Environmental, and Economic Systems Analysis (CEEESA) website: http://www.researchgate.net/profile/Vladimir_Koritarov/publication/228605359_E-laboratories_agent-based_modeling_of_electricity_markets/links/0deec524c3d61ae0cc000000.pdf

Oehsen, A. von. (2012). *Entwicklung und Anwendung einer Kraftwerks- und Speicherinsatzoptimierung für die Untersuchung von Energieversorgungsszenarien mit hohem Anteil erneuerbarer Energieversorgungsszenarien mit hohem Anteil erneuerbarer Energien in Deutschland: Dissertation zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften (Dr. -Ing.) im Fachbereich Elektrotechnik/Informatik der Universität Kassel*. Retrieved from http://d-nb.info/1038379601/34

Okou, A. F., Akhri, O., Beguenane, R., & Tarbouchi, M. (2012). Nonlinear control strategy insuring contribution of PV generator to voltage and frequency regulation. In *6th IET International Conference on : Power Electronics, Machines and Drives (PEMD 2012)* (pp. 1–5). doi:10.1049/cp.2012.0332

Oren, S. (2004). When is a pay-as bid preferable to uniform price in electricity markets: Power Systems Conference and Exposition, 2004. IEEE PES. *Power Systems Conference and Exposition, 2004. IEEE PES*, 1618-1620 vol.3.

Pachauri, R. K., & Mayer, L. (2014). *Climate change 2014: Synthesis report.*

Padhy, N. P. (2004). Unit Commitment - A Bibliographical Survey. *IEEE Transactions on Power Systems*, *19*(2), 1196–1205. doi:10.1109/TPWRS.2003.821611

Papaefthymiou, G., van Doorn, J., Kakorin, A., van der Meijden, Mart, Laurisch, L., Meulenbroeks, J.-W., & Nabe, C. (2015). Future provision of control reserve from offshore wind farms: An analysis of benefits and barriers. In *2015 12th International Conference on the European Energy Market (EEM)* (pp. 1–5). doi:10.1109/EEM.2015.7216710

Papula, L. (2009). *Mathematische Formelsammlung für Ingenieure und Naturwissenschaftler: 10. Auflage*. Wiesbaden: Vieweg + Teubner.

Pigou, A. C. (1920). *The economics of welfare*. London: MacMillan.

Ping-Kwan Keung, Pei Li, Banakar, H., & Boon Teck Ooi. (2009). Kinetic Energy of Wind-Turbine Generators for System Frequency Support: Power Systems, IEEE Transactions on. *Power Systems, IEEE Transactions on*, *24*(1), 279–287.

Pinson, P. (2006). *Estimation of the uncertainty in wind power forecasting: These pour obtenir le grade de Docteur de l`Ecole des Mines de Paris - Spécialité "Energétique"*. Disseration.

Pinson, P., Chevallier, C., & Kariniotakis, G. N. (2007). Trading Wind Generation From Short-Term Probabilistic Forecasts of Wind Power. *IEEE Transactions on Power Systems*, *22*(3), 1148–1156. doi:10.1109/TPWRS.2007.901117

Pinson, P., & Madsen, H. (2009). Ensemble-based probabilistic forecasting at Horns Rev. *Wind Energy*, *12*(2), 137–155. doi:10.1002/we.309

Power2Energy. (2013). IntradayS Market Aufnahmeunterlagen. Retrieved from http://www.power2energy.eu/ism/start/100/ISM-Aufnahmeunterlagen-131015d.pdf

Quaschning, V. (2015). Vergütung für Strom aus Photovoltaikanlagen nach dem Erneuerbare-Energien-Gesetz (EEG). Retrieved from http://www.volker-quaschning.de/datserv/EEG-PV/index.php

Ramakrishnan Kirshna, S. (2009) USA 2012/0078518 A1. USA.

Ravnaas, K. W., Farahmand, H., & Doorman, G. (2010). Optimal wind farm bids under different balancing market arrangements: Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference on. *Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference on*, 30–35.

Rebours, Y. G., Kirschen, D. S., Trotignon, M., & Rossignol, S. (2007a). A Survey of Frequency and Voltage Control Ancillary Services—Part I: Technical Features: Power Systems, IEEE Transactions on. *Power Systems, IEEE Transactions on*, *22*(1), 350–357.

Rebours, Y. G., Kirschen, D. S., Trotignon, M., & Rossignol, S. (2007b). A Survey of Frequency and Voltage Control Ancillary Services—Part II: Economic Features: Power Systems, IEEE Transactions on. *Power Systems, IEEE Transactions on*, *22*(1), 358–366.

Richter, J. (2012). *On the interaction between product markets and markets for production capacity: The case of the electricity industry: EWI Working Paper No 11/09*. Köln.

Rivero, E., Barquin, J., & Rouco, L. (2011). European balancing markets: Energy Market (EEM), 2011 8th International Conference on the European. *Energy Market (EEM), 2011 8th International Conference on the European*, 333–338.

Robèrt, M. (2005). Backcasting and econometrics for sustainable planning. *Journal of Cleaner Production*, *13*(8), 841–851. doi:10.1016/j.jclepro.2003.12.028

Rohrig, K., Richts, C., Bofinger, S., Jansen, M., Siefert, M., Pfaffel, S., & Durstewitz, M. (2013). *Energiewirtschaftliche Bedeutung der Offshore-Windenergie für die Energiewende: Langfassung*. Kassel. Retrieved from Fraunhofer IWES website: http://www.offshore-stiftung.com/60005/Uploaded/SOW_Download|Langfassung-EnergiewirtschaftlicheBedeutungderOffshore-Windenergie.pdf

Ruiz, P. A., Philbrick, C. R., & Sauer, P. W. (2009). Wind power day-ahead uncertainty management through stochastic unit commitment policies: Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES. *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, 1–9. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4840133

Saiz-Marin, E., Lobato, E., & Linares, P. (2012). Optimal Band Provision by Wind Generation in the Spanish Secondary Regulation Market: Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific, 27-29 March 2012, Shanghai.

Saiz-Marin, E., Garcia-Gonzalez, J., Barquin, J., & Lobato, E. (2012). Economic Assessment of the Participation of Wind Generation in the Secondary Regulation Market. *IEEE Transactions on Power Systems*, *27*(2), 866–874. doi:10.1109/TPWRS.2011.2178618

Saravanan, B., Das, S., Sikri, S., & Kothari, D. P. (2013). A solution to the unit commitment problem—a review. *Frontiers in Energy*, *7*(2), 223–236. doi:10.1007/s11708-013-0240-3

Schäfer-Stradowsky, S., Gerhardt, N., Holzhammer, U., Richts, C., Stelzer, M., Klobasa, M.,. . . Lehnert, W. (2014). *10. Quartalsbericht Laufende Evaluierung der Direktvermarktung von Strom aus Erneuerbaren Energien: Stand 08/2014: Monitoring - Erstellt im Auftrag des Bundesministeriums für Wirtschaft und Energie*. Berlin.

Schaich, A. (2010). Die Bereitstellung negativer Minutenreserve durch Windenergieanlagen: Eine anwendungsorientierte Analyse.

Schneider, D., Kaminski, K., Siefert, M., & Speckmann, M. (2013). Available Active Power Estimation for the Provision of Control Reserve by Wind Turbines: EWEA 2013, Vienna, 4.2. - 7.2.2013. In European Wind Energy Association (EWEA) (Ed.), *European Wind Energy Conference & Exhibition 2013.* Red Hook, NY: Curran.

Schneider, D., Tietz, S., Siefert, M., & Speckmann, M. (2013). Available Active Power Estimation of Wind Power Plants with 3-Second Data. In U. Betancourt & T. Ackermann (Eds.), *Proceedings / 12th Wind Integration Workshop, International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 22 - 24 October 2013, London, UK* (pp. 1–5). Langen: Energynautics. Retrieved from http://publica.fraunhofer.de/documents/N-360057.html

Schuller, A., & Rieger, F. (2013). Assessing the Economic Potential of Electric Vehicles to Provide Ancillary Services: The Case of Germany. *Zeitschrift für Energiewirtschaft*, *37*(3), 177–194. doi:10.1007/s12398-013-0112-x

Schulz, C. (2011). Aktuelle und Zukünftige Anforderungen an EEG-Einspeiseprognosen: Netzführungskonzepte. Retrieved from https://www.uni-oldenburg.de/fileadmin/user_upload/physik/ag/ehf/enmet/download/proc/A01_Schulz_EEG.pdf

Schwinn, R. (2011). Vorschläge zur Anpassung der deutschen Regelleistungsmärkte zur verbesserten Teilnahme Erneuerbarer Energien: Masterarbeit an der Universität Kassel.

Sensfuß, F., Ragwitz, M., & Genoese, M. (2007). The Merit-Order Effect: A Detailed Analyis of the Price Effect of Renewable Electricity Generation on Spot Market Prices in Germany. Retrieved from http://www.isi.fraunhofer.de/publ/downloads/isi07a18/merit-order-effect.pdf

Sensfuß, F. (2010). *Analysen zum Merit-Order Effekt erneuerbarer Energien - Update für das Jahr 2010.*

Shafiei, E., Thorkelsson, H., Ásgeirsson, E. I., Davidsdottir, B., Raberto, M., & Stefansson, H. (2012). An agent-based modeling approach to predict the evolution of market share of electric vehicles: A case study from Iceland. *Technological Forecasting and Social Change*, *79*(9), 1638–1653. doi:10.1016/j.techfore.2012.05.011

Shahidehpour, M., Yamin, H., & Li, Z. (2002). *Market operations in electric power systems: Forecasting, scheduling, and risk management*. [New York]: Institute of Electrical and Electronics Engineers, Wiley-Interscience.

SMA, TU Braunschweig, & GEWI AG. (2015). PV Regel: Forschung Stromnetze: Regelleistung mit PV-Anlagen für stabilen Netzbetrieb. Retrieved from http://forschung-stromnetze.info/projekte/regelleistung-mit-pv-anlagen-fuer-stabilen-netzbetrieb/

Son, Y. S., Baldick, R., Lee, K.-H., & Siddiqi, S. (2004). Short-Term Electricity Market Auction Game Analysis: Uniform and Pay-as-Bid Pricing. *IEEE Transactions on Power Systems*, *19*(4), 1990–1998. doi:10.1109/TPWRS.2004.836192

Speckmann, M. (2016). *Bereitstellung von Regelleistung durch fluktuierende Erzeuger am Beispiel der Windenergie* (1. Auflage). *Schriftenreihe des Energie-Forschungszentrums Niedersachsen (EFZN): Vol. 35*. Göttingen, Niedersachsen: Cuvillier, E.

Speckmann, M., & Baier, A. (2011). Provision of Frequency Control by Wind Farms: 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants; 25 - 26.10.2011.

Spitalny, L., Unger, D., & Myrzik, J. M. A. (2012). Potential of small hydro power plants for delivering control energy in Germany. In *Energytech, 2012 IEEE : Energytech, 2012 IEEE : Energytech, 2012 IEEE* (pp. 1–6). doi:10.1109/EnergyTech.2012.6304700

Statkraft Markets GmbH. (2015). *Press information: Statkraft succeeds in delivering tertiary reserve from wind power plant*. Essen. Retrieved from http://www.statkraft.de/presse/Pressemitteilungen/20151/Statkraft-liefert-erstmals-Minutenreserve-aus-windkraft/

Sterner, M., Gerhardt, N., Saint-Drenan, Y.-M., Oehsen, A. von, Hochloff, P., Kocmajewski, M.,. . . Rohrig, K. (2010). *Energiewirtschaftliche Bewertung von Pumpspeicherwerken und anderen Speichern im zukünftigen Stromversorgungssystem: Endbericht*. Laufenburg, Kassel.

Stobrawe, M. (2012). Activiation of tertiray control reserve when 60% of secondary control reserve is actived (oral).

Stromnetze. (2015). Forschung Stromnetze: Regelleistung durch Wind- und Photovoltaikparks. Retrieved from http://forschung-stromnetze.info/projekte/regelleistung-durch-wind-und-photovoltaikparks/

Swider, D. J. (2005a). Sequential Bidding in Day-Ahead Auctions for Spot Energy and Power Systems Reserve.

Swider, D. J. (2005b). Simultaneous bidding on day-ahead auction markets for spot energy and power systems reserve: Proceedings 15th Power Systems Computation Conference (PSCC) 2005.

Swider, D. J., & Weber, C. (2007). Bidding under price uncertainty in multi-unit pay-as-bid procurement auctions for power systems reserve. *European Journal of Operational Research*, *181*(3), 1297–1308. doi:10.1016/j.ejor.2005.11.046

TenneT TSO GmbH. (2015). Actual and forecast wind energy feed-in - TenneT TSO GmbH. Retrieved from http://www.tennettso.de/site/en/Transparency/publications/network-figures/actual-and-forecast-wind-energy-feed-in

Tesfatsion, L., & Judd, K. L. (2006). *Handbook of computational economics*. *Handbooks in economics: Vol. 13*. Amsterdam, New York: Elsevier.

Tuohy, A., Brooks, D., Ela, E., & Kirby, B. (2012). Provision of Regulating Reserve from Wind Power - Economic Benefits and Steady State System Operation Implications: Proceedings of 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 13 - 15 November 2012, Lisbon.

UCTE. (2009). Policy 1: Load-Frequency Control and Performance: UCTE Operation Handbook.

Veit, D. J., Weidlich, A., & Krafft, J. A. (2009). An agent-based analysis of the German electricity market with transmission capacity constraints. *Energy Policy*, *37*(10), 4132–4144. doi:10.1016/j.enpol.2009.05.023

Ventosa, M., Baíllo, Á., Ramos, A., & Rivier, M. (2005). Electricity market modeling trends. *Energy Policy*, *33*(7), 897–913. doi:10.1016/j.enpol.2003.10.013

Walck, C. (2007). Hand-book on STATISTICAL DISTRIBUTIONS for experimentalists. Retrieved from http://www.fysik.su.se/~walck/suf9601.pdf

Wassermann, S., Reeg, M., & Nienhaus, K. (2015). Current challenges of Germany's energy transition project and competing strategies of challengers and incumbents: The case of direct marketing of electricity from renewable energy sources. *Energy Policy*, *76*, 66–75. doi:10.1016/j.enpol.2014.10.013

Waver, T. (2007). Förderung erneuerbarer Energien im liberalisierten deutschen Strommarkt: Dissertation an der Universität Münster.

Weber, C. (2010). Adequate intraday market design to enable the integration of wind energy into the European power systems: Large-scale wind power in electricity markets with Regular Papers. *Energy Policy*, *38*(7), 3155–3163. doi:10.1016/j.enpol.2009.07.040

Weidhas, G. (2012, June). *Vom deutschen Netzregelverbund zur International Grid Control Cooperation (IGCC): Die Integration der niederländischen TenneT und der Energinet.dk*. Regelenergiemarkt Strom 2012, Berlin. Retrieved from http://www.inform-you.de/Referentenbeitrag.aspx?id=301954&code=P1105338

Weidlich, A., & Veit, D. (2008). A critical survey of agent-based wholesale electricity market models. *Energy Economics*, *30*(4), 1728–1759. doi:10.1016/j.eneco.2008.01.003

Weißbach, T. (2009). Verbesserung des Kraftwerks- und Netzregelverhaltens bezüglich handelsseitiger Fahrplansprünge: Doktorarbeit an der Universität Stuttgart.

Weron, R. (2006). *Modeling and forecasting electricity loads and prices: A statistical approach*. *Wiley finance series*. Chichester, England, Hoboken, NJ: John Wiley & Sons.

Wingenbach, C. (2011). *Präqualifikation von Windenergieanlagen für die Erbringung negativer Minutenreserve. Bachelor-Thesis an der FH Flensburg* (Bachelor-Thesis). Fachhochschule Flensburg, Flensburg.

Wissel, S., Fahl, U., Blesl, M., & Voß, A. (2010). *Erzeugungskosten zur Bereitstellung elektrischer Energie von Kraftwerksoptionen in 2015*. Retrieved from Universität Stuttgart; Institut für Energiewirtschaft und Rationelle Energieanwendung website: http://www.ier.uni-stuttgart.de/publikationen/arbeitsberichte/downloads/Arbeitsbericht_08.pdf

Wright, B. (2013). *A Review of Unit Commitment*. New York. Retrieved from Department of Electrical Engineering - Columbia University website: http://www.ee.columbia.edu/~lavaei/Projects/Brittany_Wright.pdf

www.solaranlagen-portal.com. Einspeisevergütung für Photovoltaik Anlagen 2015. Retrieved from http://www.solaranlagen-portal.com/photovoltaik/wirtschaftlichkeit/einspeiseverguetung

Yuen, C., Oudalov, A., & Timbus, A. (2011). The Provision of Frequency Control Reserves From Multiple Microgrids: Industrial Electronics, IEEE Transactions on. *Industrial Electronics, IEEE Transactions on*, *58*(1), 173–183.

Zhang, Z.-S., Sun, Y.-Z., & Cheng, L. (2013). Potential of trading wind power as regulation services in the California short-term electricity market. *Energy Policy*. (0). doi:10.1016/j.enpol.2013.04.056

Zugno, M., Pinson, P., & Jónsson, T. (2010). Trading wind energy based on probabilistic forecasts of wind generation and market quantities.

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List of acronyms and abbreviations

AAP	Available active power
AB	Agent-based, describes an out-of-equilibrium modelling approach which uses behavioural patterns of agents
ACE	Area Control Error
ACER	European Agency for the Corporation of Energy Regulators
ACT	Actual feed-in
AS	Ancillary Services
Balancing Energy	Energy that is exchanged by the BRP with the TSO due to deviations between the schedule and actual production/consumption
Balancing Group	A balancing group consists of several grid connection points within one control area and pools their feed-in respectively withdrawal. A balancing group is managed by its BRP.
Base	All day, sum of Peak and Off-Peak
BMWi	Federal ministry of economics and energy
BNetzA	Bundesnetzagentur (English: Federal network agency)
BRP	The Balance Responsible Party is responsible for forecasting and balancing the generation and consumption of one or more balancing group as well as the exchange of energy with other balancing groups
CDF	Cumulative distribution function
CHP	Combined Heat and Power; Cogeneration of heat and power
Control Area	Part of the transmission system that is operated by a single TSO
Control Block	Several control areas
CR	Control reserve
DAFC	Day-ahead forecast

Dispatch	Activation of units for the delivery of energy
EEX	European Energy Exchange. Facilitates the trading of futures and options for the German/Austrian market area
ENTSO-E	European Network of Transmission System Operators
EPEX SPOT	Market operator for the German/Austrian market area for day-ahead and intraday markets
Exchange	Electricity trading place for the exchange members
FIT	Feed-in Tariff
Fluctuating RES	RES which fluctuate feed-in according to environmental variables. Usually covers onshore wind, offshore wind, and photovoltaic systems. May also cover run-off hydro or tidal technologies.
GCC	Grid control cooperation
GW	Giga watts
ICT	Information and communications technology
IDFC	Intraday forecast (shortest-term forecast with one hour lead time)
IGCC	International grid control cooperation
KDE	Kernel density estimator
LOWESS	Locally weighted scatterplot smoothing
LOESS	Locally weighted regression
MaBiS	Market rules for balancing group billing in the area of electricity (Marktregeln für die Durchführung der Bilanzkreisabrechnung Strom)
Market Coupling	Connection of two or more market areas for joint operation
MO	Merit-order
MOL	Merit-order list
MOLS	MOL-Server
MW	Megawatt
MWh	Megawatt hour

n-1	Compensation for the outage of the largest unit in the system
n-2	see n-1
Off-peak	Hours between 20:00 and 08:00 from Monday to Saturday and for the entire day on Sundays and public holidays
OTC	Over-the-counter, opposite to exchange trade products
Peak	Hours between 08:00 and 20:00, excluding Sundays and public holidays
PCR	Primary control reserve
PDF	Probability density function
PHELIX	Physical electricity index, also the name for futures and options traded on EEX
Pool	Various numbers of units connected through ICT which are marketed together
p.u.	Per unit
reBAP	unique and common balancing energy price for the four German control areas (regelzonenübergreifender einheitlicher Bilanzausgleichsenergiepreis)
REMIT	Regulation on Wholesale Energy Market Integrity and Transparency
RES	Renewable Energy Sources
Residual Load	Remaining load after the inclusion of fluctuating RES (Residual Load = Load – feed-in fluctuating RES)
SCR	Secondary control reserve
SLP	Standard Load Profile; analytic load curve for non-measured load
TCR	Tertiary control reserve
Trading Day	Day on which energy is traded on the exchange. Differs between different exchanges
TSO	Transmission System Operator - Company that is responsible for operating the transmission system for a control area

UC	Unit commitment, describes an optimization technique to obtain equilibrium based results for the power system modelling
UCTE	Union for the Co-ordination of Transmission of Electricity – predecessor of the ENTSO-E regional group of Continental Europe
VoLL	Value of lost load
VPP	Virtual Power Plant; Software solution for the aggregation of different decentralized units
Week-daily	Days from Monday to Friday

Previous publications by the author

The topic was conceived and first results presented in previous publications. For the publications known algorithms were used to calculate probabilistic forecasts which were provided by the co-authors and were derived from the literature review. The implementation of the algorithms into the bid creation for the control reserve markets was performed by the main author. The bid creation and economic impact assessment has not been carried out before for wind turbines and PV systems. The ability to assess the economic impact from the suppliers' point of view and the system's point of view is a novelty. The new method to prove the delivery of control reserve was not developed by the author. However it was used by the author to create bids for the control reserve market.

The first publication on the methodology was presented at the **EWEA Annual Event 2012** in Copenhagen (Jansen, Speckmann, & Baier, 2012). The conference paper includes the presentation of different proof methods previously presented by Speckmann and Baier (Speckmann & Baier, 2011), and demonstrates the basic bidding principles on the German control reserve market that a wind farm has to face. The creation of bids for the control reserve markets using a kernel density estimator are shown for the first time in a scientific environment. The data used was for the entire German wind portfolio. The installed capacity was set to be 30 GW. This value is kept in later papers in order to ensure comparability between them. This paper shows how the individual bids are placed in a market environment and how the economic benefits are calculated. The results of this methodology are presented for data from July 2010 to December 2010. The results show a significant cost reduction potential of more than 20 % of the control reserve costs in the secondary or tertiary control reserve market with a reliability of 99.99 %. The results also show the economic advantages of the new proof method for the delivery of control reserve, presented in (Speckmann & Baier, 2011). In this publication the author presents a methodology which is implemented as a Matlab model, later to be named as the REBal (Renewable

Energy Balancing) model. The publication was designed and written by the author in dialogue with the co-authors, the calculation was carried out by the main author alone.

At the **Wind Integration Workshop 2012** in Lisbon (Jansen, Speckmann, & Schwinn, 2012) the author first presented an improved version of the Matlab model. The model has been expanded to assess the economic impact for the balance responsible parties more precisely by calculating the anticipated changes in the balancing settlement price, which is induced by the participation of wind farms in the control reserve markets. For a reliability of 99.99 % the balancing settlement prices could decrease on average by as much as 12.23 EUR/MWh on average. In addition to the previous paper this publication expands the level of security to 99.999 % and assesses the economic effects of a wind farm pool with an installed capacity of 1 GW. The results at this stage have also been published in the Deliverable 16.4 of the EU Framework 7 project TWENTIES (Jansen, Hochloff et al., 2013).

At the **EWEA Annual Event 2013** in Vienna (Jansen et al., 2014) the paper presented the concept of the calculation of the available active power which is used in the new proof method (Speckmann & Baier, 2011). The calculation of the available active power is based on data with a 10 minute time resolution and produces about the same error as the production error of a conventional power plant. The time period of ten minutes would not be short enough for the delivery of control reserve. Detailed results of the calculation can be seen in (Schneider, Tietz et al., 2013). In this publication a more precise calculation of the probabilistic forecasts is introduced into the model, allowing the inclusion of pre-errors into the probabilistic intraday-forecast. This paper states that the level of reliability of the offer should be at least 99.994 % to ensure that the reliability is not declining as a result of the inclusion of wind farms in the control reserve market.

The paper on the **22nd International Conference on Electricity Distribution** (Jansen & Speckmann, 2013a) showed how PV systems could deliver control reserve, using the knowledge gained from wind farms (Jansen et al., 2014). The methodology is transferred to apply to PV systems. The potentials are calculated for the entire German portfolio of PV systems using the kernel density estimator. The installed capacity is set to be 30 GW to ensure comparability. This paper includes the calculation of the available active power signal for a real PV system, using real data with a time resolution of one second. It was proven that the available active power can be calculated with high precision. The macro- and micro economic potential is much smaller compared to the wind farms, due to fewer full load hours and feed-in tariffs.

The paper presented at the **Solar Integration Workshop 2013** in London (Jansen, Speckmann, Harpe et al., 2013) presents the potentials of a real portfolio of PV systems for the time between the 1st of November 2012 and the 31st of May 2013. The data were derived from a growing portfolio of PV systems. The portfolio has 39 PV systems, representing 400 MW of installed capacity. The data was merged and normalized to make it comparable over the assessment period. It is in this paper that the model is first named as the REBal (Renewable Energy Balancing) model.

