Positioning of operating responsibility of electrical energy storage

Case study: EES implementation in the Dutch electricity system

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Challenge the future

Positioning of operating responsibility of electrical energy storage

Case study: EES implementation in the Dutch electricity system

by

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Summary

In the recent past years, the Netherlands has tendered 3.5 GW of offshore wind power. The instalment of these variable renewable energy sources has as consequence that the variability of the total electricity supply grows. To solve the problems associated with high variability, the network needs flexibility. A special form of flexibility is electrical energy storage. An application of this technique on large scale is applied in South Australia where a 129 MWh and 100 MW electrochemical storage is installed in a high volatile electricity system. Many researches have indicated that the implementation of storage capacity will be needed in the future to deal with the variability of these new renewable energy sources. Still, no researches have been found where operating responsibility is a variable in research parameters. Therefore, the problem in this research is defined as; It is unknown how different actors in the Netherlands will operate an electrical energy storage. The goal of this research is to investigate the objectives of actors in the Dutch electricity system and how these objectives change the operating profile of the electrical energy storage and how they influence the network by operating the storage capacity. The research question is defined as: *What is the impact of different objectives of actors behind operation profiles of electrical energy storage on the imbalance of the Dutch electricity network?* This research question is answered by using research methods such as desk research, expert interviews, modelling and statistical analysis.

In the beginning (chapter 2), the Dutch electricity system will be researched by doing a desk research. The outcome of this chapter is a subsection of the system which is used as scope for the research. Then (chapter 3), actors are investigated and objectives of actors are validated by expert interviews. In chapter 4, the performance metrics of the model are investigated and defined. The last step before simulating is creating the model which is described in chapter 5.

In chapter 5, a set of experiments are chosen to research the changes the operational profile and network imbalances encounter for different operational parties for the storage capacity. The experiments have as input an actor portfolio and an actor objective. The actors and objectives have been chosen are presented in the table below.

	Base case	**VRES case**	**Gas case**	**Consumer**	**Prosumer**
Type actor	Before transmission	Before transmission	Before transmission	After transmission	After transmission
Optimisation	Revenue maximisation	Revenue maximisation	Revenue maximisation	Peak minimisation	Peak minimisation
Asset	-	Wind farm	Gas turbine	Demand profile	Demand profile + Pv panels

These are then used to optimise the operational profile of the storage capacity with respect to their objective within the conditions set for the model. The conditions consist of market prices of both day ahead market and balancing market, the nominated portfolio power for the day ahead market and the portfolio position for the balancing market. From there, optimisation problems are defined to calculate the operational profile of the storage capacity to optimise the portfolio objective.

This results in operational profiles of the storage capacity within different conditions. The operating responsible parties can be divided into two categories. The first category is before transmission. These companies are put into the same category since they have the same economic structure. Therefore, their use of storage capacity looks alike. Still some extra synergy can be found while optimising for the wind farm case due to the variable character of this energy production. The flexibility of the storage capacity is able to shift some load to more favourable imbalance volume periods. The next conclusion can be made is about the added benefit of storage capacity next to extra flexible capacity in the form of a gas-fired power plant. In this case, the storage still optimises with respect to the market and market results are found to be still very volatile even after adding extra flexible capacity. Therefore, even with the decreased benefit with respect to the wind farm case, the balancing still favours the network balance. The second category of storage usage is after transmission. The costs structure changes and therefore an other optimisation has been done. This optimisation does not favour the imbalance of the network but there is not concluded is has a negative effect. The optimisation after transmission results in an average daily cycle for which in the end energy retailers can respond in the market due to this change. This optimisation does favour local distribution networks since the peak demand periods are lowered by substituting network power by storage power. The overall peak consumption for the consumer case drops to 75% of earlier peak consumption under 2015 conditions. The prosumer case is even more able to drop the peak power by an extra of 10%. Finally, the research question is answered by concluding the following. The change of operating responsibility does have influence on the usage of the storage. The biggest difference of storage usage is due to the fact that the cost structure of the operating responsible parties change due to the institutional location in the network. The storage operating responsible party's institutional position in the system has influence on the implications of network imbalance volume. To minimise societal costs, the focus on implementing storage capacity should be on the supply side of the electricity system.