At the **Wind Integration Workshop 2013** in London (Jansen, Speckmann, Schneider et al., 2013) a paper was presented that examines the economic differences between the current implementation of the proof mechanism to the delivery of control reserve and the newly proposed proof mechanism presented in (Speckmann & Baier, 2011). The paper presents a comparison between three different criteria. A first criterion is the assessment of the impact on the procurement costs. According to the analysis in the paper the procurement costs of control reserve will decrease with the participation of wind energy. The proof method using the available active power signal will reduce procurement costs much more than they would be reduced with the conventional method applied. Control reserve can be offered at lower opportunity costs by the market participants, assuming the available active power proof method is applied. This leads to lower costs for the procurement of control reserve by the TSO. The main reason why control reserve can be provided more economically with the available active power proof method applied is the fact that the wind turbines do not need to be curtailed under this scheme. The second criterion is the amount of volatility introduced into the system. The available active power proof method induces more volatility in the system than the conventional proof method. Wind farms are not forced to be curtailed to their schedule and therefore fluctuate more. This leads to more volatility in the power system. With the conventional proof method applied these fluctuations are much smaller. In order to evaluate this effect, an assessment is undertaken into how much more control reserve is needed in a system with these fluctuations. With the conventional proof method applied the energy production is less volatile and therefore needs less control reserve to balance these fluctuations. Less control reserve leads to smaller procurement costs for the Transmission System Operators (TSOs). The dimensioning developed for the project "Dynamische Bestimmung des Regelleistungsbedarfs im Stromnetz" was used by Dominik Jost to assess the reduction in the demand for control reserve. In order to assess the economic effects it was assumed that the decreased demand leads to shortened control reserve merit-order lists. The now redundant bids from the original merit-order lists can be seen in the decrease in procurement costs. The reduction of volatility only happens with the conventional proof method applied. For the available active power proof method no changes in the system's volatility is assumed, since wind farms do not change their production pattern compared to the current situation. The last criterion is the reduction of wind energy available in the market when the conventional proof method is applied. This is for the reason that a part of the wind energy production is curtailed. This curtailed energy has to be replaced by other sources. To evaluate these replacement costs two approaches have been used. One takes into account average fuel costs, the other one the prices that would have to be paid on the EPEX Spot market. Both show that the curtailed energy is of significant economic value. The overall results using the three criteria are that the usage of the new proof method with the available active power will decrease system costs greatly whilst ensuring economic benefits for the market participants.

The results for wind energy from the previously presented paper are also published in the project report for "**Regelenergie durch Windkraftanlagen**". These results, amongst other results from the project, have been disseminated at the **Symposium Energieinnovationen 2014** in Graz (Jansen et al., 2014).

The methodology presented has been adapted to assess the economic potentials provided in different scenarios with offshore wind energy in the study „Energiewirtschaftliche Bedeutung der Offshore-Windenergie“ (English: energy-economic relevance of offshore wind energy) for the **German Offshore Wind Foundation** (Rohrig et al., 2013). It was possible to show that offshore wind farms are capable of providing control reserve with high reliability at many more full load hours than onshore wind, not taking into account the constraints given by the lack of n-1 grid security.

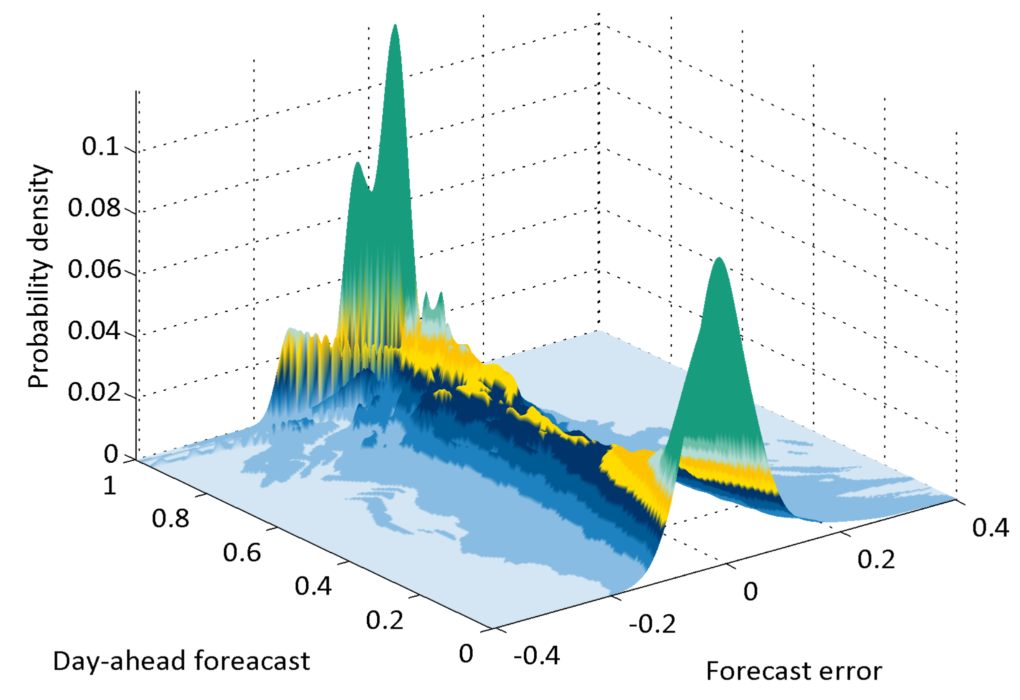
Results from the papers above were merged into the study “Optimierung der Marktbedingungen für die Regelleistungserbringung durch Erneuerbare Energien” (English: Optimisation of market conditions for the provision of control reserve by renewable energies) conducted for the **German Renewable Energy Federation BEE** (Bundesverband Erneuerbare Energie e.V.) and the **Hannover Messe** in April 2014 (Jansen, 2014). The novelty in this study is that real market conditions have been applied to theoretical potentials of wind farms and PV systems that have been presented in the papers mentioned above. The study concludes with specific suggestions for policy makers.

An as-yet non-published working paper for the **German Federal Ministry of the Environment** used the methodology to assess the macro-economic impact of biogas power plants. The module for the offering was replaced by an alternative module to account for the bidding strategy of controllable generation.

In the paper by **Hennig** (Hennig et al., 2014) the delivery of control reserve by offshore wind farms was discussed. Besides many technical aspects of this paper the offering of control reserve followed the approach presented previously.

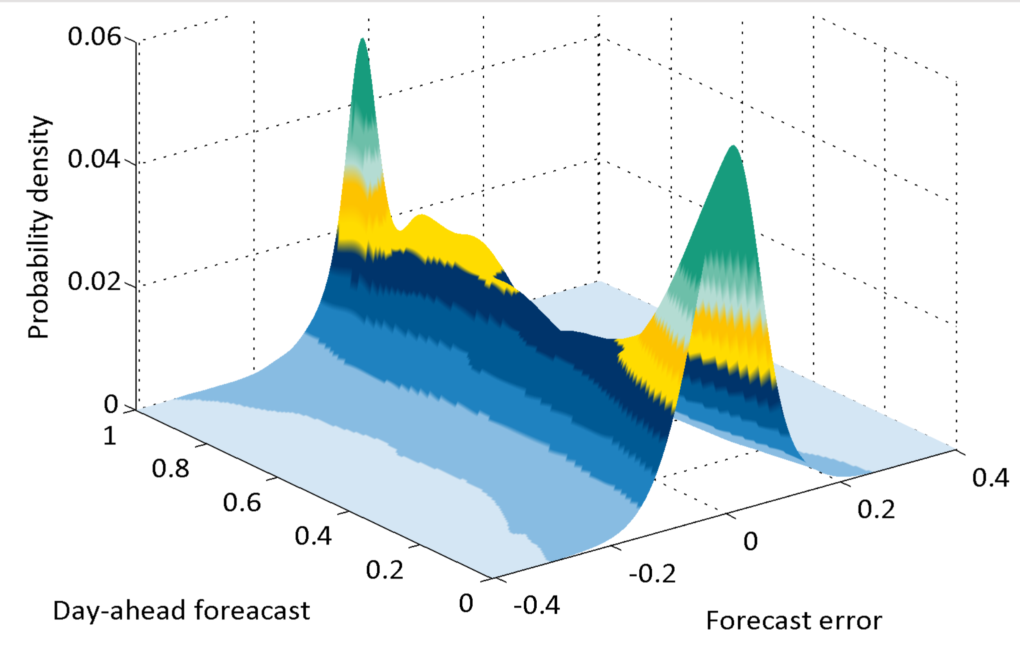
A conference paper by Jansen (forthcoming 2016) presents the results from this doctoral thesis with the same parametrization and version of REBal. It focusses on the possible additional income for wind farms and PV systems. The paper is accepted for publishing.

Appendix A Distribution estimation functions



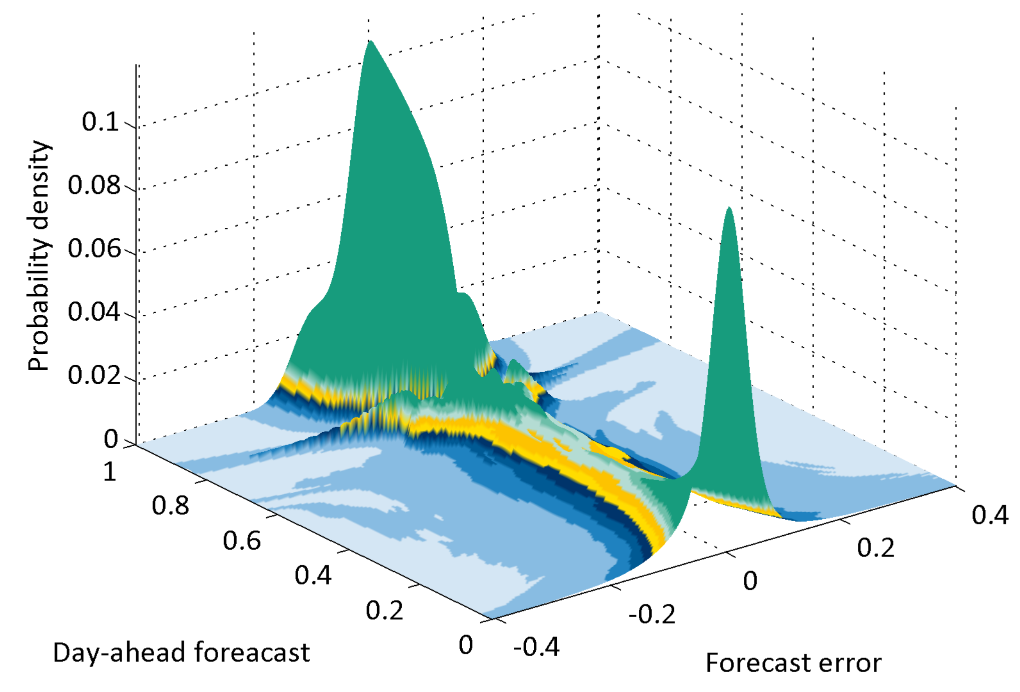
Source: Own analysis

Figure A-1: Illustration of the two-dimensional KDE based on the day-ahead probabilistic forecasting of the German 1 GW onshore wind farm pool



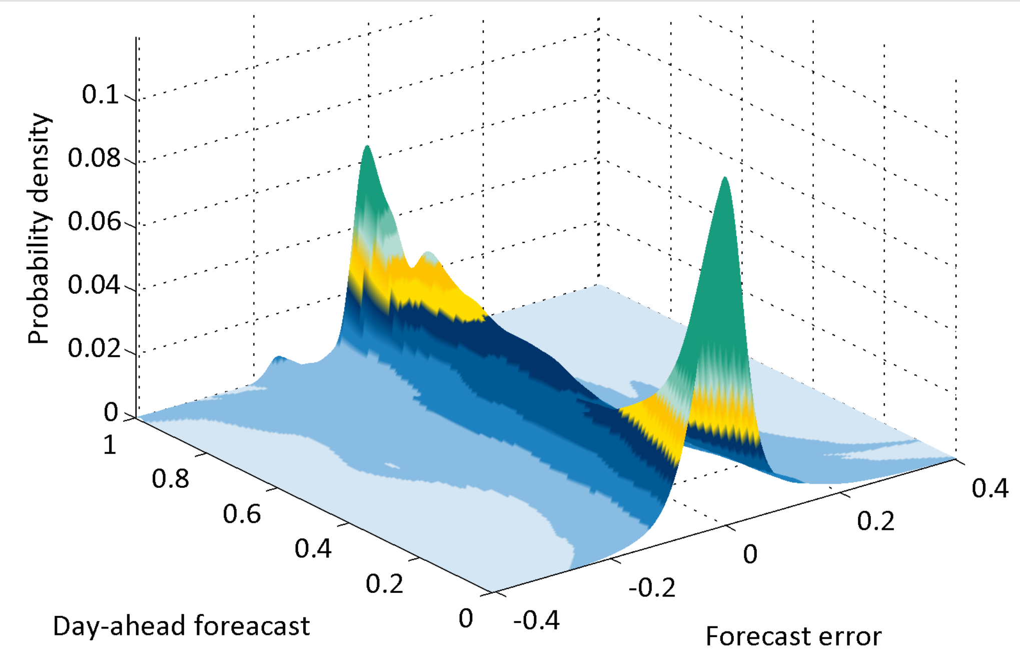
Source: Own analysis

Figure A-2: Illustration of the two-dimensional KDE based on the day-ahead probabilistic forecasting of the German 1 GW offshore wind farm pool



Source: Own analysis

Figure A-3: Illustration of the two-dimensional KDE based on the day-ahead probabilistic forecasting of the German 30 GW pool of PV systems

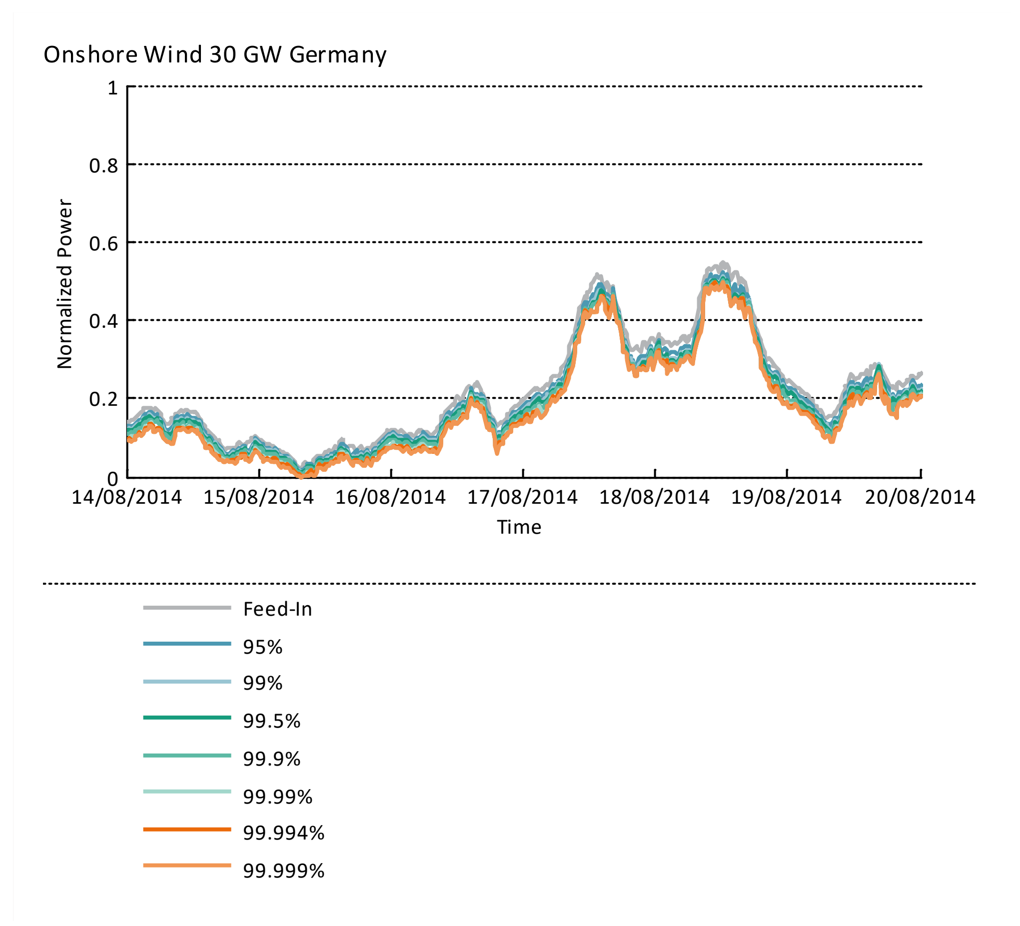


Source: Own analysis

Figure A-4: Illustration of the two-dimensional KDE based on the day-ahead probabilistic forecasting of the 1 GW pool of PV systems

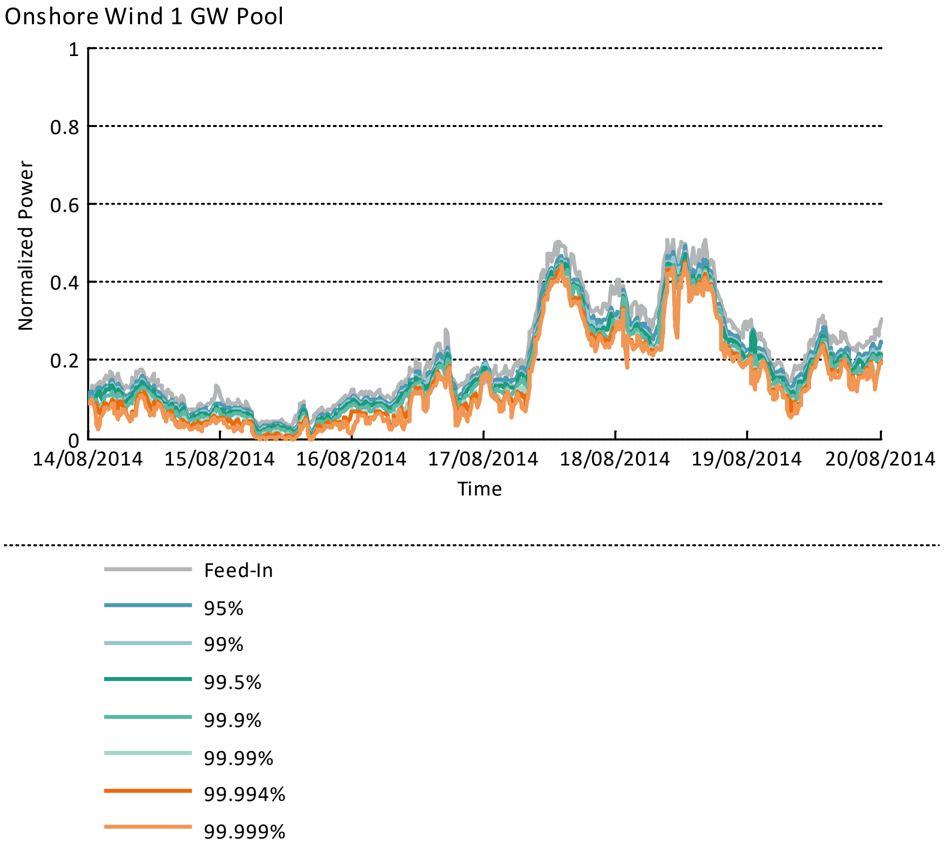
Appendix B Plots on economics of fluctuating RES generators

Appendix B-A Probabilistic intraday forecasts for time of the 14th of August 2014 to the 20th of August 2014



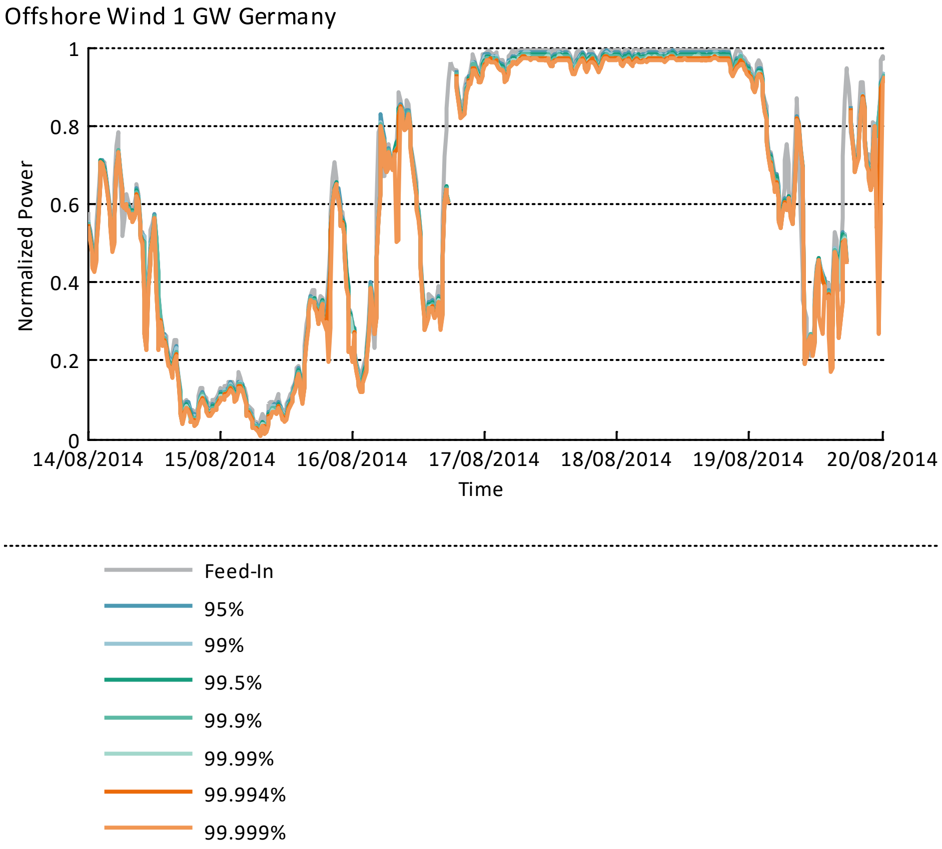
Source: Own analysis

Figure B-5: Probabilistic one-hour ahead intraday forecast of the German 30 GW wind farm pool



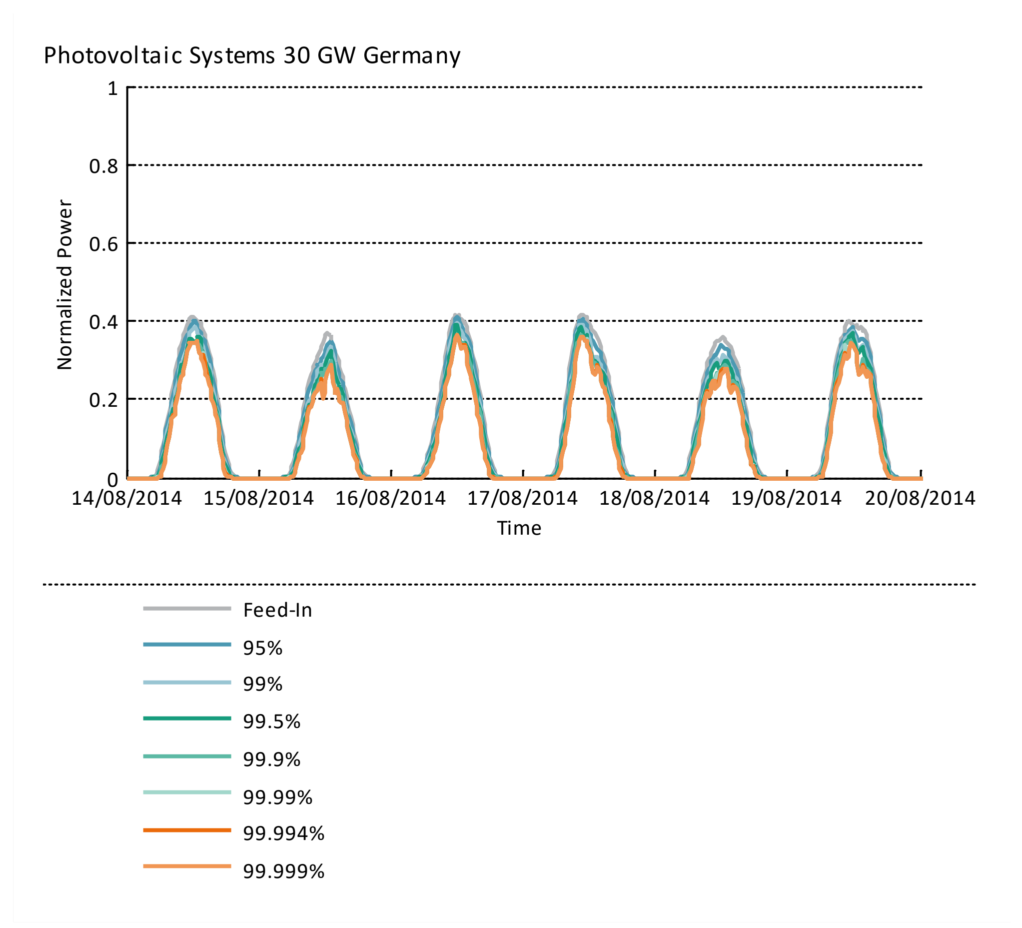
Source: Own analysis

Figure B-6: Probabilistic one-hour ahead intraday forecast of the 1 GW wind farm pool