Preface

I would like to dedicate this report to my grandfather, Jacobus Everaert (08-11-1929 - 14-08-2018). As long as I remember I have lived in the neighbourhood of my grandparents. From the beginning of my school career, my grandfather has always helped me with my languages and with maths. This has as consequence, that my interest in maths and the STEM courses were enhanced. I can literally say that the interests I have today have been a direct derivative from the actions of my grandfather 20 years ago. The reason for this paragraph is the extreme sadness I am experiencing at the moment of typing this section. The news of my grandfather being put to sleep to rest his final days of his life has just been received. Just a few months ago, my grandfather told me he was so very proud of the fact that I will become an engineer, graduated from the University of Technology Delft. Seventy years ago, my grandfather tried to do the same but unfortunately was not able to succeed. The overwhelming feelings for not being able to show and tell my grandfather of my graduation will probably stick with me forever but I am certain that my grandfather always has believed in my abilities to graduate and I can only praise the support he has given me from the start. Lieve Opa, bedankt voor al je hulp en mag de trotsheid tot in uw allerlaatste dagen een stukje geluk geven.

After this piece, I would like to thank all my other friends and family. During my period at university, my mental health was not always the best but in the end, my friends and family helped me true these hard times. Especially, I want to thank my girlfriend Ivana. She has been my rock in tough times. Finally, a big thanks need to head over to the university and its staff. Thanks to their policies, I was able to find the best pace for me to finish my studies. I want to thank my graduation committee, Paulien Herder, Rob Stikkelman and Daniel Scholten. Even though I am not the easiest student to work with, they have managed to pull me through this graduation period and have learned to not to take the biggest bite and to be more thoughtful in general.

I look forward to the future. I have set some big goals for myself in the future to aim my career. Let this be the unveiling of my goal in summarised form: STOP EMITTING CO_2.

R.J. Everaert
Delft, August 2018

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Research definition

A well accepted fact is that the world wide climate change is a direct result of the emission of carbon dioxides. A big factor in the emission of these carbon dioxides is the generation of electricity. This is the reason why governments all over the world including the Netherlands are pushing to create more sustainable electricity sectors. This results in the instalment of variable renewable energy sources (VRES). A total of 3,5 GW of offshore wind power is bound to be build in the Netherlands for coming years.

A research is designed to investigate one of the challenges with respect to this innovation. This chapter is set out to first define a problem and give a research goal and then divide the research into sub questions. The methods used in this thesis are defined in the following section and finally the structure of the thesis is reported.

1.1. Problem definition

The experience from systems with high variable renewable energy production has indicated that the integration of these VRES comes with technical challenges. The technical challenges are a consequence of the different characteristics of the VRES with respect to conventional power plants, in particular, the high volatility. Variable renewable energy sources, for example wind turbines or photovoltaic cells, are dependant on weather conditions such as wind speed for wind power and solar irradiance for PV cells. Sudden changes in the weather pattern can result in more or less power than anticipated. The rapidly changing characteristics of these power producing metrics and the unpredictability, results in a high volatility of generated power [4]. The change of generated power with respect of the nominated power on the day ahead is called imbalance. The electricity network is subject to bigger unpredictable power spikes (imbalances) due to the increase of the capacity of the variable renewable energy sources. This poses a problem due to policies which dictate security of supply. The network operators are obliged to alleviate the power peaks without losing performance [5]. The increasing uncertainty of production has created a notion called Variability.

To counter the problems which are associated with variability the system needs flexibility [6]. Flexibility is defined as: one that enables the utility to quickly and inexpensively change the systems configuration or operation in response to varying market and regulatory conditions[7]. If not enough flexibility is present in the system, processes should be stopped to alleviate the imbalance of the system. When rebooting the processes from a stand still, also known as a ”black start”, large additional costs are the consequence [8]. These additional cost will eventually be payed by the society. Extra flexibility can abate these additional costs due to the decrease of number of black starts. The social welfare will be greatly benefited when these costs are abated. One of the possibilities to increase the flexibility of the system is to implement reversible electrical energy storage. Implementation of storage on large scale can be seen in South Australia. A big battery, built by Tesla, has been incorporated in the electricity system. This battery has a 129 MWh capacity and a 100 MW maximum power. If this battery is installed in the Netherlands, some questions arise such as who should operate this electrical energy storage to increase the social welfare and is there a viable business case for storage.

Many researches have indicated the electric energy storage (EES) as a possible solution to variability.

Still none of the studies have implemented responsible operating party objectives as a variable in the possible parameters. The objective of using such storage is dependent on the incentive of the type of actor having the responsibility over the usage of the storage and the structures related to this incentive. In literature, characterisations of storage with respect to markets have been given [9, 10]. Future values of storage capacity have been calculated by many [11–14] but none of them had operating responsibility as a research variable. This can be seen as the knowledge gap in the scientific literature.

Ownership and division of operating responsibility of such asset is possible in multiple manners [15]. The ownership of this asset from an outside investor could lead to an common operating responsibility. If this is true, a framework can be used to align individual objectives to obtain individual and total benefits. This framework is emanated from political science and is called IAD framework [16]. For a single operating responsible party, it can be the case that the party owns the storage capacity or that there has been agreed on an operating responsibility agreements. In this research, it is assumed that the single operating responsible party is owner of the objective of operating of the storage capacity.

In this thesis, the problem is defined as; It is unknown how different parties in the Netherlands will operate a electrical energy storage. It is important to know, how possible operators of storage will use this storage to increase their performance with respect to their objective. This is important since the government tries to increase the social welfare of the electricity system. Using a storage could change the states of the system and therefore change the social welfare. To ensure the social welfare increases, the government should set out to help implement the storage at the correct actors. To find out how they would operate the storage, their objectives, regulatory conditions and technical constraints must be researched.

The goal is to investigate the objectives of actors in the Dutch electricity system and how these objectives change the operating profile of the electrical energy storage if this is part of their portfolio. If this goal can be achieved, this report could do a recommendation with respect to implementation of storage in the Dutch electricity system so that the social welfare will increase.

For this problem statement, a representation has been made to visualise the obtained structure of the problem.

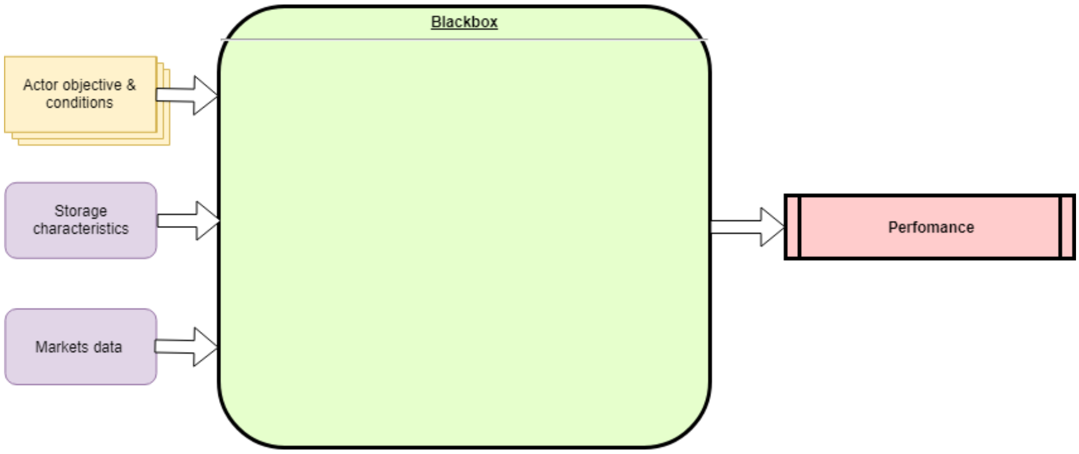


Figure 1.1: Problem structure found in problem introduction

During this research, the representation will be expanded to create a full research representation.