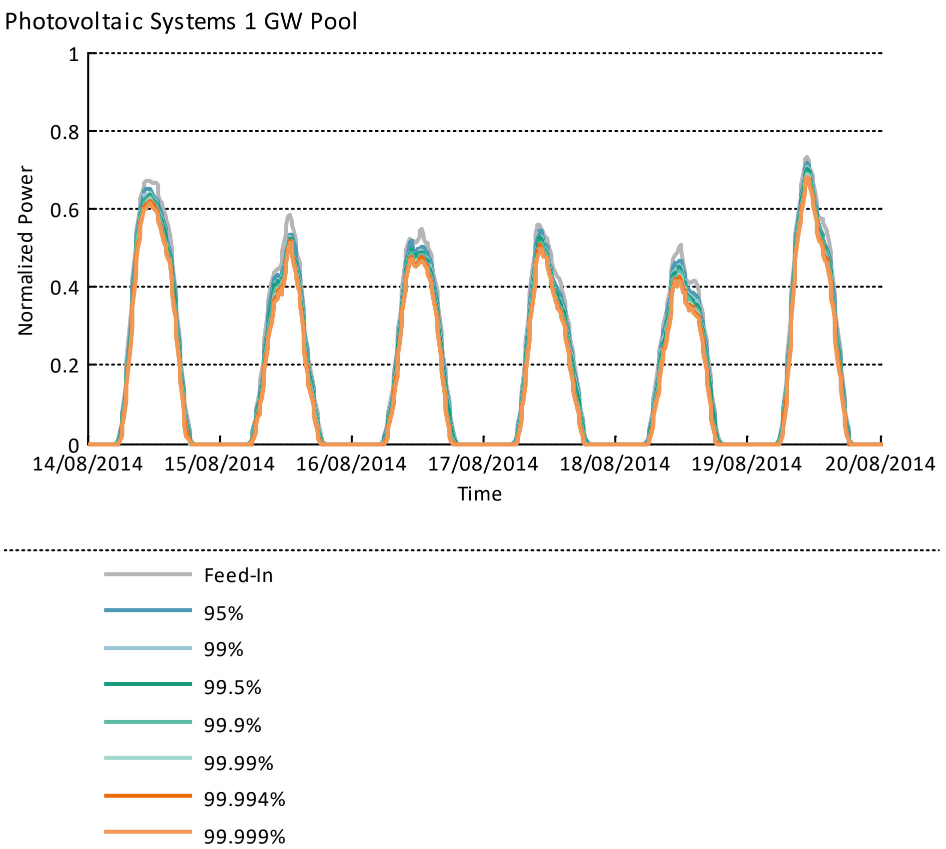
Source: Own analysis

Figure B-7: Probabilistic one-hour ahead intraday forecast of the German 1 GW offshore wind farm pool



Source: Own analysis

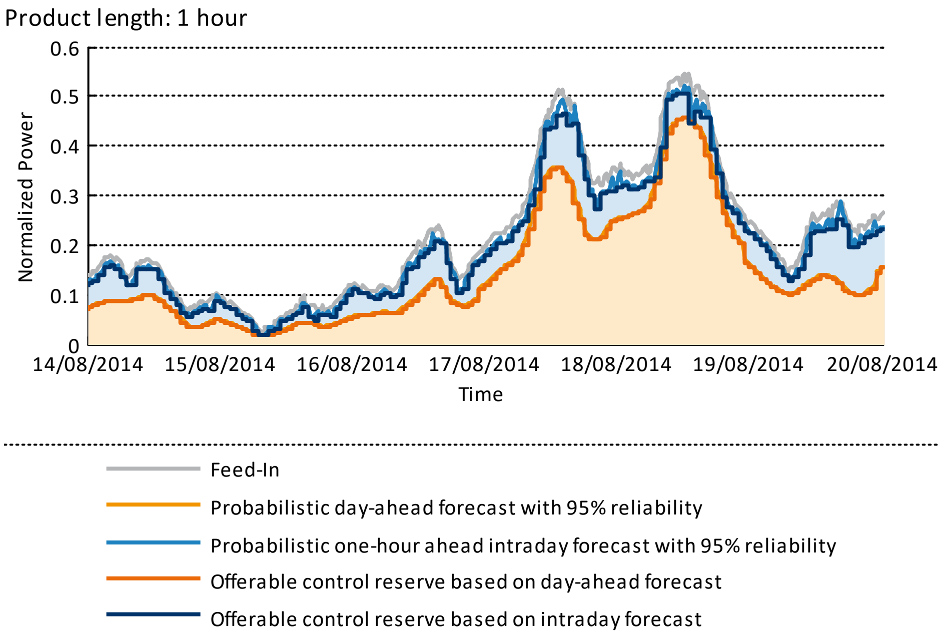
Figure B-8: Probabilistic one-hour ahead intraday forecast of the German 30 GW pool of PV systems



Source: Own analysis

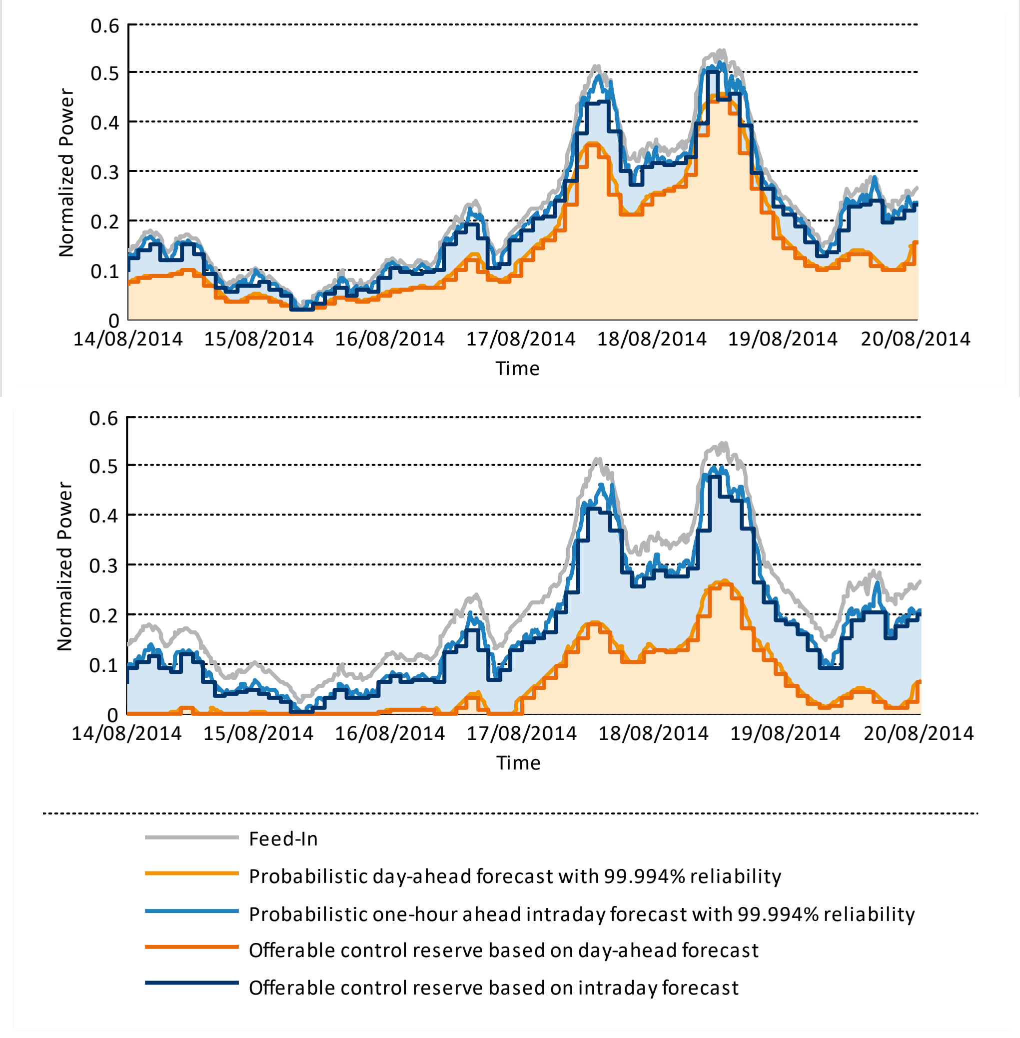
Figure B-9: Probabilistic one-hour ahead intraday forecast of the 1 GW pool of PV systems

Appendix B-B Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve



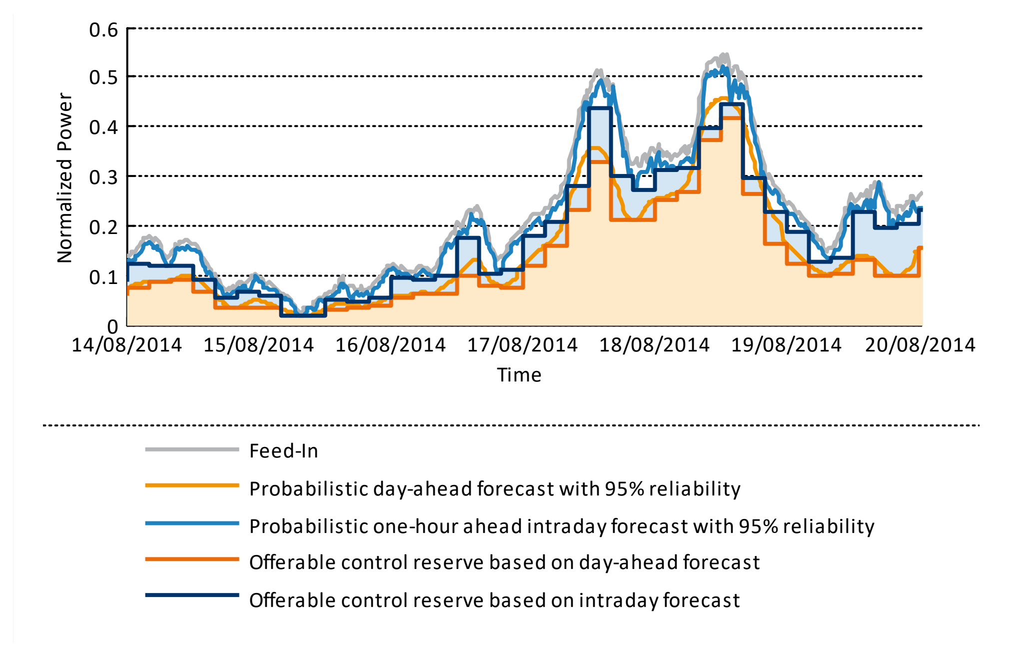
Source: Own analysis

Figure B-10: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the German 30 GW pool of wind farms for the reliability of 95 % and a product length of one hour



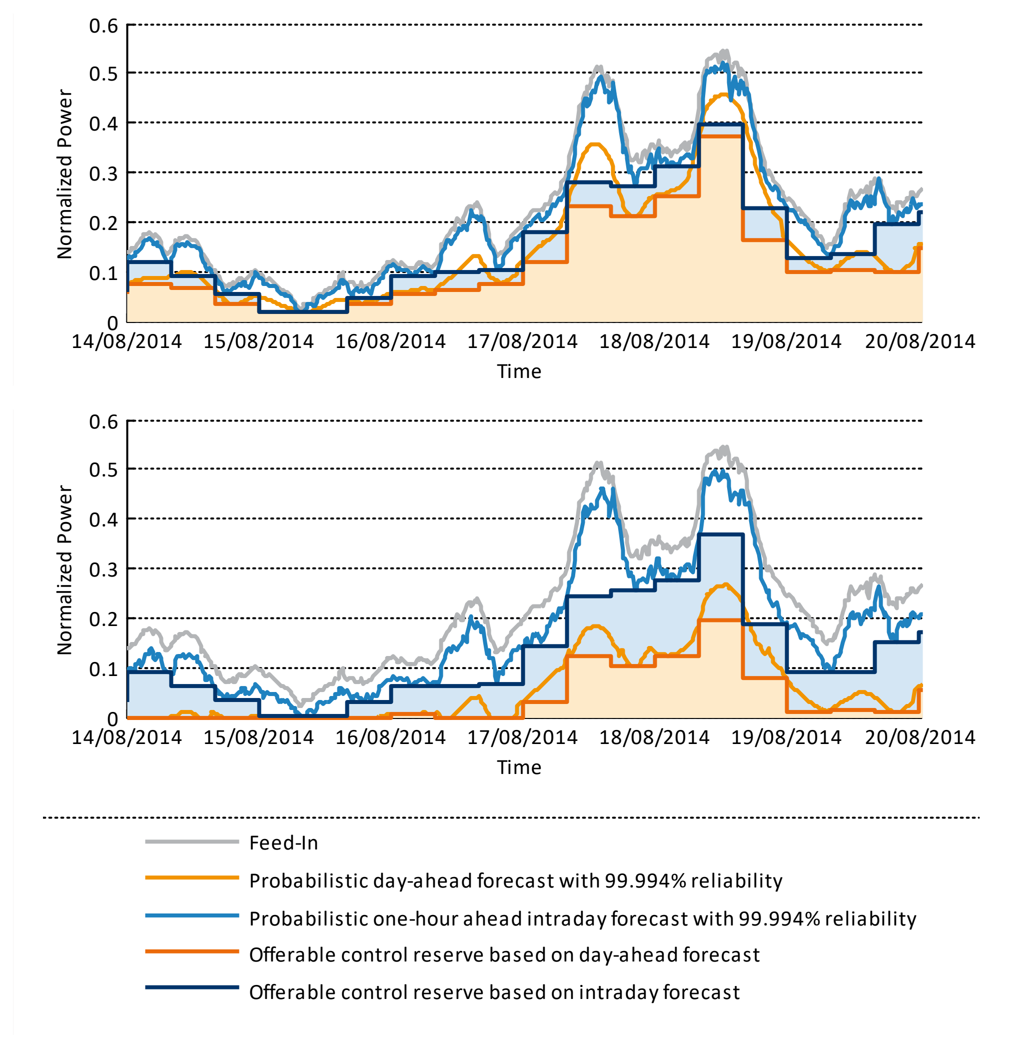
Source: Own analysis

Figure B-11: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the German 30 GW pool of wind farms for the reliability of 95 % (top) and 99.994 % (bottom) and a product length of two hours



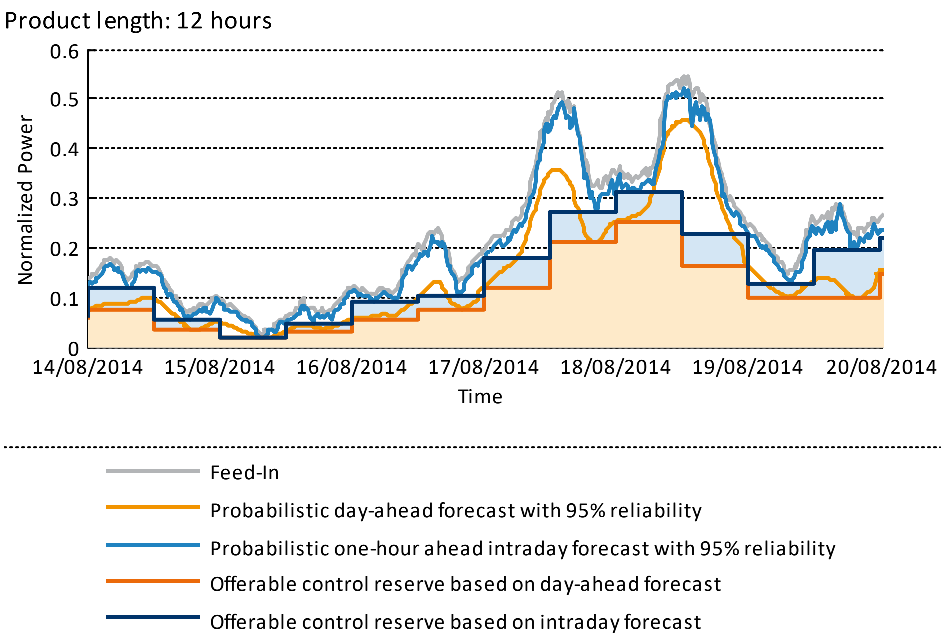
Source: Own analysis

Figure B-12: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the German 30 GW pool of wind farms for the reliability of 95 % and a product length of four hours



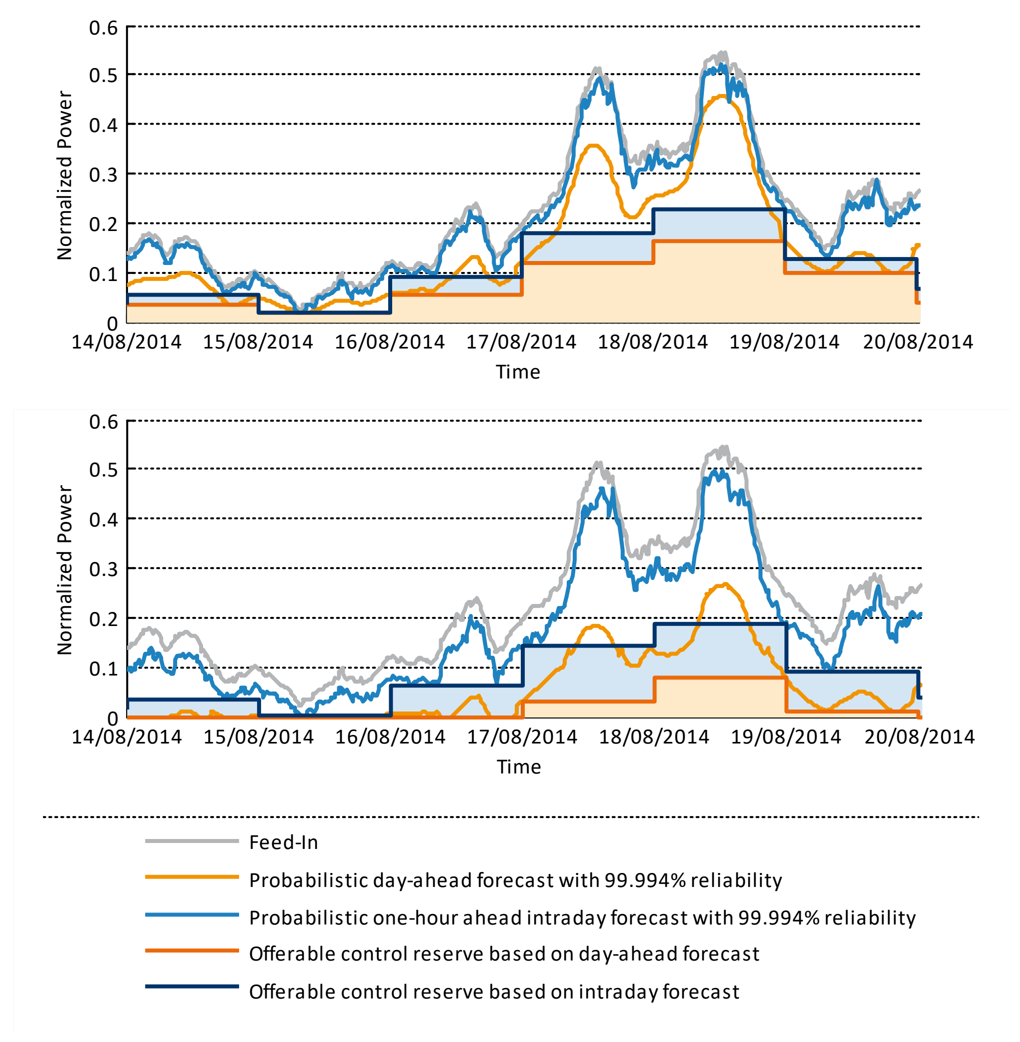
Source: Own analysis

Figure B-13: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the German 30 GW pool of wind farms for the reliability of 95 % (top) and 99.994 % (bottom) and a product length of eight hours



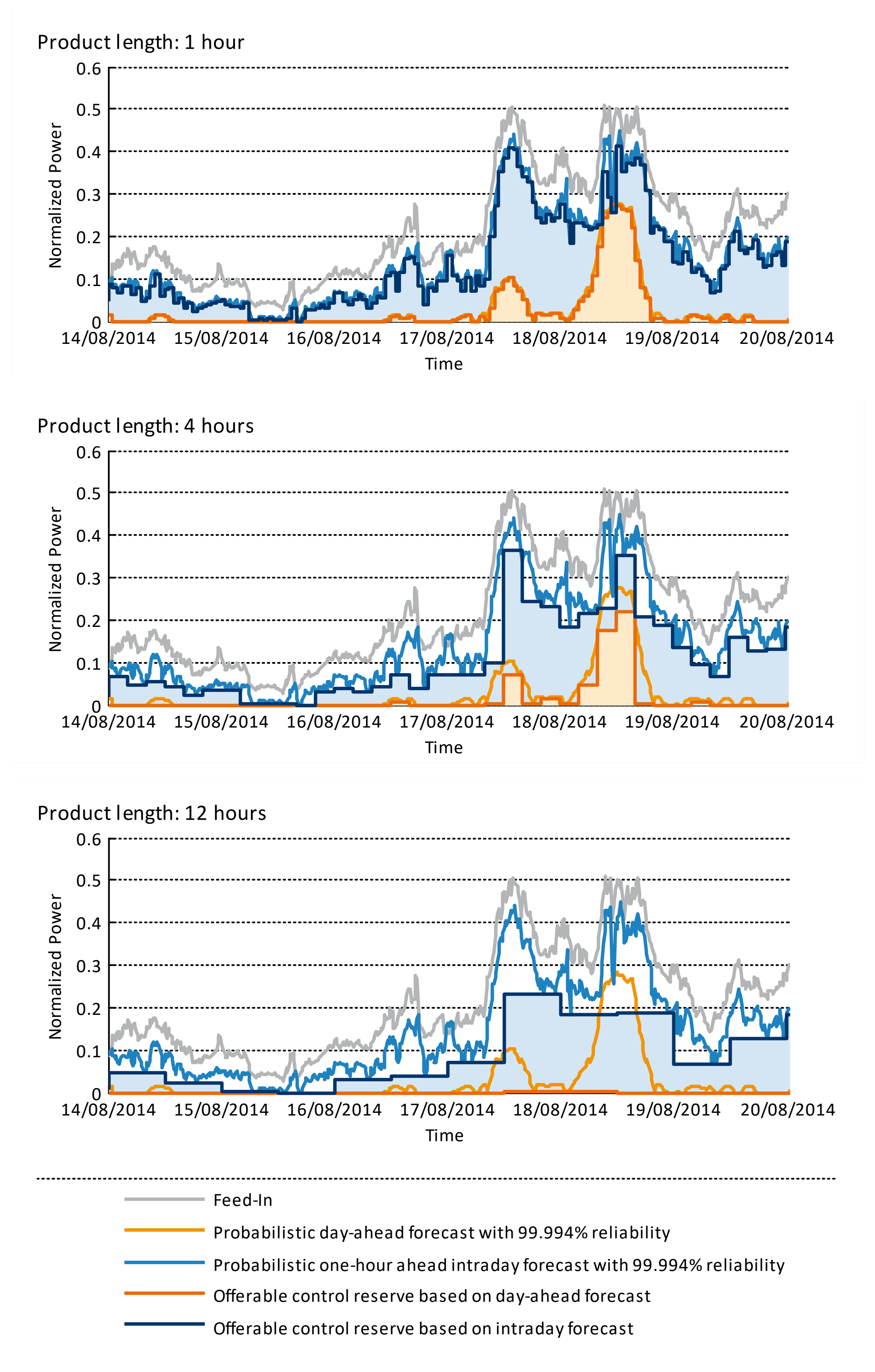
Source: Own analysis

Figure B-14: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the German 30 GW pool of wind farms for the reliability of 95 % and a product length of twelve hours



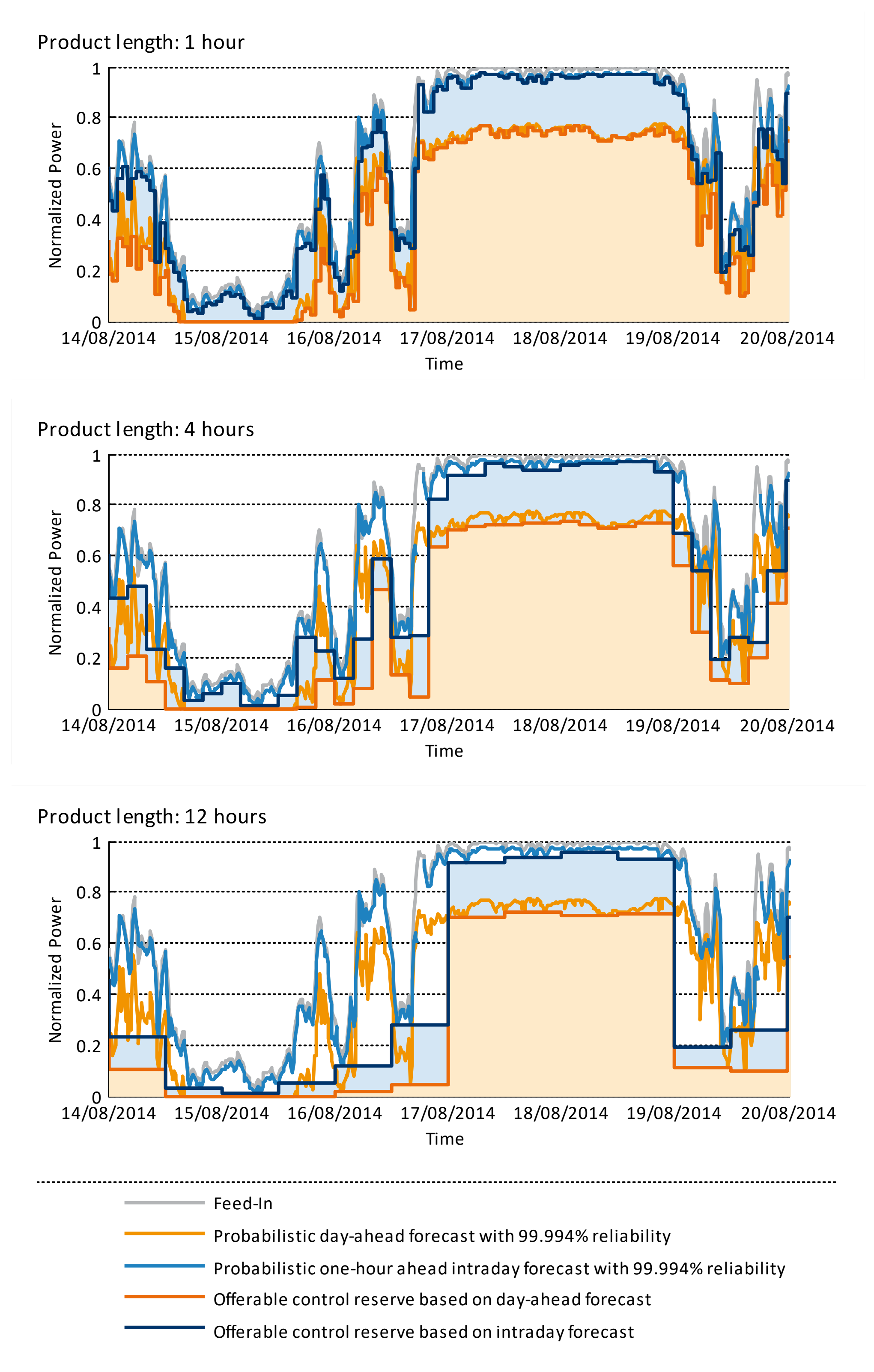
Source: Own analysis

Figure B-15: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the German 30 GW pool of wind farms for the reliability of 95 % (top) and 99.994 % (bottom) and a product length of 24 hours



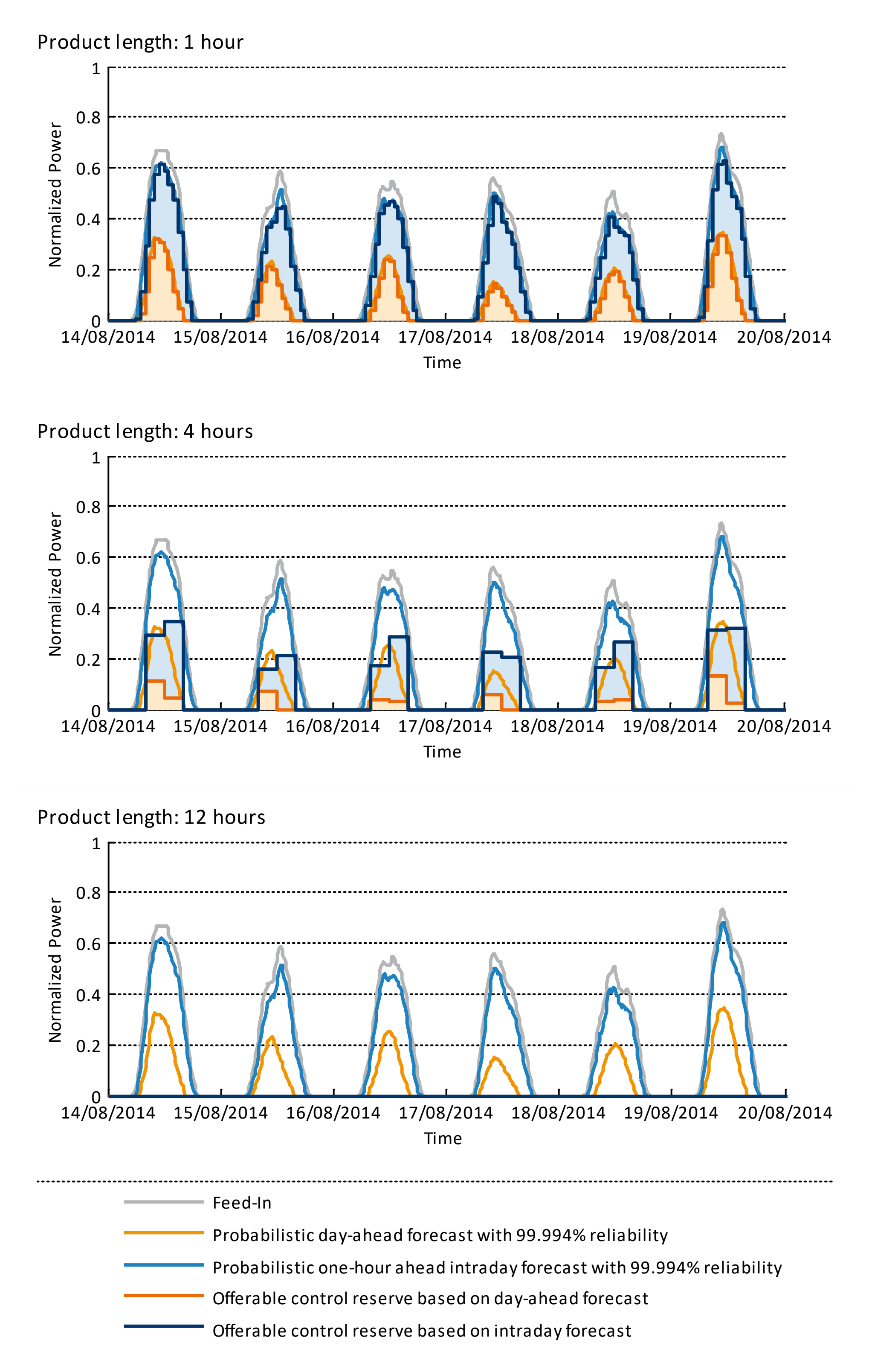
Source: Own analysis

Figure B-16: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the 1 GW onshore wind farm pool for the reliability of 99.994 % and a product length of one, four and twelve hours



Source: Own analysis

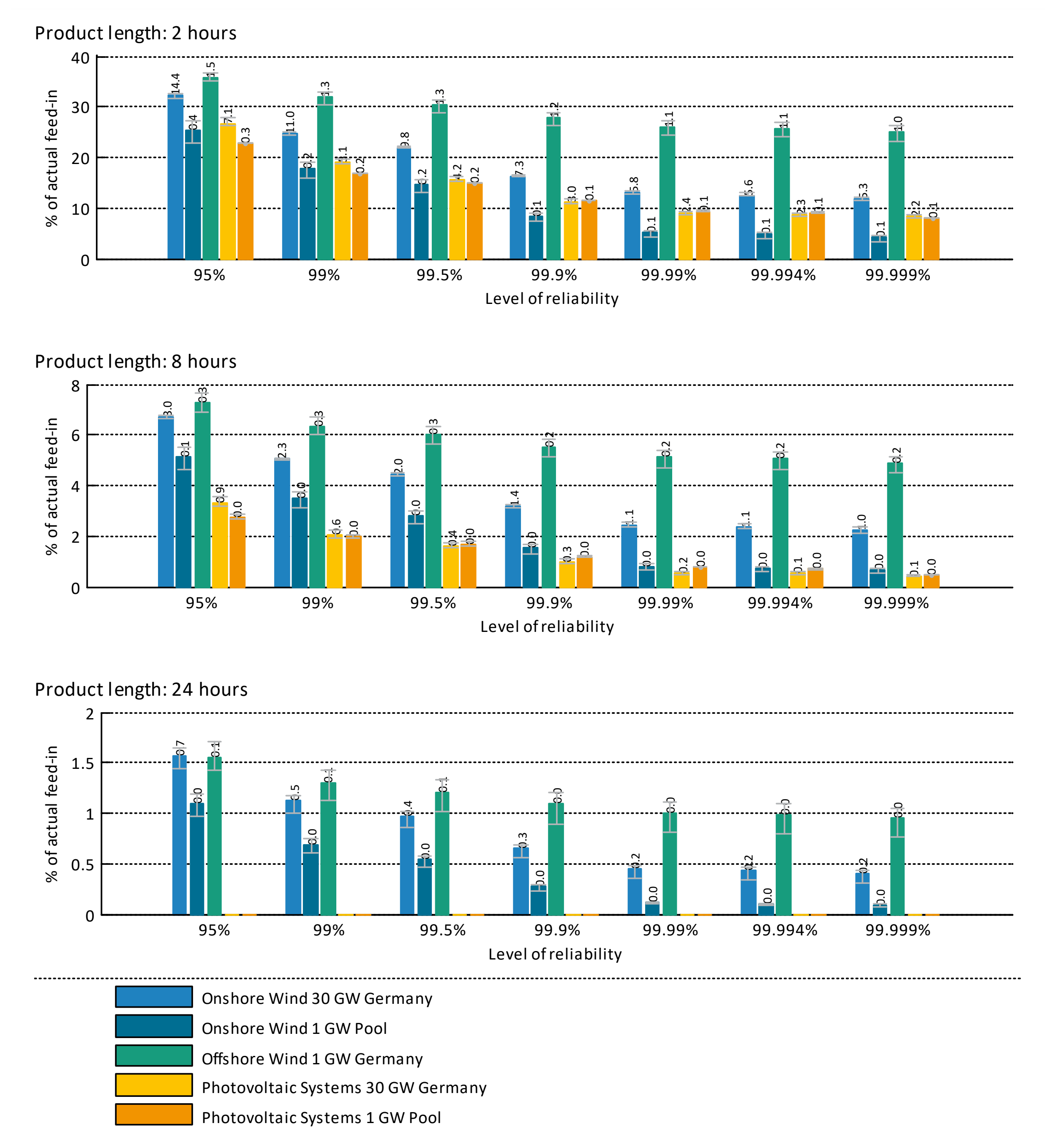
Figure B-17: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the German 1 GW offshore wind farm pool for the reliability of 99.994 % and a product length of one, four and twelve hours



Source: Own analysis

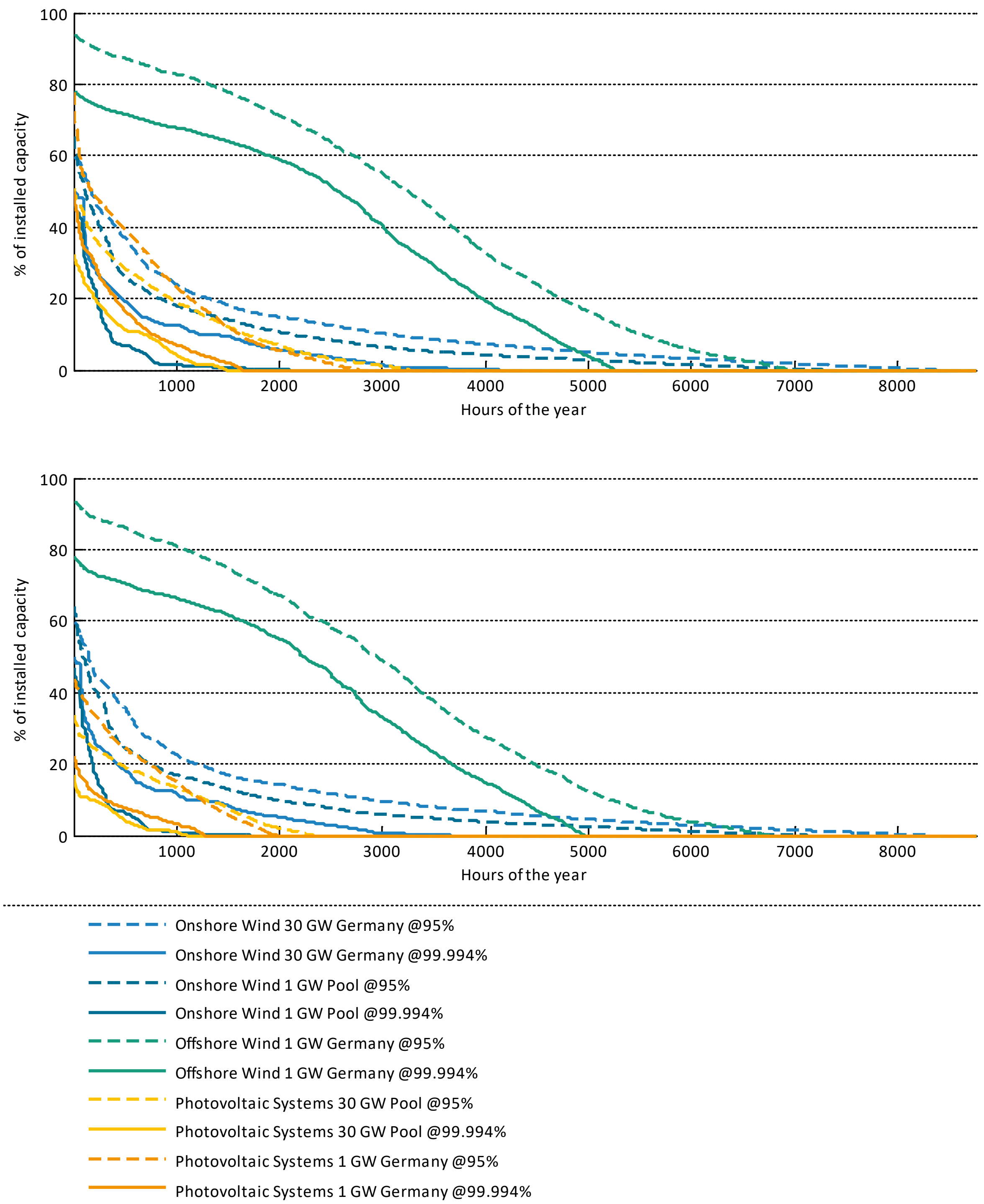
Figure B-18: Probabilistic day-ahead and one-hour ahead intraday forecasts, feed-in and offerable amounts of control reserve based on the day-ahead and intraday probabilistic forecasts for the 1 GW pool of PV systems for the reliability of 99.994 % and a product length of one, four and twelve hours

Appendix B-C Potentials for offering control reserve based on the day-ahead forecast



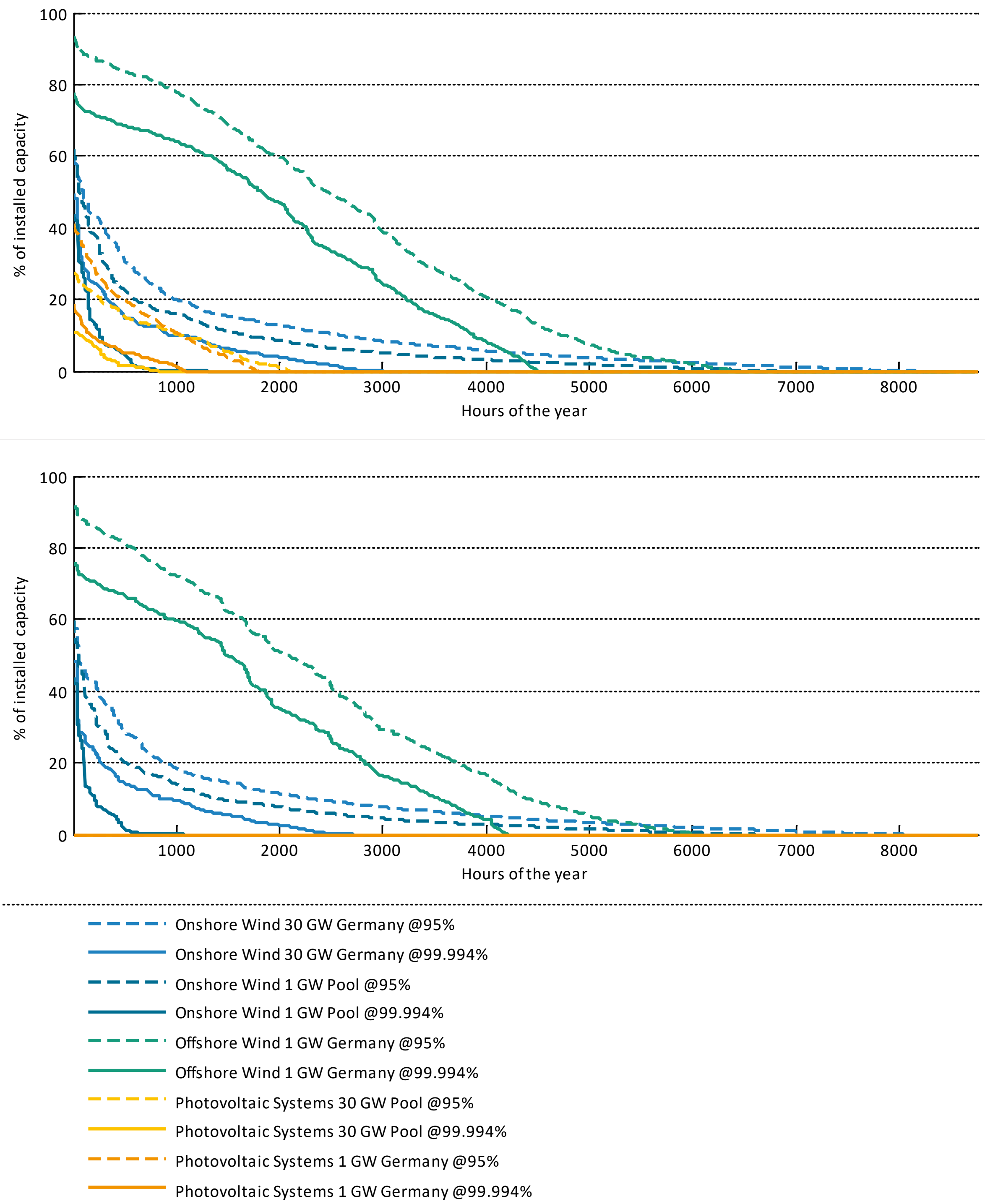
Source: Own analysis

Figure B-19: Potentials for offering control reserve based on the day-ahead forecast for different fluctuating RES generators with varying levels of reliability and product lengths of two, eight and 24 hours



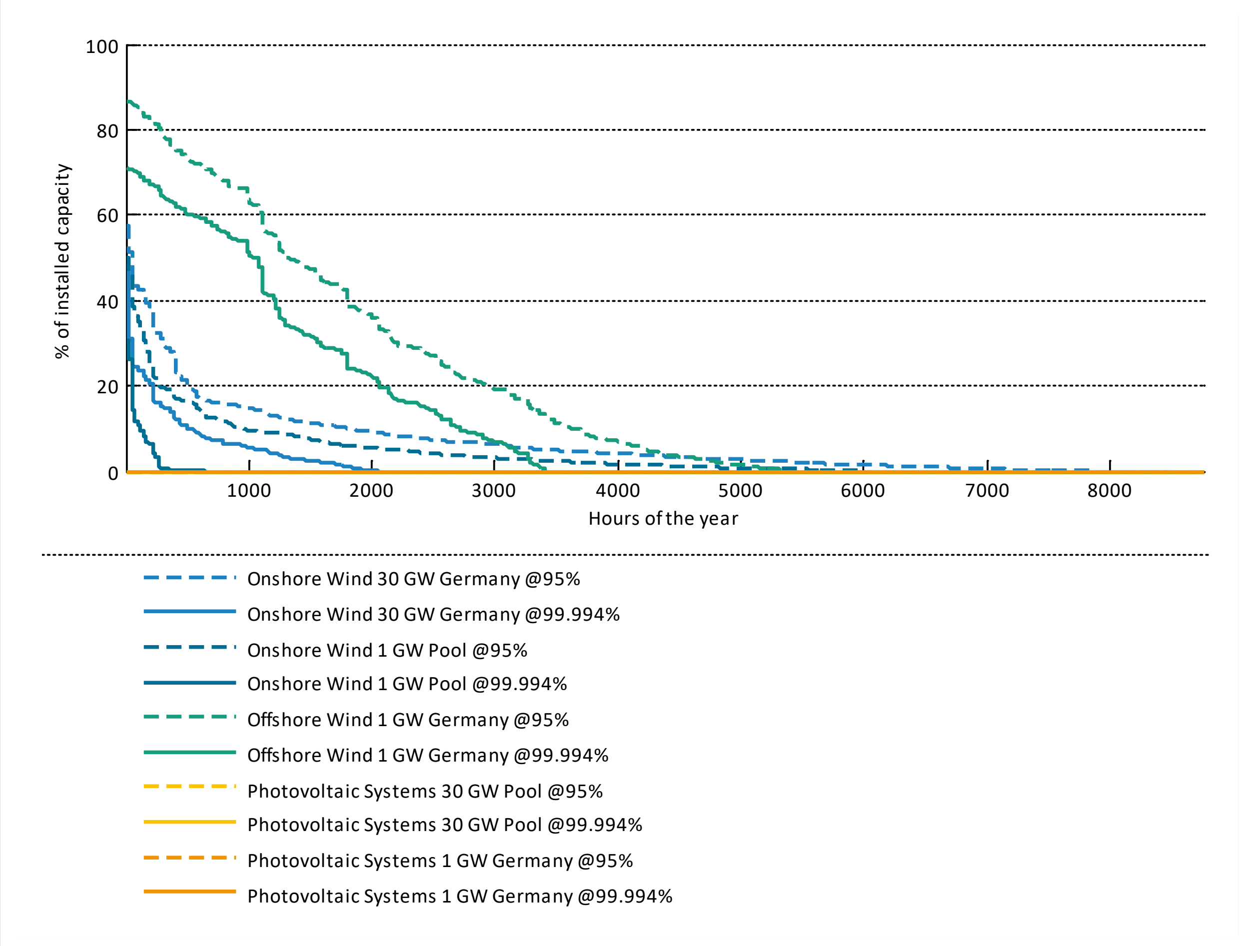
Source: Own analysis

Figure B-20: Duration curve for the offerable control reserve based on the day-ahead forecast for different fluctuating RES generators for the levels of reliability of 95 % (dashed line) and 99.994 % for the year 2014 and a product length of two (top) and four hours (bottom)



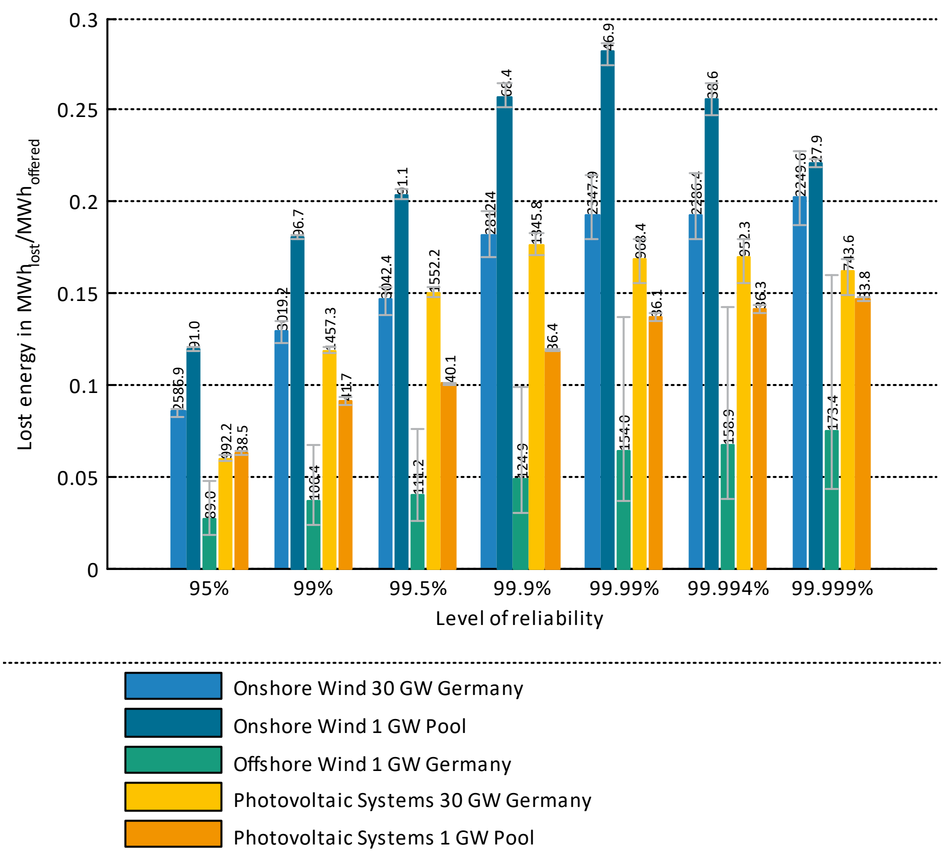
Source: Own analysis

Figure B-21: Duration curve for the offerable control reserve based on the day-ahead forecast for different fluctuating RES generators for the levels of reliability of 95 % (dashed line) and 99.994 % for the year 2014 and a product length of eight and twelve hours



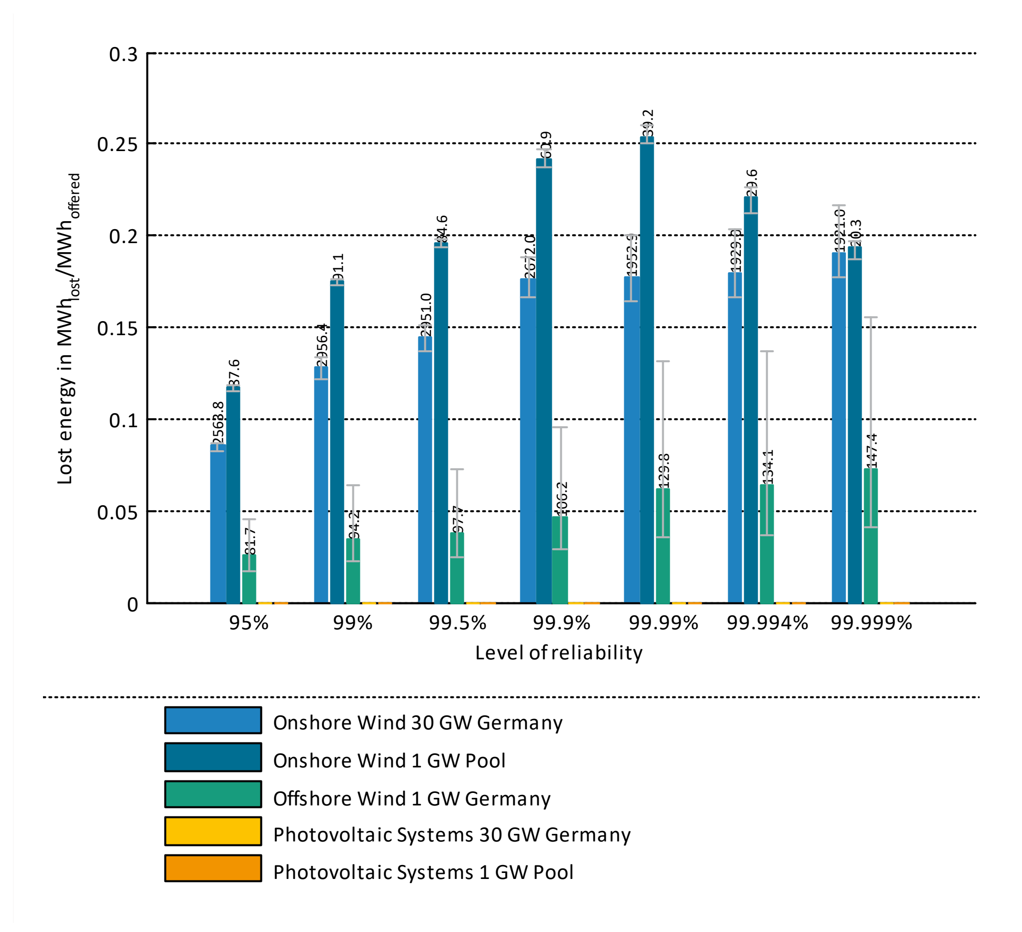
Source: Own analysis

Figure B-22: Duration curve for the offerable control reserve based on the day-ahead forecast for different fluctuating RES generators for the levels of reliability of 95 % (dashed line) and 99.994 % for the year 2014 and a product length of 24 hours



Source: Own analysis

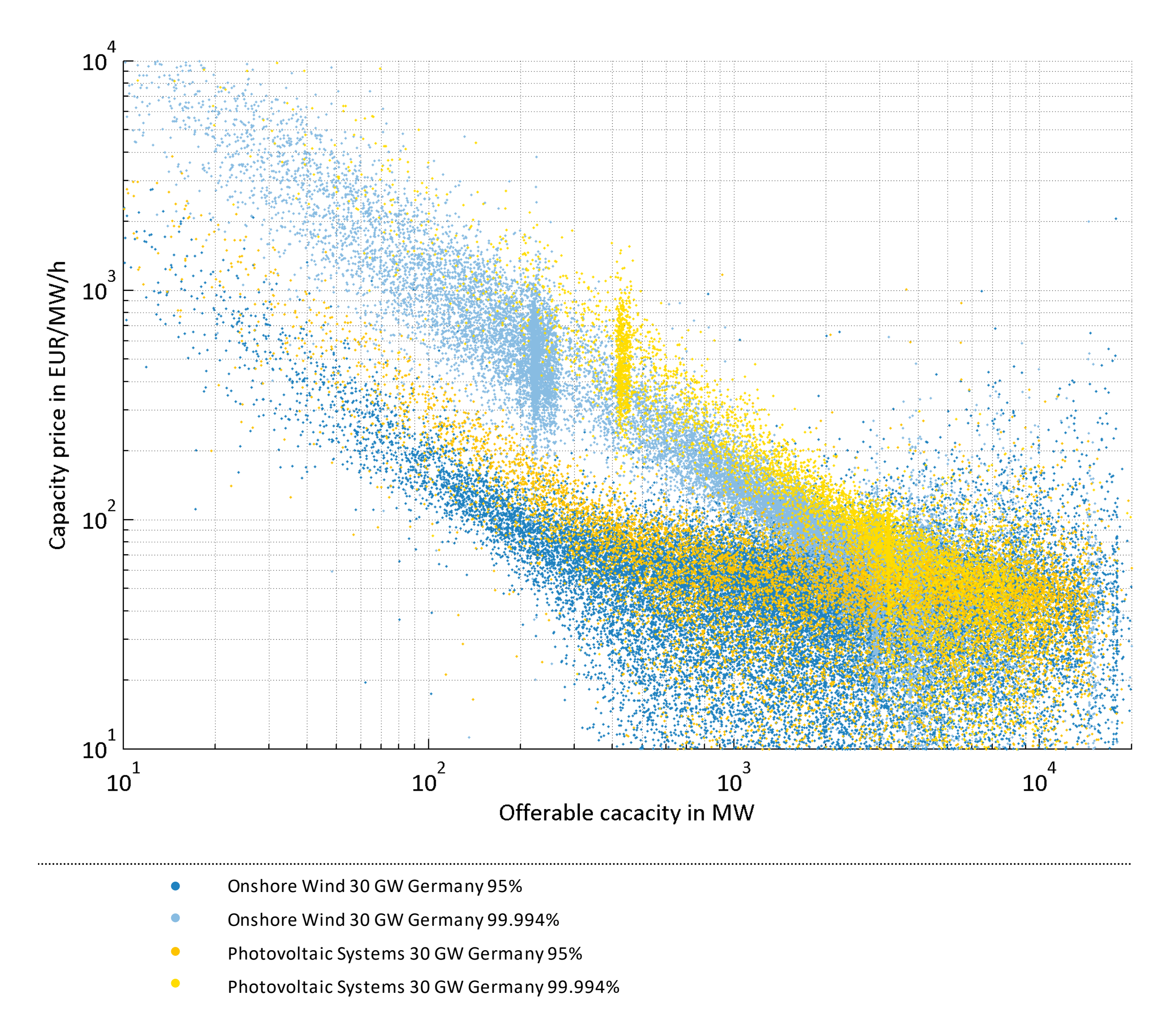
Figure B-23: Average annual specific energy losses with control reserve being offered day-ahead under the balance control proof mechanism (bars) for different types of fluctuating RES generators for the product length of four hours and different levels of reliability and the average annual total losses as numbers on the bars in gigawatt hours



Source: Own analysis

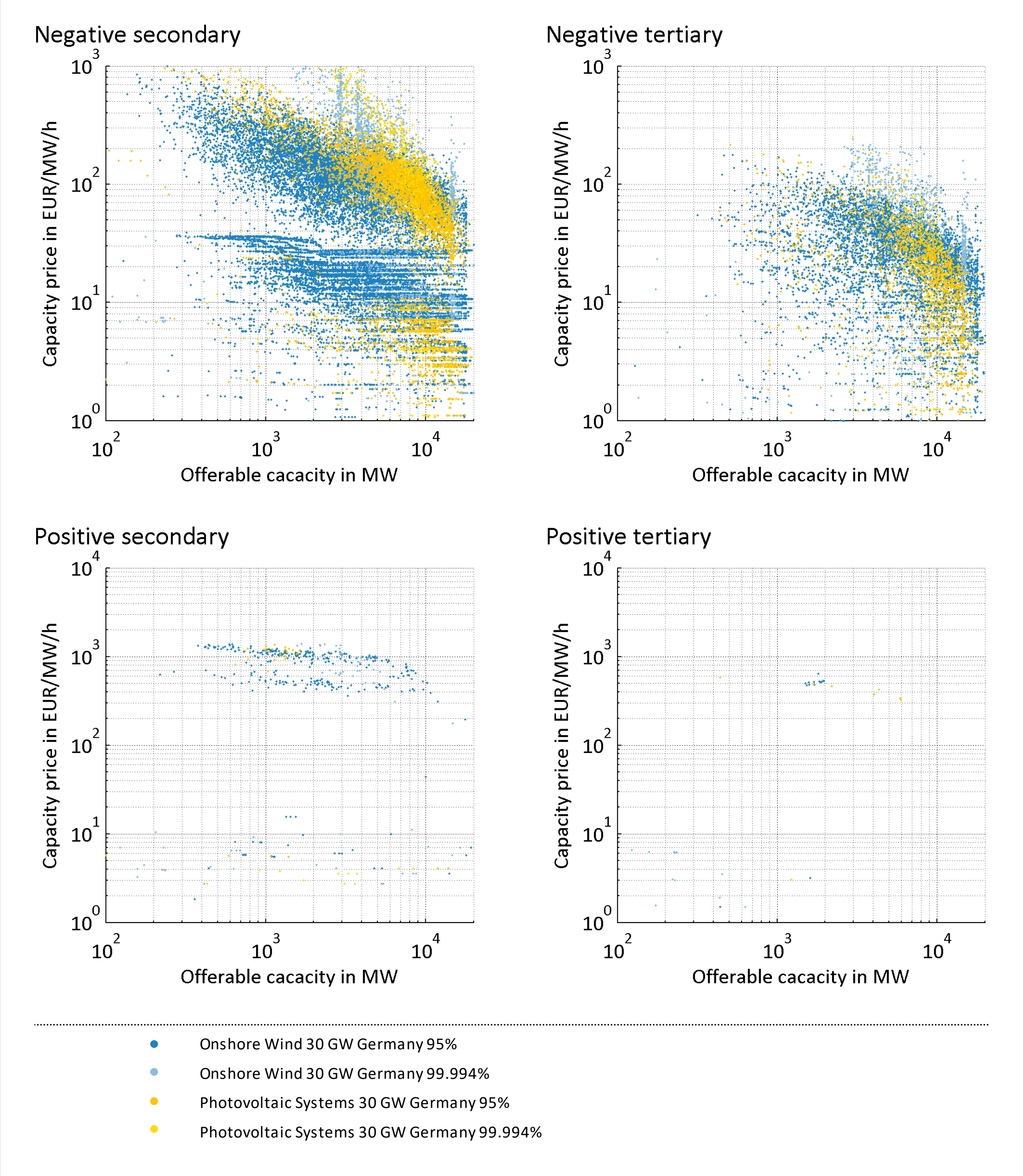
Figure B-24: Average annual specific energy losses with control reserve being offered day-ahead under the balance control proof mechanism (bars) for different types of fluctuating RES generators for the product length of twelve hours and different levels of reliability and the average annual total losses as numbers on the bars in gigawatt hours

Appendix B-D Offer calculation



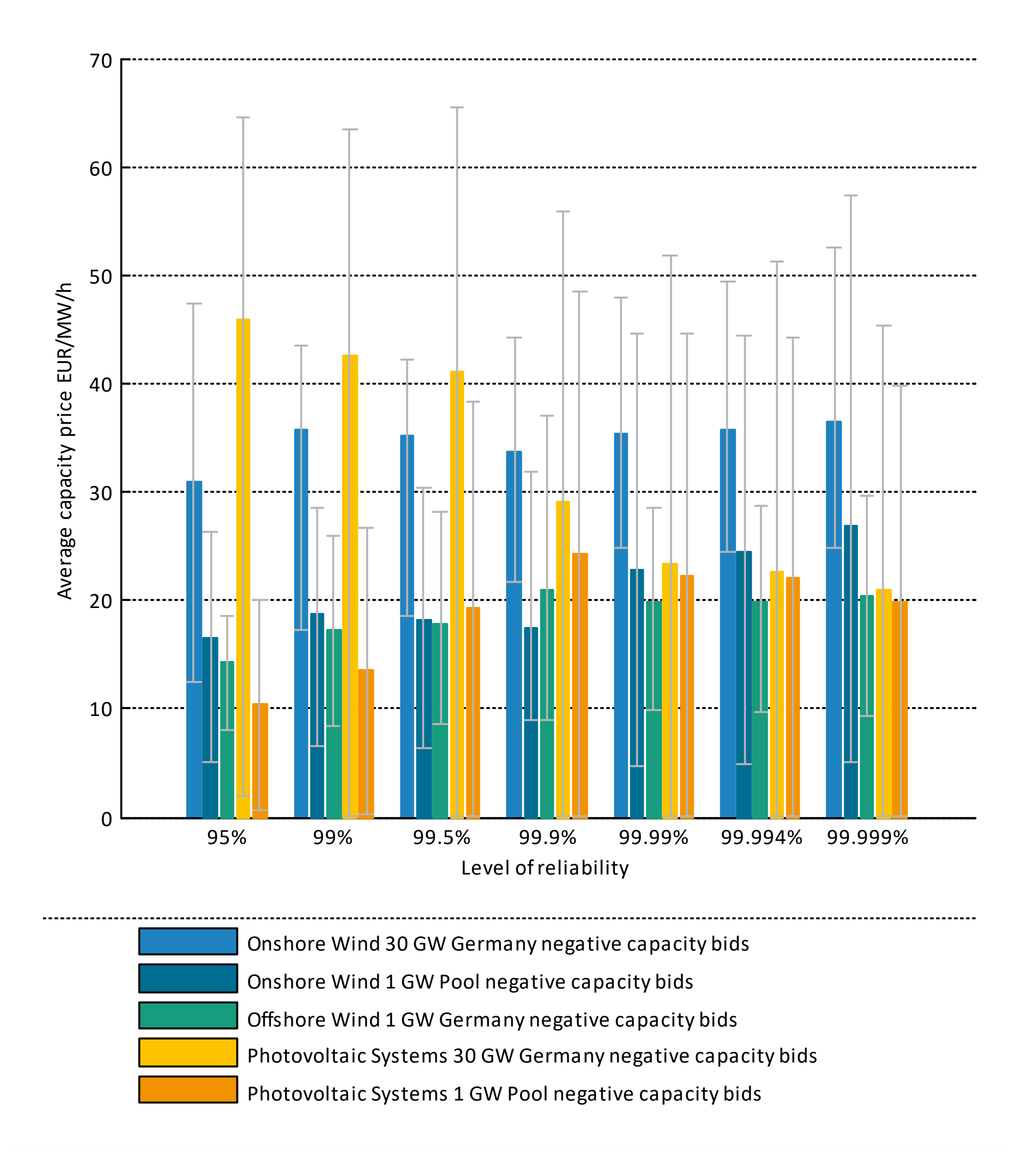
Source: Own analysis

Figure B-25: Opportunity cost based capacity price bids for different fluctuating RES generators with a level of reliability of 95 % and 99.994 % under the available active power proof mechanism for the product length of one hour for any positive control reserve market



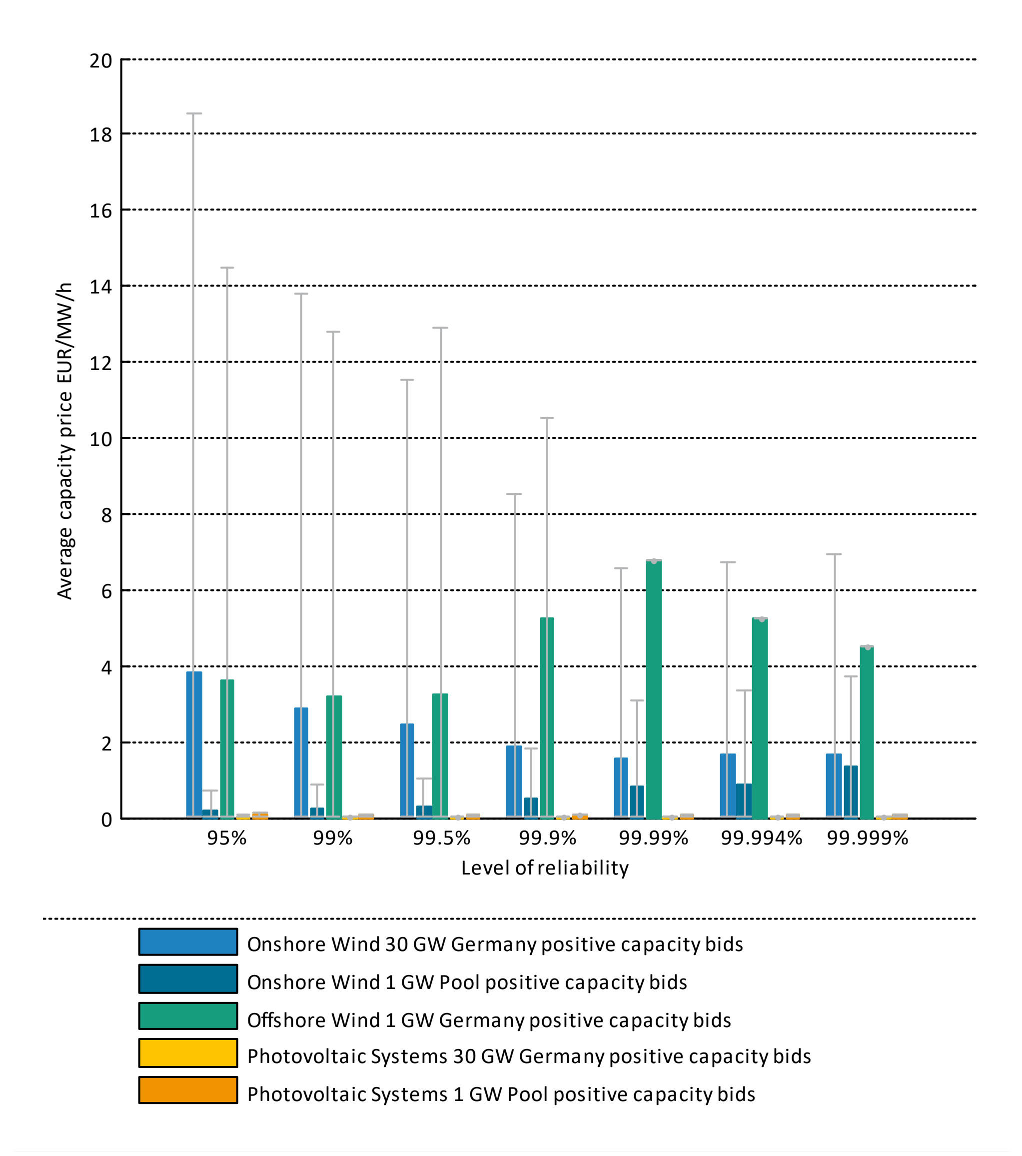
Source: Own analysis

Figure B-26: Profit maximizing capacity price bids for different fluctuating RES generators with a level of reliability of 95 % and 99.994 % under the balance control proof mechanism for the product length of one hour for four control reserve market segments



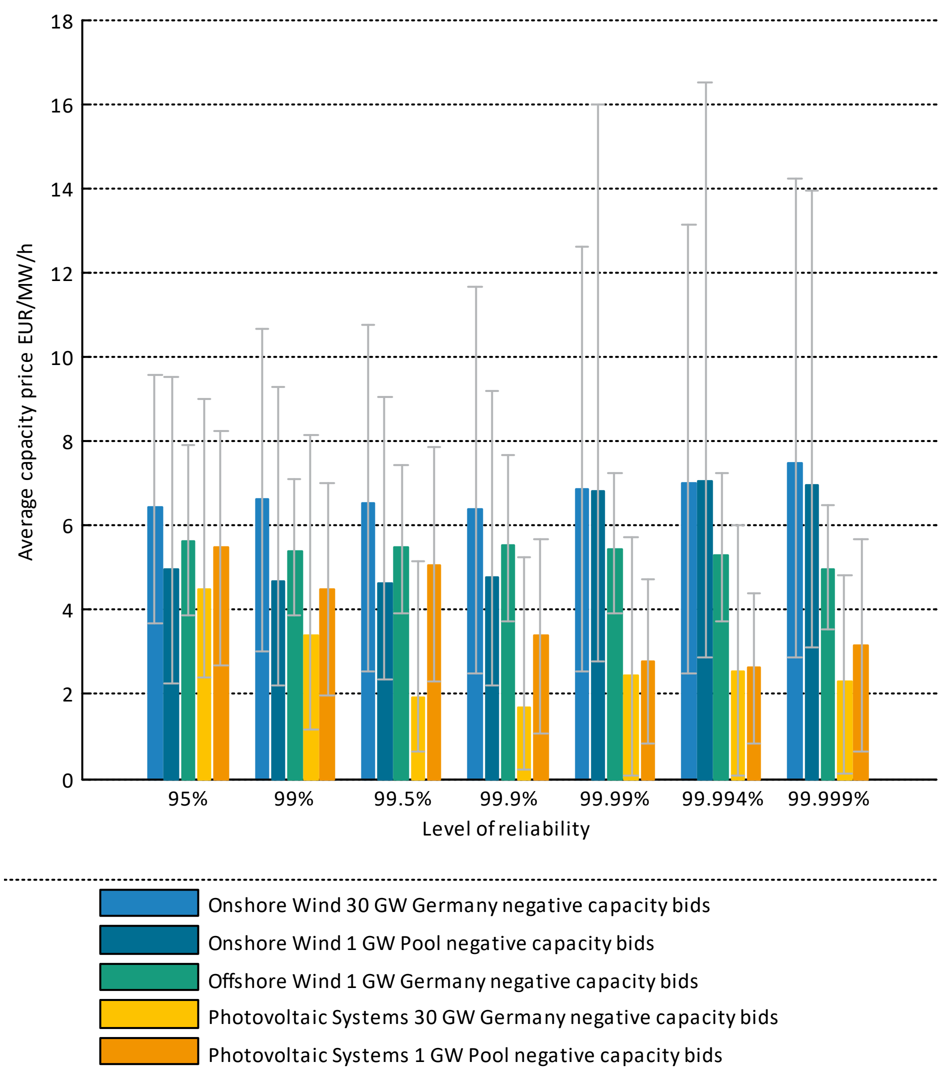
Source: Own analysis

Figure B-27: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of four hours in the negative secondary control reserve market



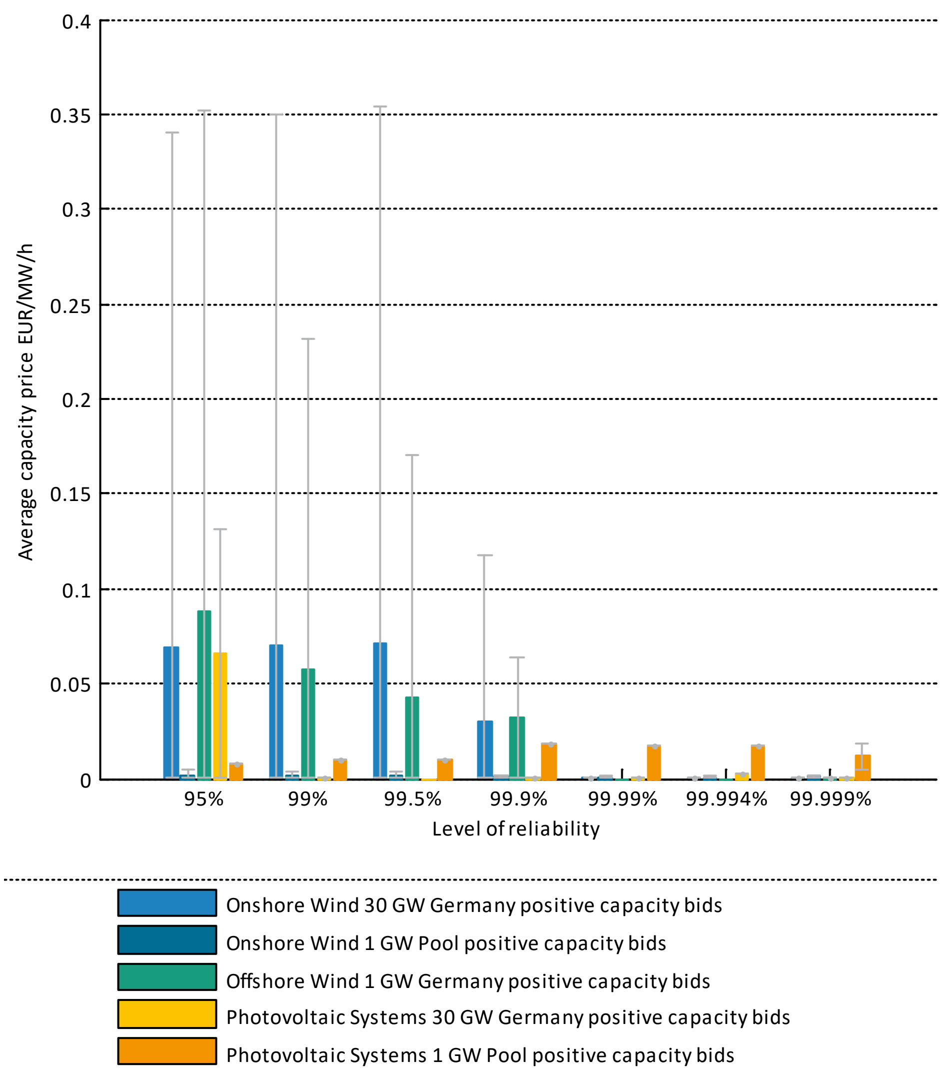
Source: Own analysis

Figure B-28: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of four hours in the positive secondary control reserve market



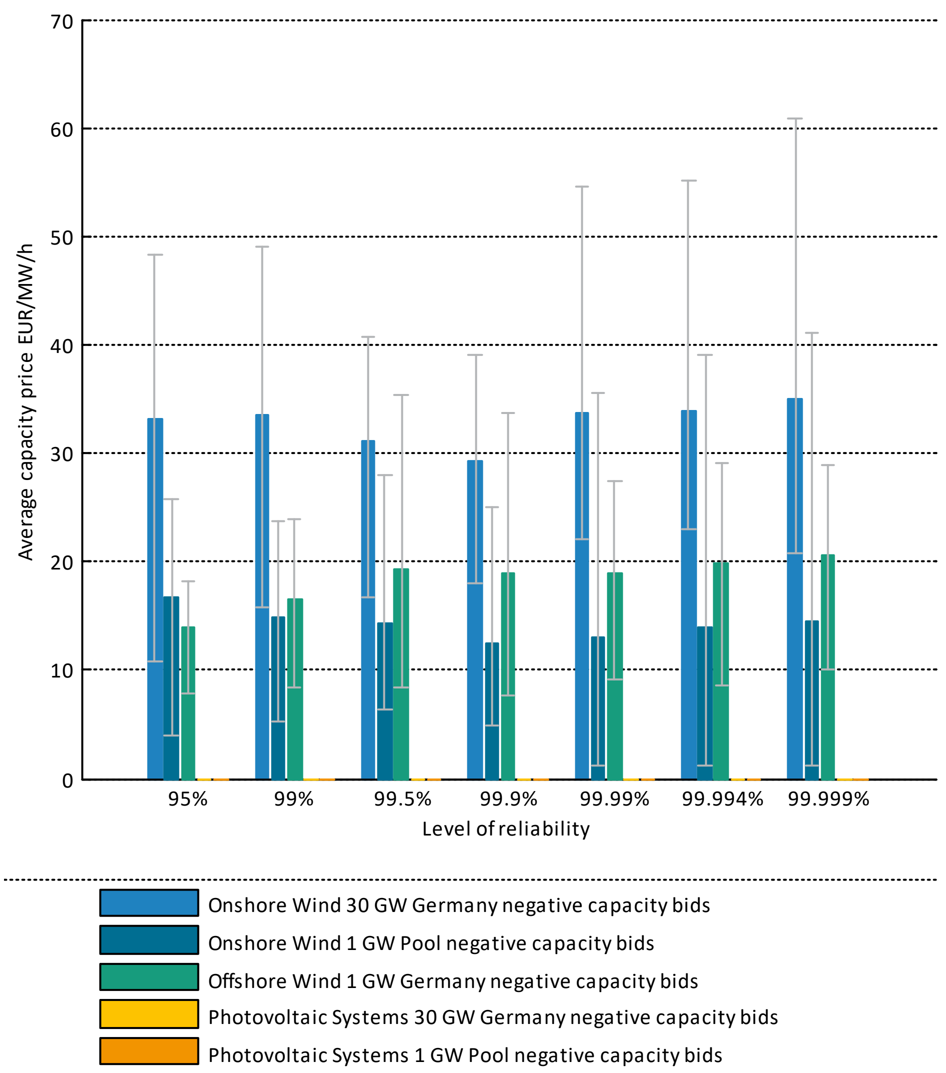
Source: Own analysis

Figure B-29: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of four hours in the negative tertiary control reserve market



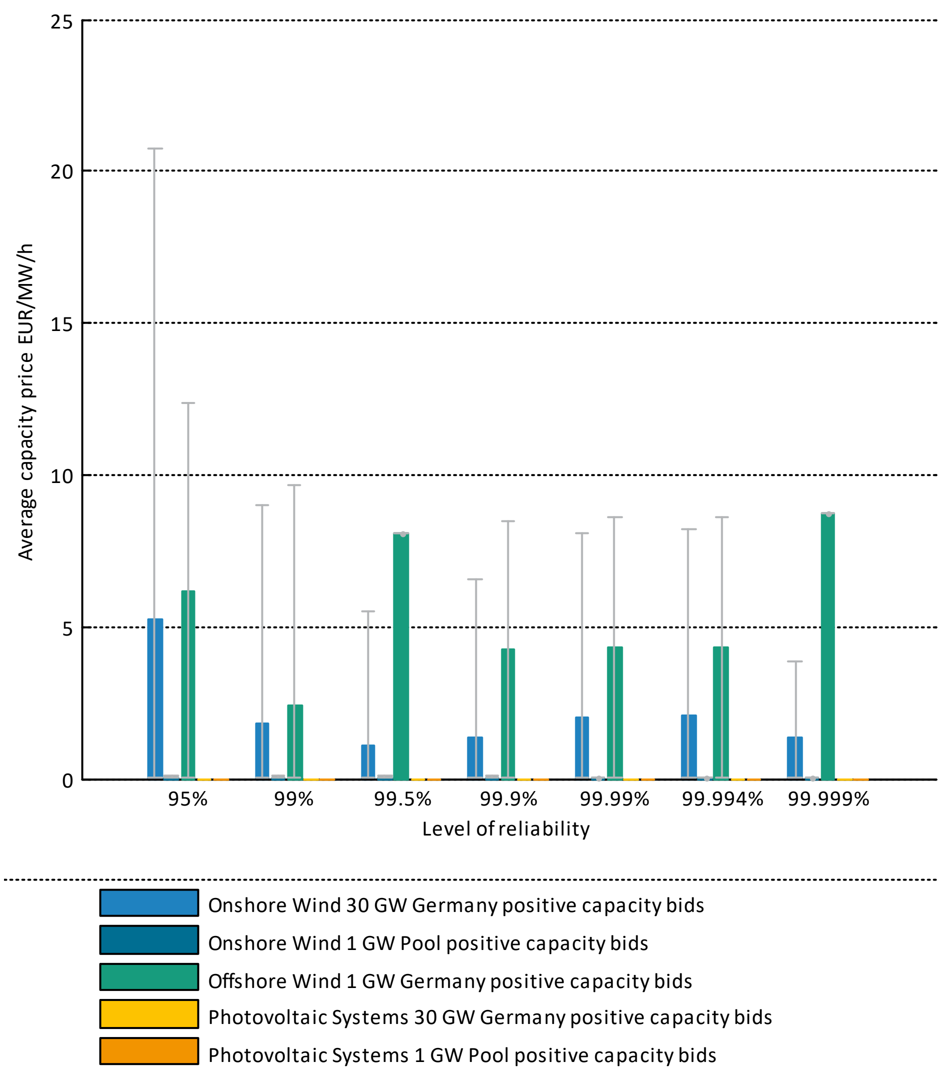
Source: Own analysis

Figure B-30: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of four hours in the positive tertiary control reserve market



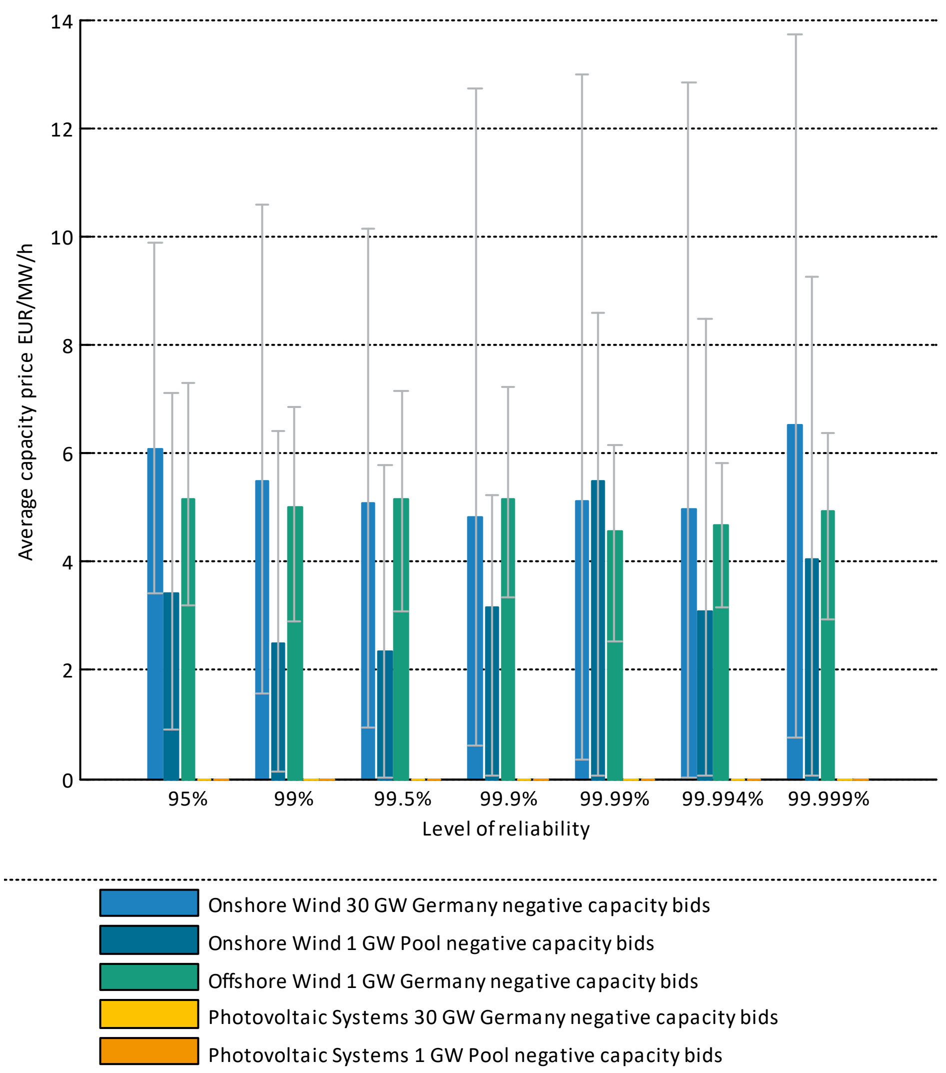
Source: Own analysis

Figure B-31: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of twelve hours in the negative secondary control reserve market



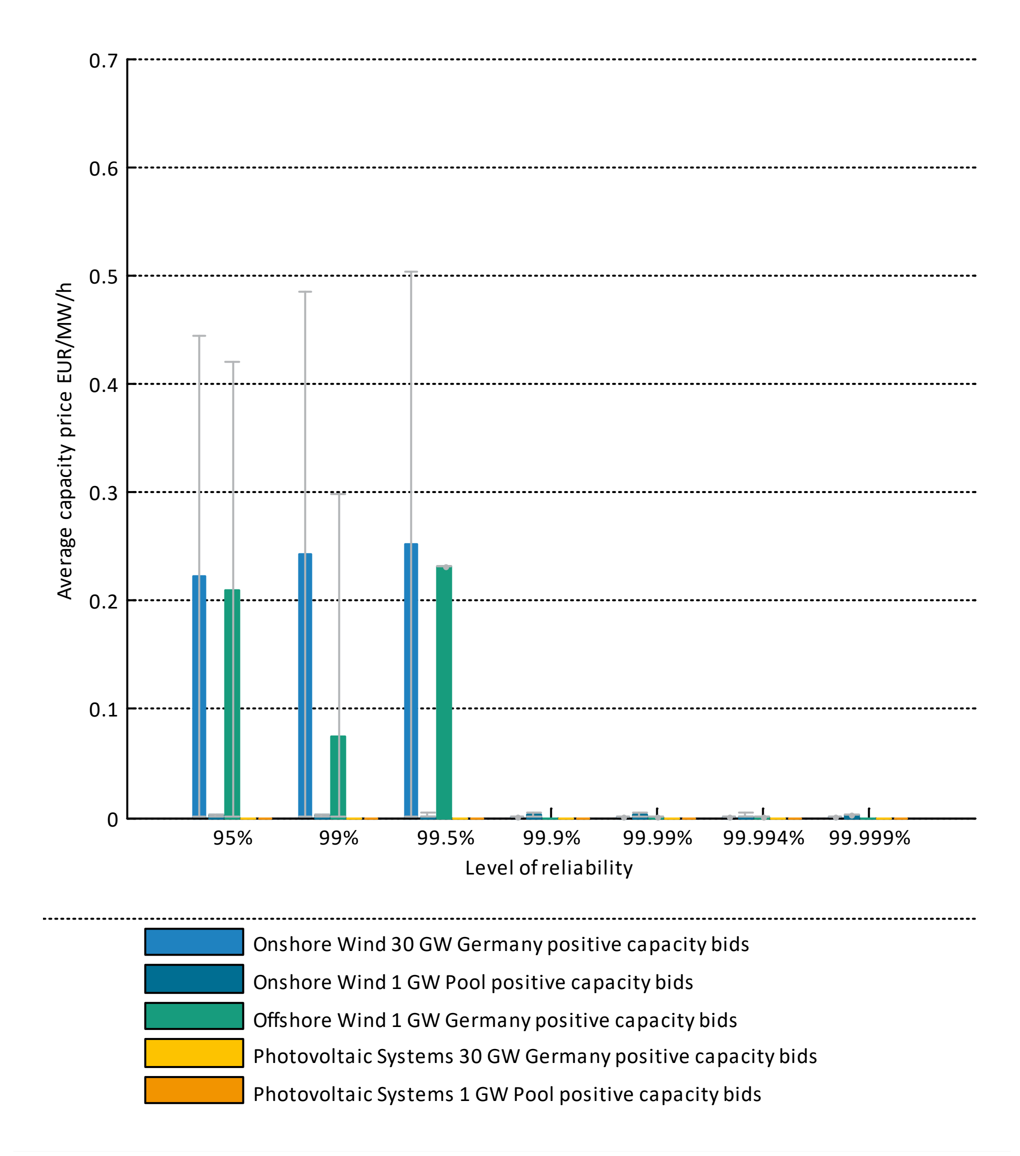
Source: Own analysis

Figure B-32: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of twelve hours in the positive secondary control reserve market



Source: Own analysis

Figure B-33: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of twelve hours in the negative tertiary control reserve market

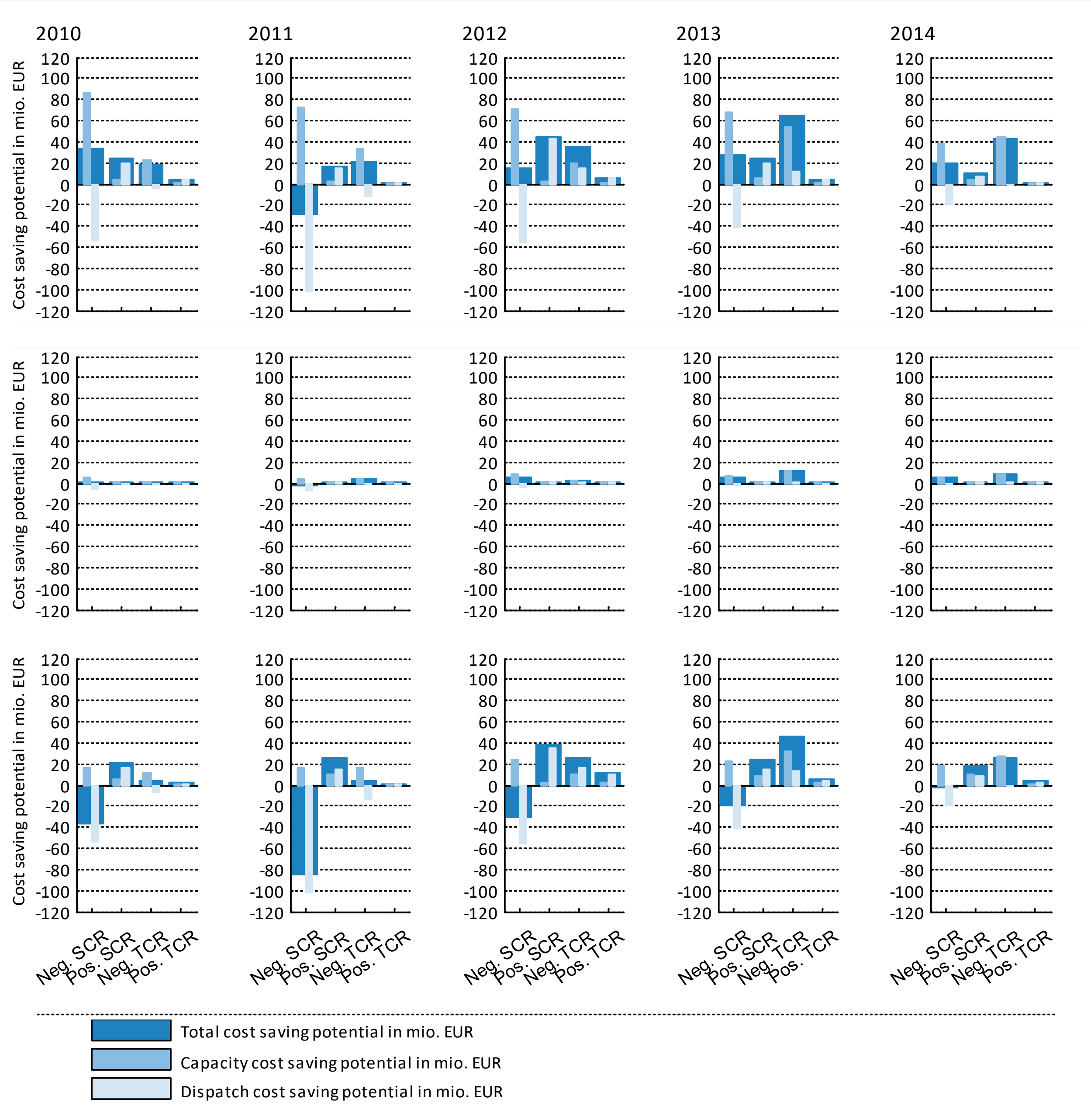


Source: Own analysis

Figure B-34: Annual average profit maximizing capacity price bids for different fluctuating RES generators with different levels of reliability for the product length of twelve hours in the positive tertiary control reserve market

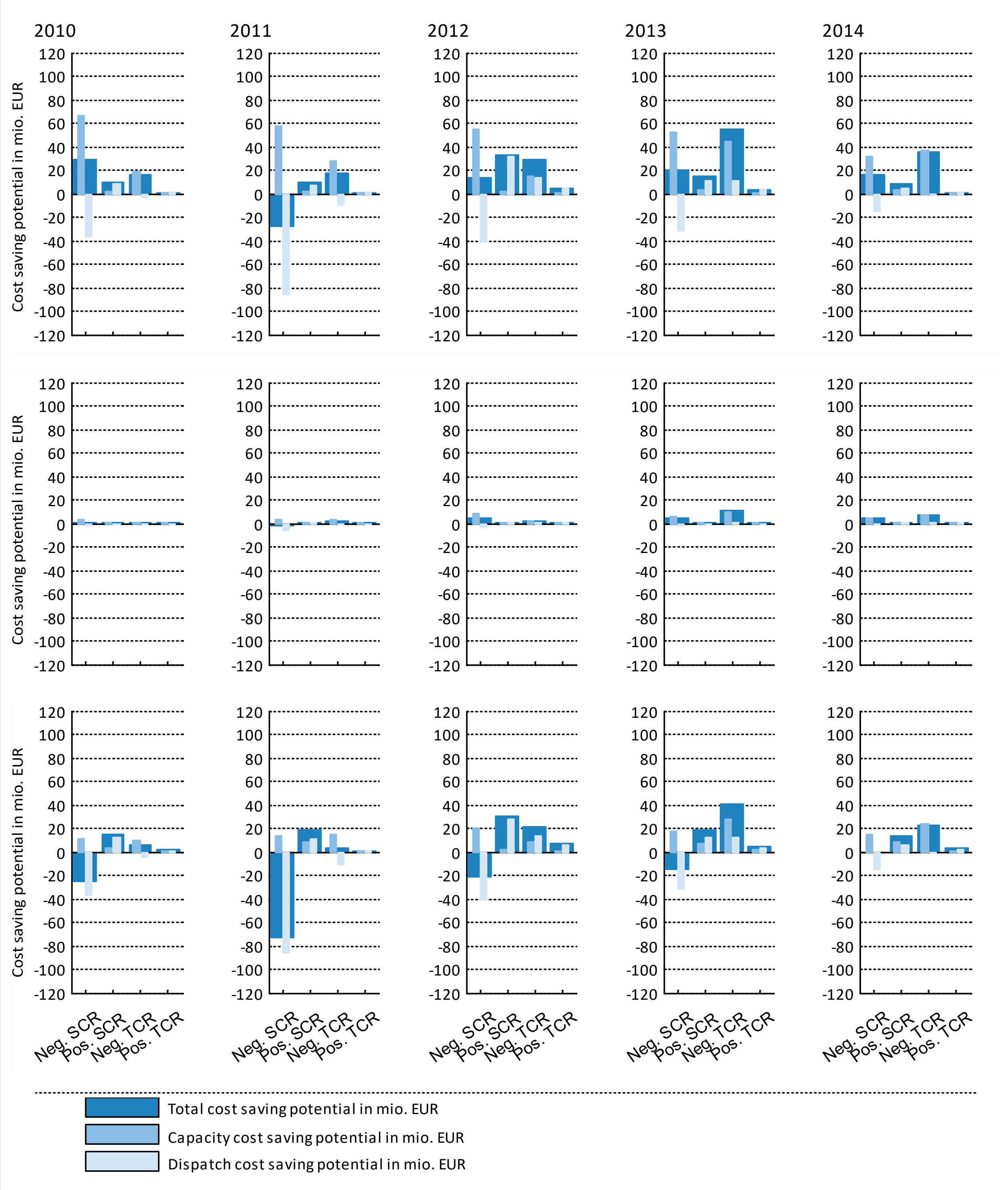
Appendix C Plots on economic impact on the system level

Appendix C-A Cost saving potentials



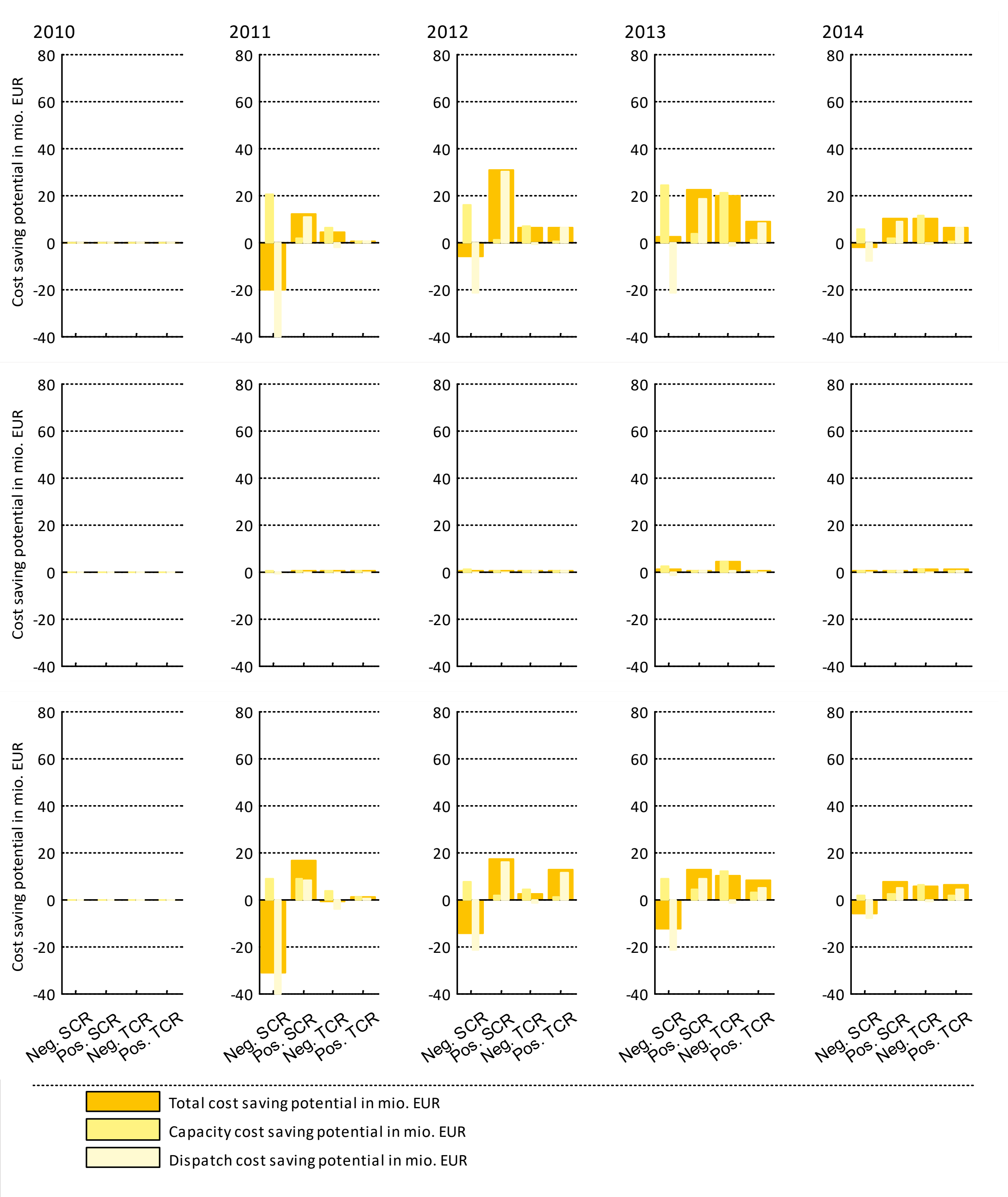
Source: Own analysis

Figure C-35: Capacity, energy and total cost saving potentials of the German 30 GW wind onshore pool in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well as the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, the years 2010 to 2014, and a product length of four hours



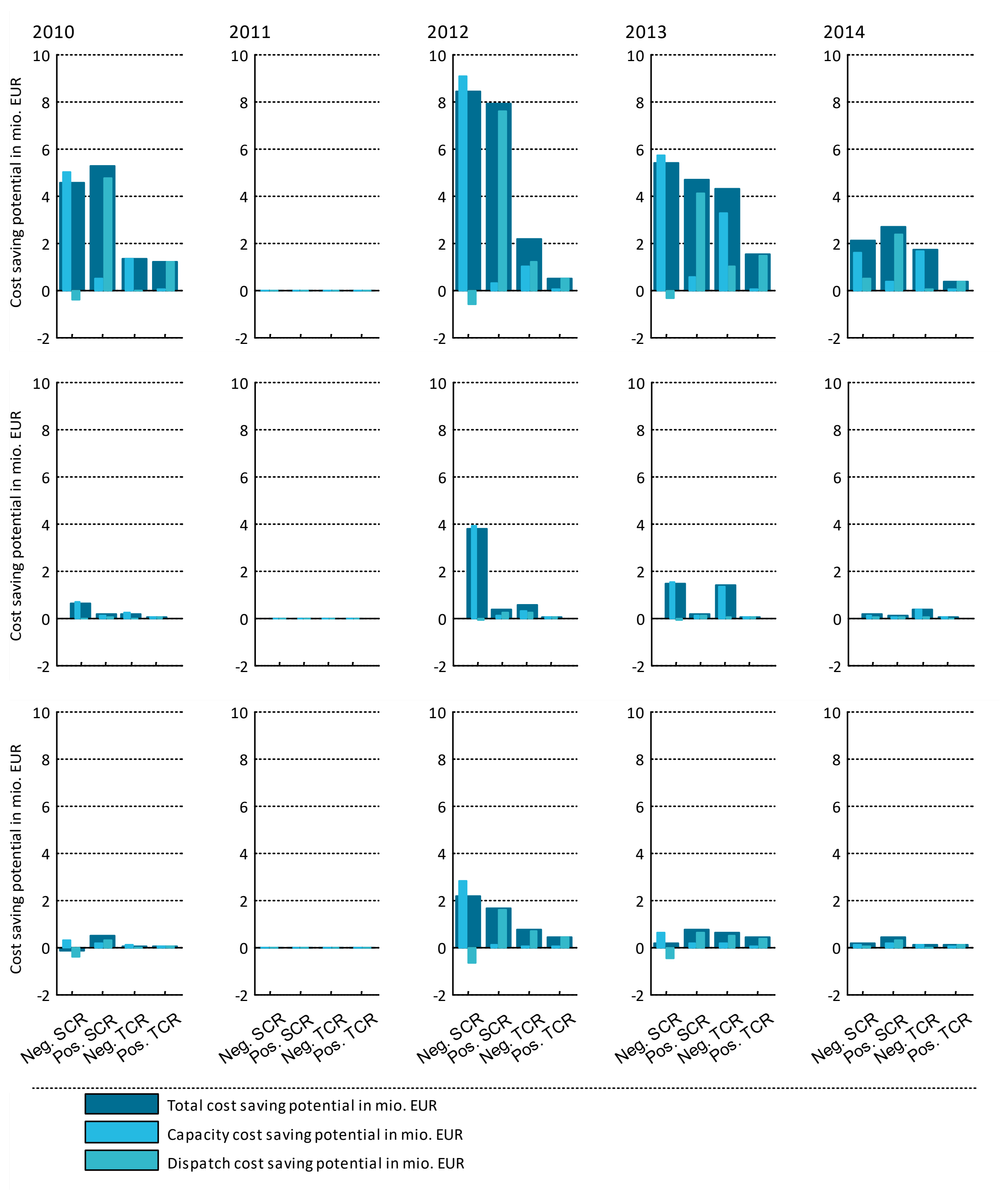
Source: Own analysis

Figure C-36: Capacity, energy and total cost saving potentials of the German 30 GW wind onshore pool in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well as the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, the years 2010 to 2014, and a product length of twelve hours



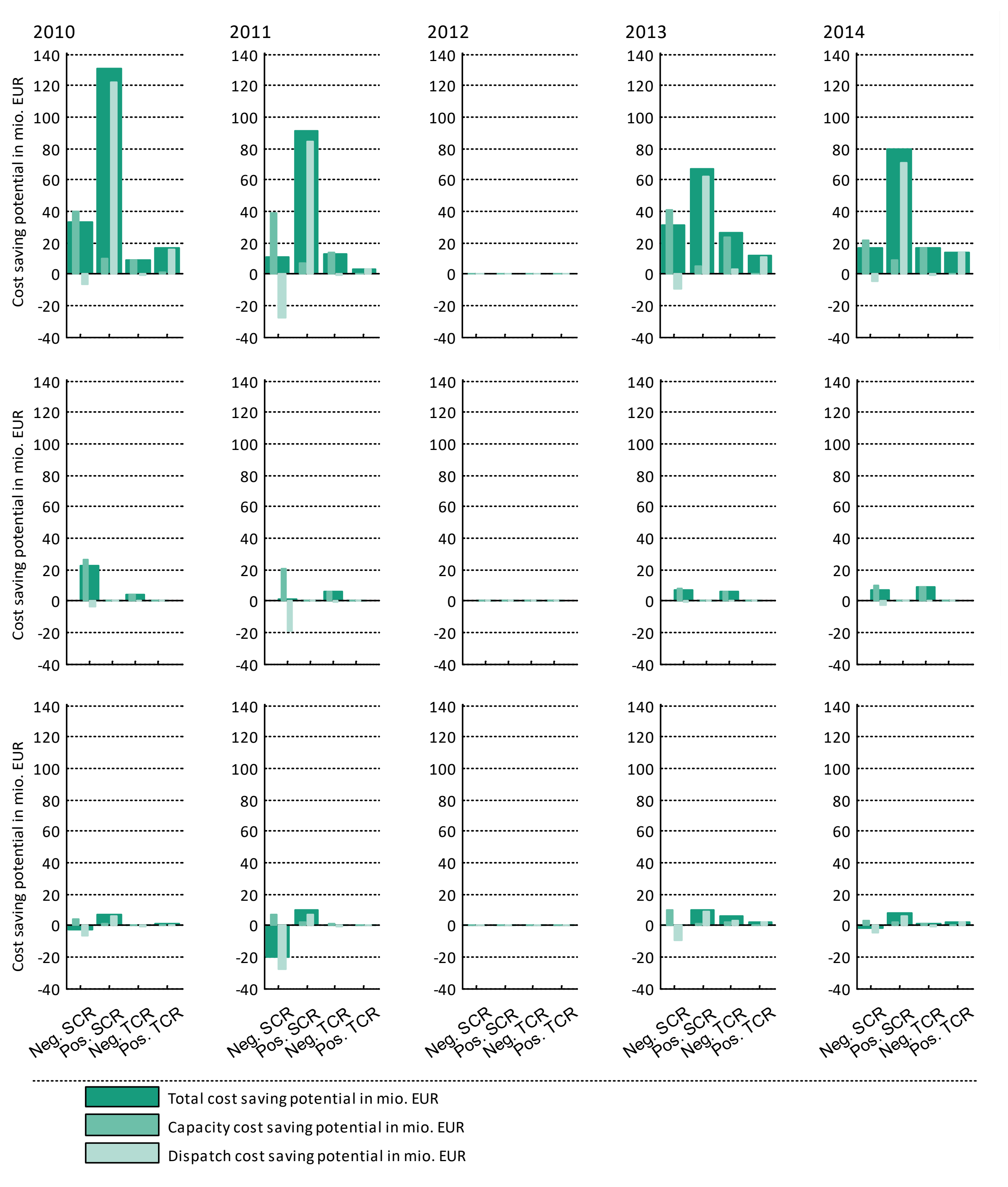
Source: Own analysis

Figure C-37: Capacity, energy and total cost saving potentials of the German 30 GW pool of PV systems in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well as the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, the years 2010 to 2014, and a product length of four hours



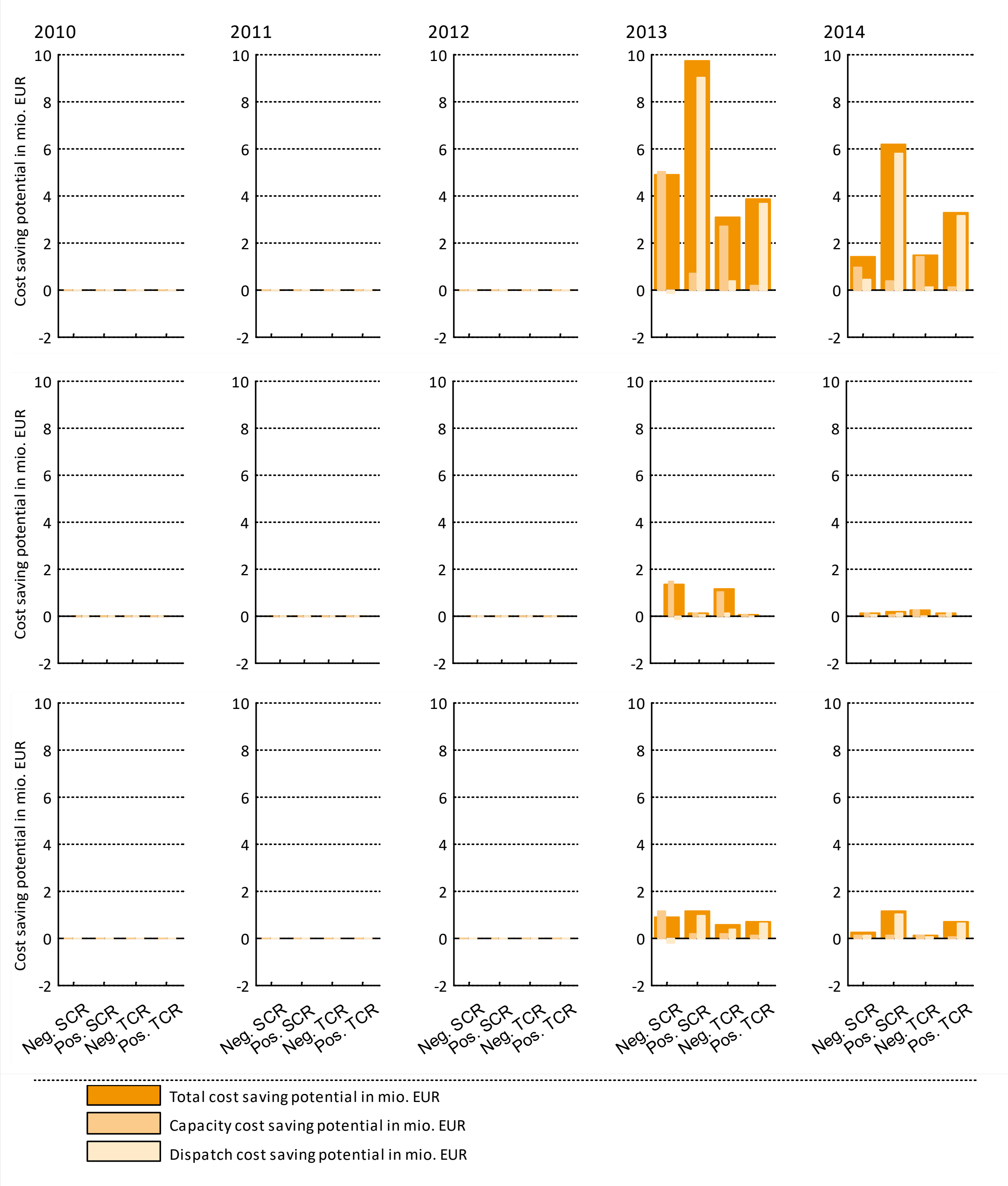
Source: Own analysis

Figure C-38: Capacity, energy and total cost saving potentials of the 1 GW wind farm pool in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well as the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, the years 2010 to 2014, and a product length of one hour



Source: Own analysis

Figure C-39: Capacity, energy and total cost saving potentials of the German 1 GW offshore wind farm pool in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well as the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, the years 2010 to 2014, and a product length of one hour

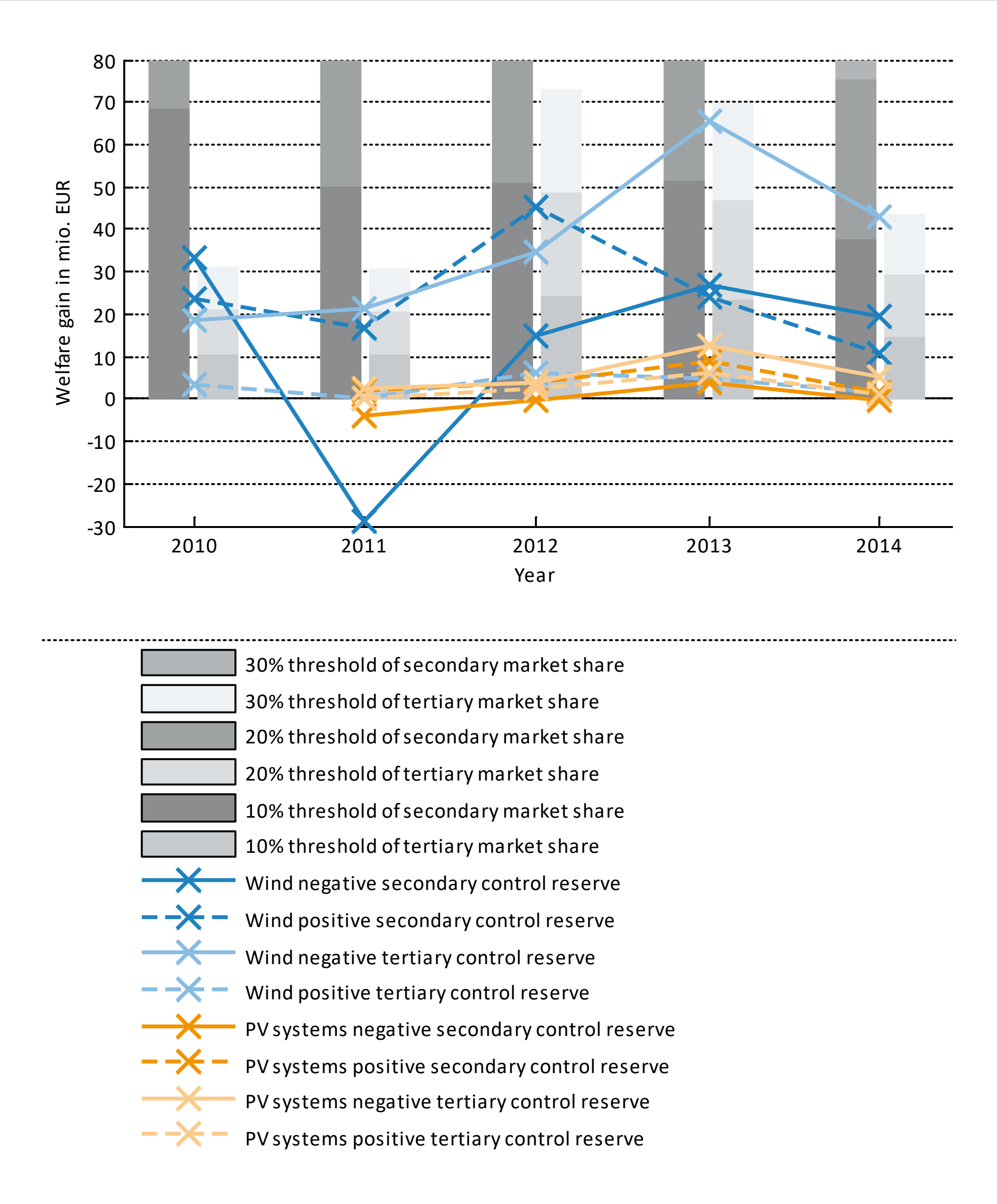


Source: Own analysis

Figure C-40: Capacity, energy and total cost saving potentials of the 1 GW pool PV systems in the negative and positive secondary and tertiary control reserve markets for the opportunity cost based approach with the available active power (top) and balance control mechanism applied (middle) as well as the profit maximizing based approach (bottom) for a level of reliability of 99.994 %, the years 2010 to 2014, and a product length of one hour

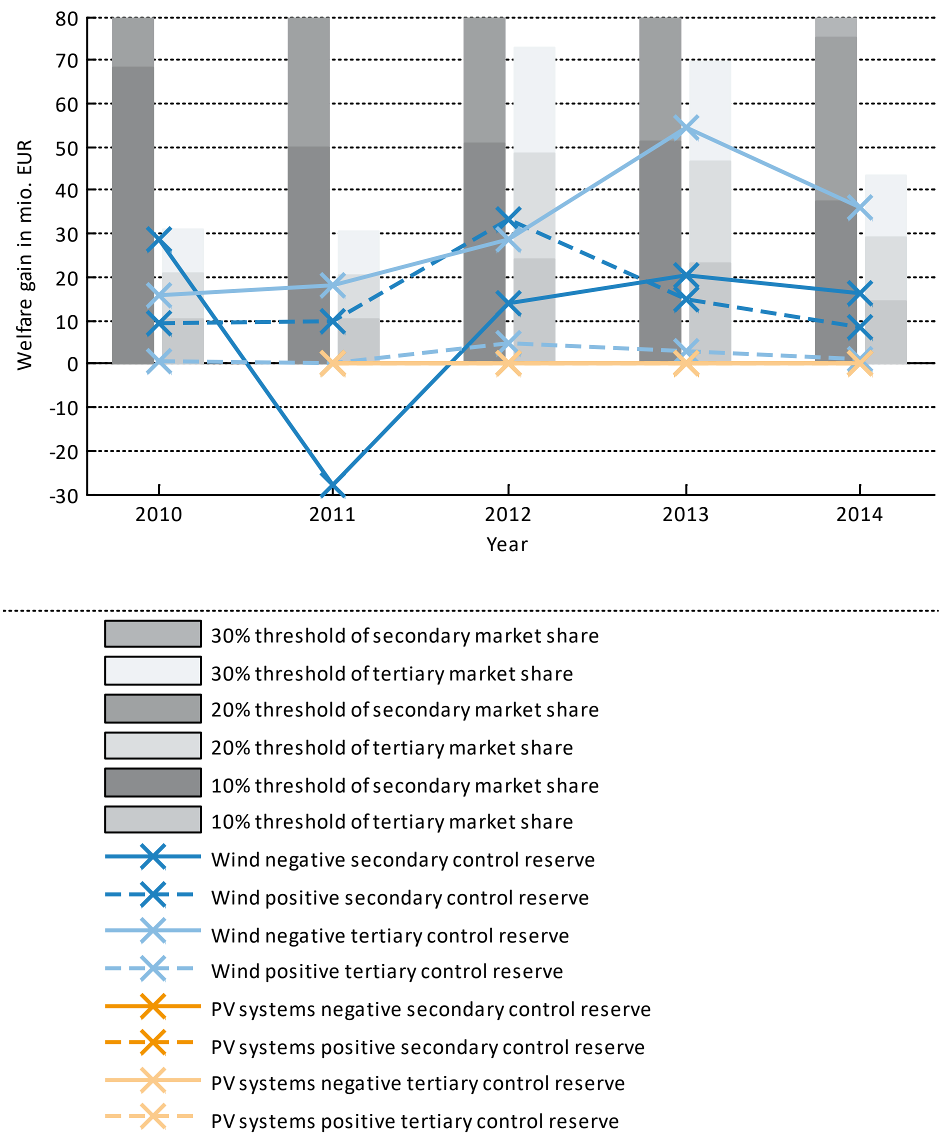
Appendix D Plots on social welfare gain

Appendix D-A Total welfare gain



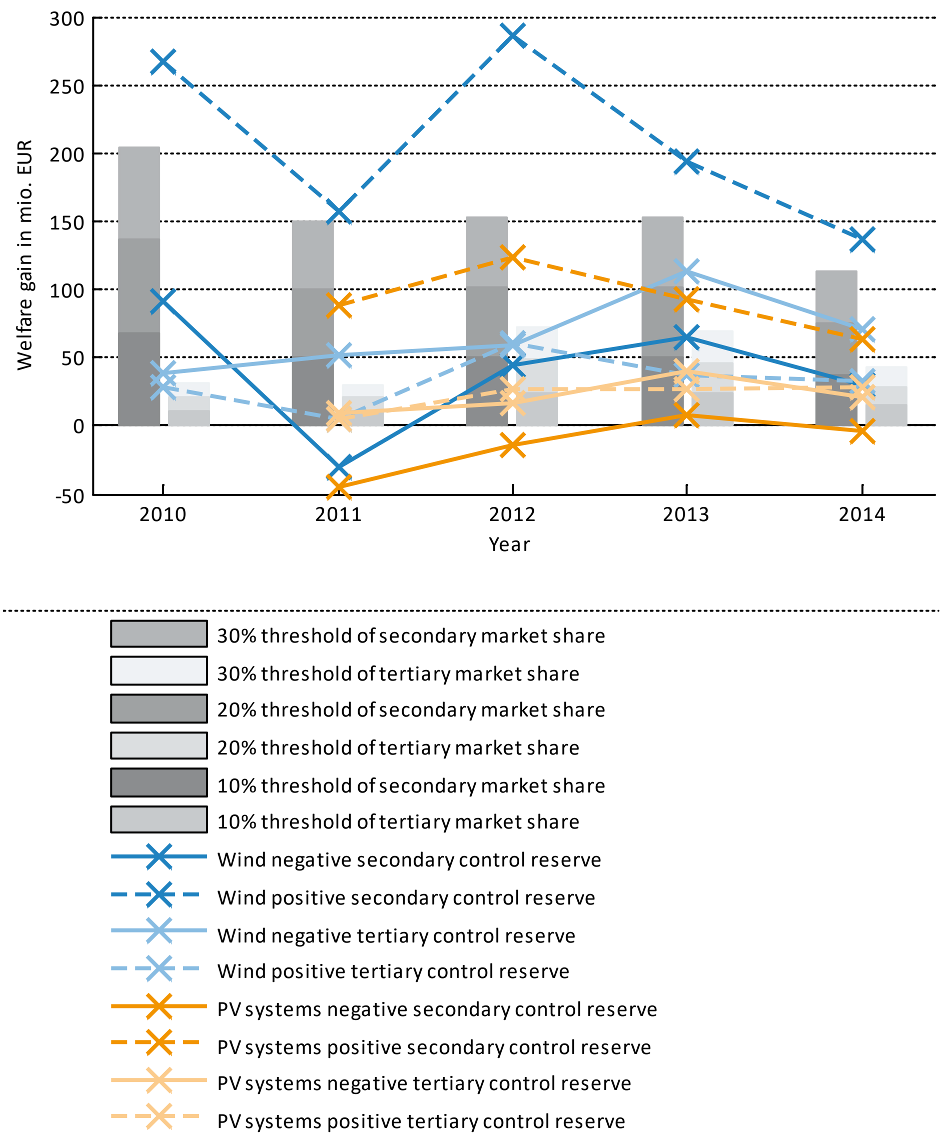
Source: Own analysis

Figure D-41: Total welfare gain induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of four hours, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market based on the total cost saving potentials



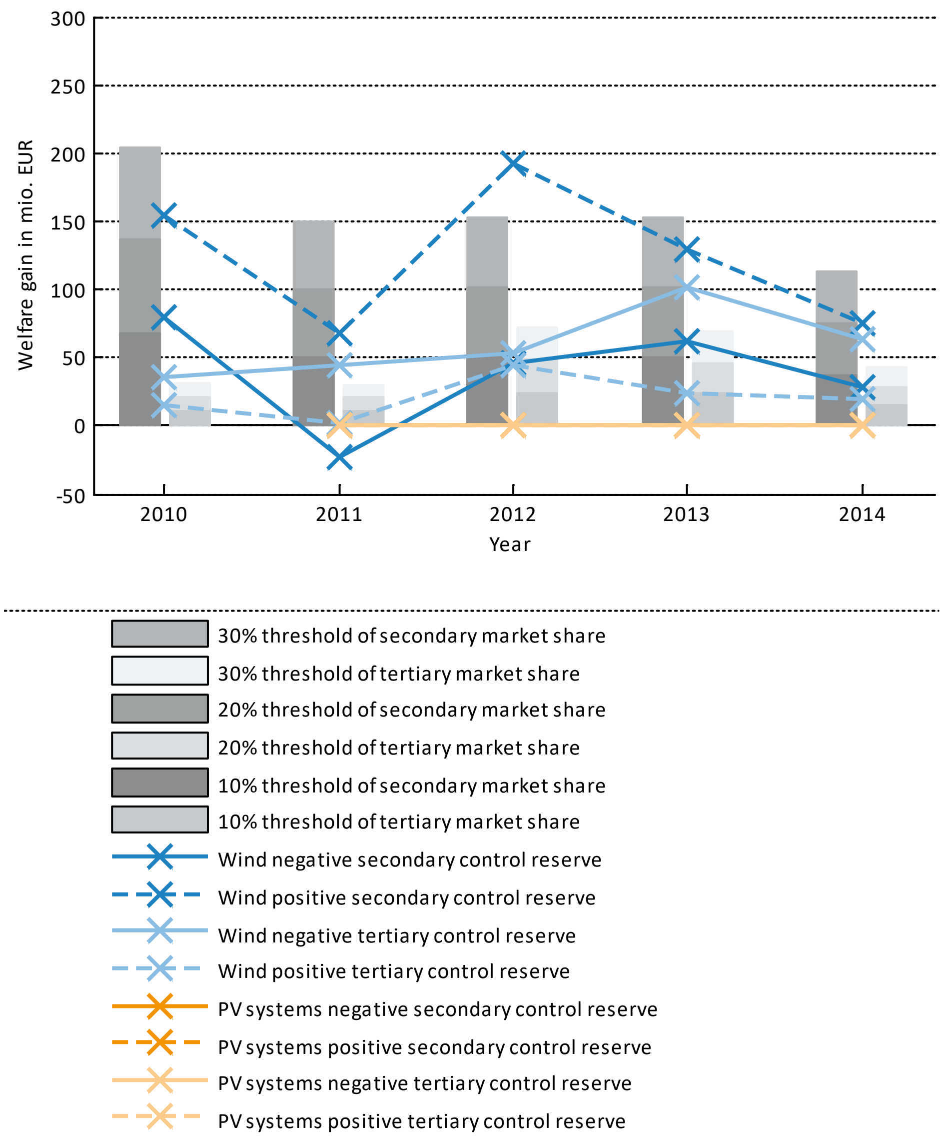
Source: Own analysis

Figure D-42: Total welfare gain induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of twelve hours, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market based on the total cost saving potentials



Source: Own analysis

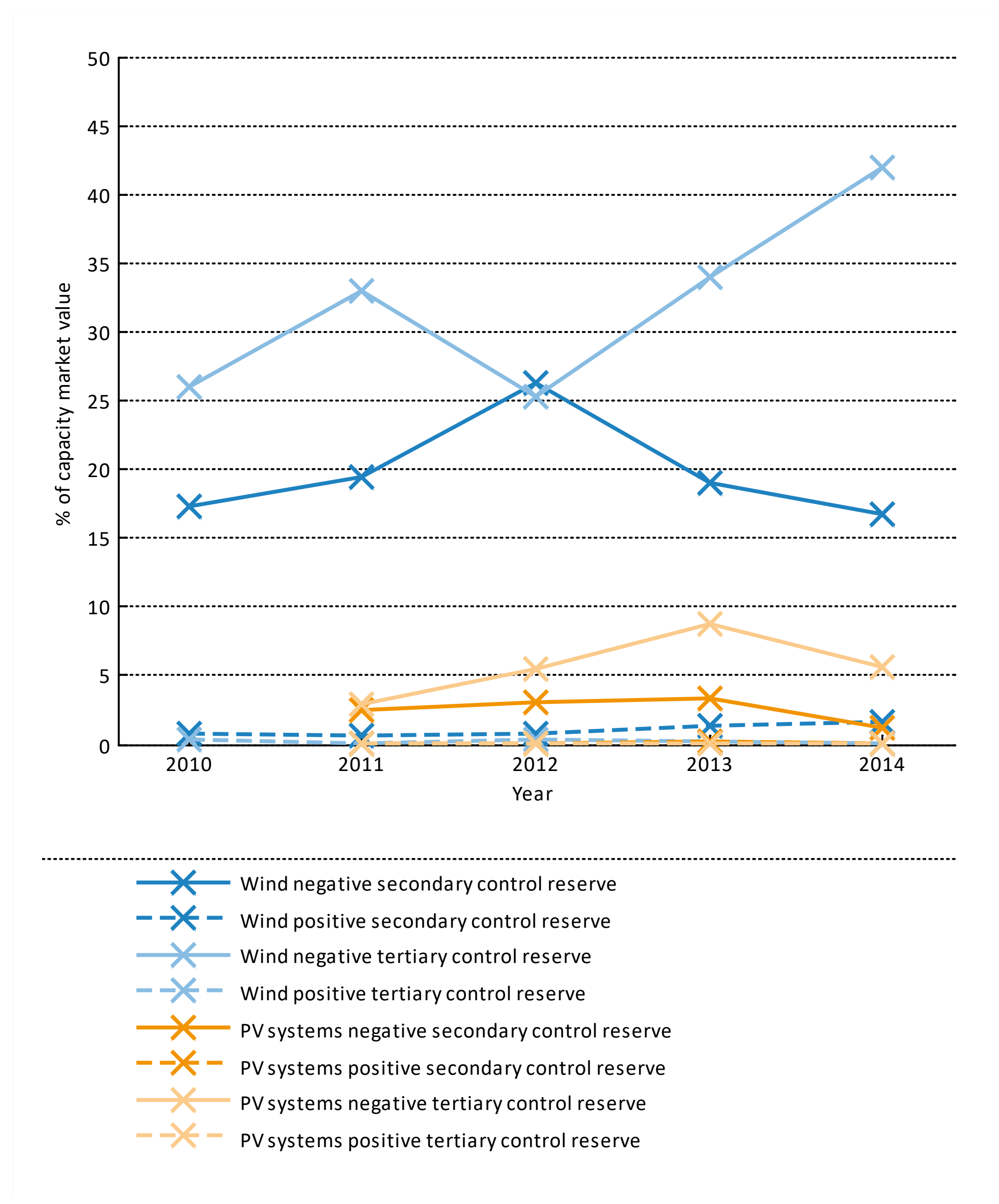
Figure D-43: Total welfare gain induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of one hour, a level of reliability of 95 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market based on the total cost saving potentials



Source: Own analysis

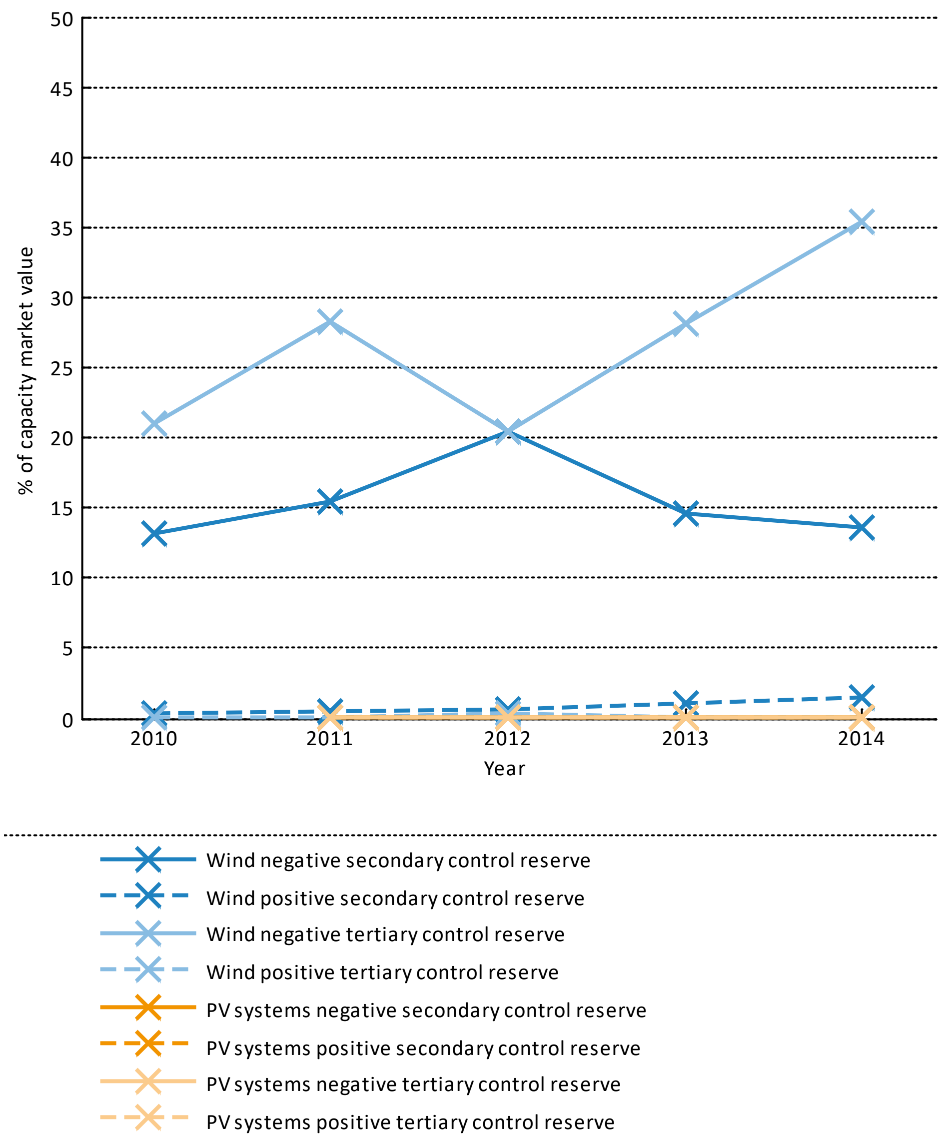
Figure D-44: Total welfare gain induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of twelve hours, a level of reliability of 95 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market based on the total cost saving potentials

Appendix D-B Ratios between capacity component welfare gain and capacity market volume



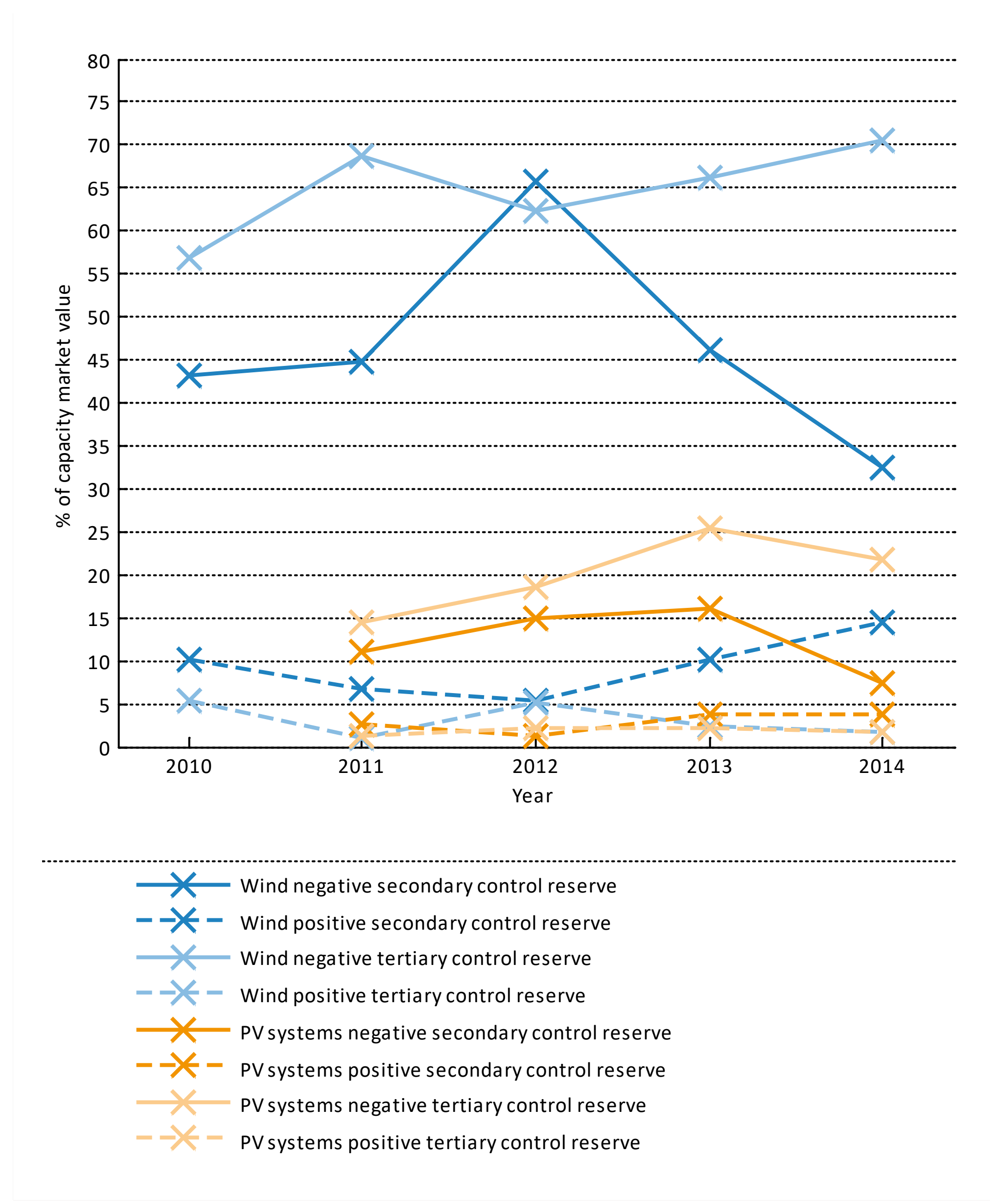
Source: Own analysis

Figure D-45: Ratio between the capacity component welfare gain and the capacity cost market value based on capacity cost reductions only induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of four hours, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market



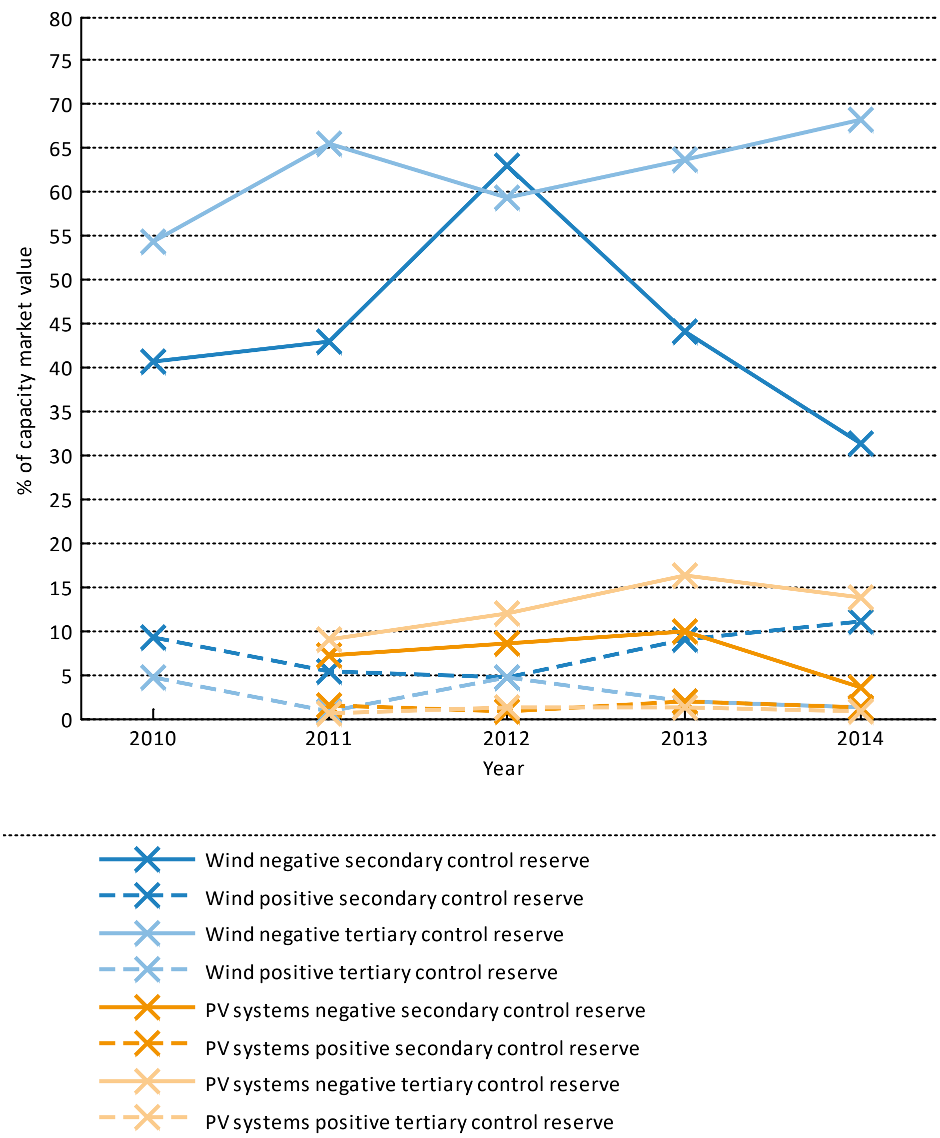
Source: Own analysis

Figure D-46: Ratio between the capacity component welfare gain and the capacity cost market value based on capacity cost reductions only induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of twelve hours, a level of reliability of 99.994 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market



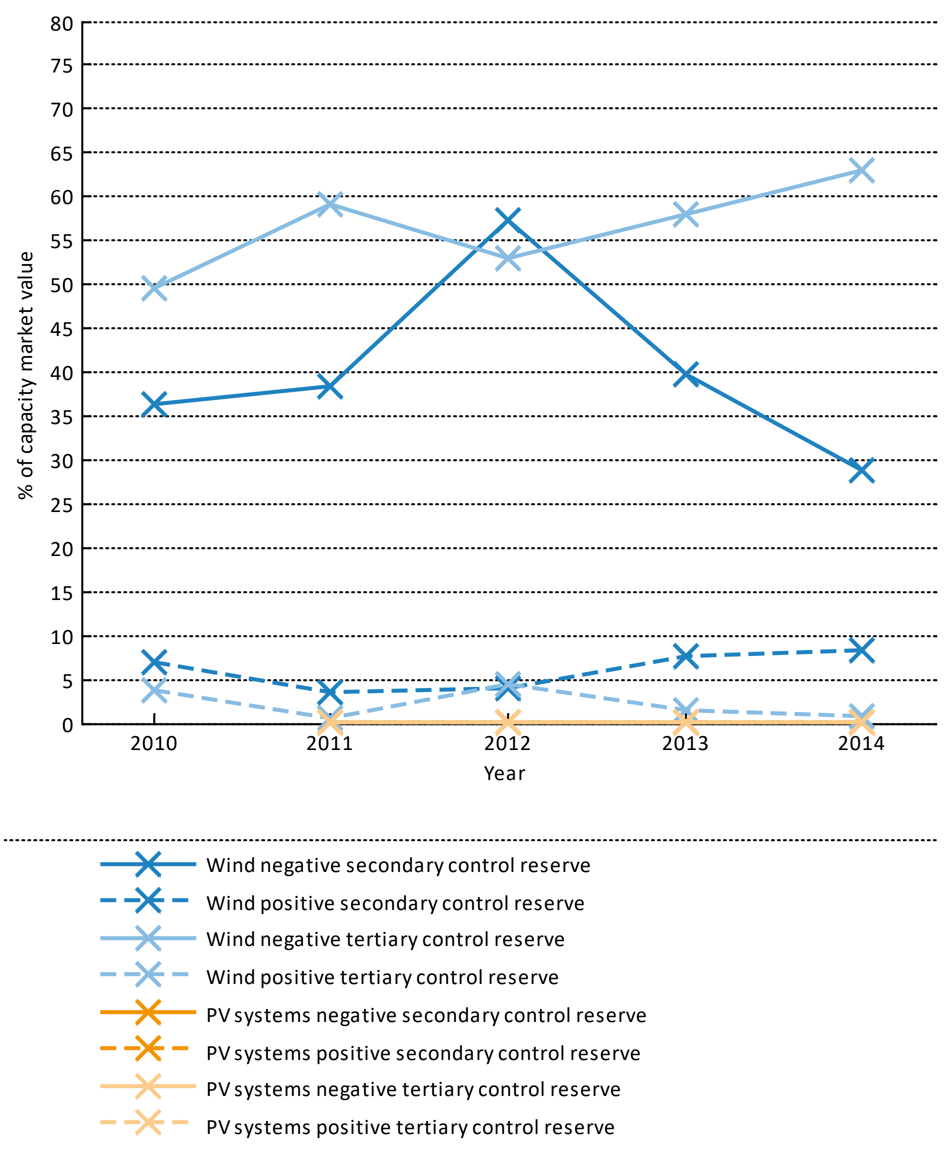
Source: Own analysis

Figure D-47: Ratio between the capacity component welfare gain and the capacity cost market value based on capacity cost reductions only induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of one hour, a level of reliability of 95 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market



Source: Own analysis

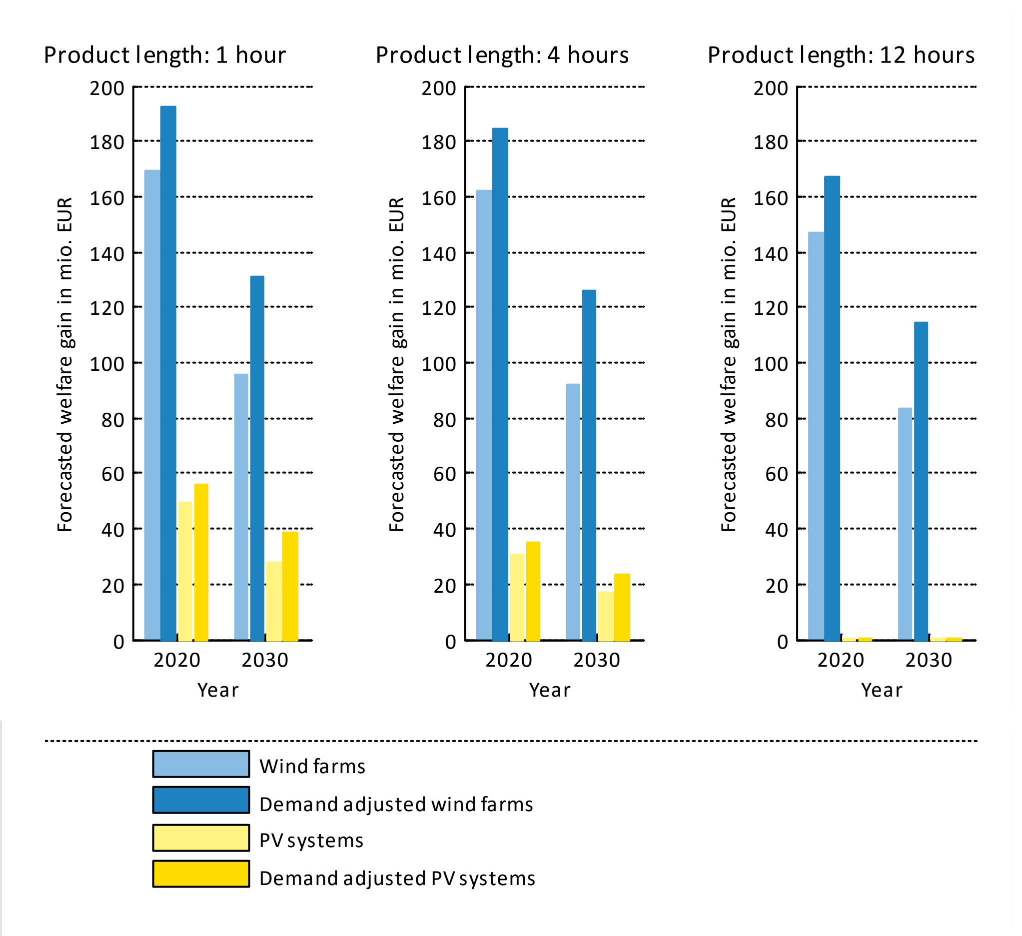
Figure D-48: Ratio between the capacity component welfare gain and the capacity cost market value based on capacity cost reductions only induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of four hours, a level of reliability of 95 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market



Source: Own analysis

Figure D-49: Ratio between the capacity component welfare gain and the capacity cost market value based on capacity cost reductions only induced by the German 30 GW pool of wind farms and the 30 GW pool PV systems for a product length of twelve hours, a level of reliability of 95 % and the available active power proof method applied in the negative and positive secondary and tertiary control reserve market

Appendix D-C Forecast welfare gain



Source: Own analysis

Figure D-50: Forecast of welfare gain by the fluctuating RES generators in the control reserve market for the years 2020 and 2030 at a level of reliability of 95 %

Appendix E Source code and sample data

In the attachment of this PDF, you will find the source code of the REBal model in the version number 1.4, which was used for this doctoral thesis. The attachment can be extracted from the PDF by clicking on the floppy disk icon and saving it to the desired location.

Note that the model is further developed and results might deviate in the future. The attached archive contains a README file with further explanation on how to use the model as well as sample data for the first two weeks in January 2014. The archive can be opened with the open source software 7zip, amongst others supporting the *.7z file extension.