1.2. Research question

A research question is defined to superintend the research with respect to a contribution to the researched system and scientific knowledge. Then, the research question is divided into sub questions to structure the research. The division creates a structural ladder for the researcher to answer the main research question in the end. The main research question is defined as:

What is the impact of different objectives of actors behind operation profiles of electrical energy storage on the imbalance of the Dutch electricity network?

From this research question a few key words are identified. From these keywords sub questions are produced.

- What are the fundamentals of the Dutch electricity markets?
- What electrical energy storages are suitable for instalment in the Dutch electricity sector?
- Which actors are considered to operate electrical energy storage capacity?
- How can there be a model developed to simulate the change of actor with operating responsibilities as a variable in storage usage determination?
- How does the operational profile change under different actor conditions in the Dutch electricity system?

1.3. Methodology

For this research, multiple methods are used to investigate the defined problem. These methods include desk research, expert interviews, modelling and statistical analysis.

Desk research is a combination of literature research and empirical research on the internet. As the name suggests, it is a research methodology which is carried out behind a desk. Websites such as Google and Yahoo are used to find information or even data which are needed for the research.

Expert interviews is a research form where the information needed is extracted with an interview from an expert in the field. This method is mostly used in social sciences to uncover social relations of groups. Expert interviews are individual interviews carried out between an interviewer and respondent. The respondent must be a specialist in the subject in question. An hypothesis must be formed beforehand of the interview and the interviewer will try to validate this hypothesis. [17]

Modelling is a research technique where a model is made to represent a system. The representation is either physical or mathematical. A mathematical model is used in this research to represent the electricity system and specifically the market-physical relation. The model is used to simulate behaviour of the modelled system. The simplifications and assumptions are needed to represent a complex system but it does make it possible to work with such model. It is important to note that the simplifications and assumptions have influence on the outcome of the model simulations.

Statistical analysis is the partition of science which focuses on data collection and presentation. Statistical analysis is usually used for presenting large data sets where statistical parameters are used to discover underlying patterns and trends.

1.4. Thesis structure

The structure of the thesis is based on the sub questions. Sub questions are the subject for a chapter. The conclusion of the chapter should answer the sub questions.

The first chapter for answering sub questions will answer two sub questions. the sub questions taken as subject are, *What are the fundamentals of the Dutch electricity sector?* and *What electrical energy storages are suitable for instalment in the Dutch electricity sector?*. These questions will be answered by doing a desk research. Scientific and institutional literature will help structure a detailed overview of the electricity sector in the Netherlands. The goal of this chapter is to have a description of the electricity sector which is good enough to have a guideline for a model to implement storage technology.

The second chapter answers the third sub question, *Which actors are considered to operate electrical energy storage capacity?*, a literature research will be done to have an indication of type of actor objectives. Then the suggested objectives found in literature will be validated by doing in-depth expert interviews with actors in the Dutch electricity network.

The fourth sub-question is *How can there be a model developed to simulate the change of actor with operating responsibilities as a variable in storage usage determination?*. To answer this question, a model will be created which has actor objectives and conditions as input and calculates the optimal operation of the storage capacity under the conditions of different actors within the framework of the conceptual model.

The final sub-question, *How does the operational profile change under different actor conditions in the Dutch electricity system?*, will be researched by doing a case study by implementing the South Australian battery storage in the Dutch electricity system model under the 2015 conditions. This will be done with a quantitative research method namely simulation. Therefore, the 2015 market results will be taken as an input and dependencies of these results are researched or assumed. Then, each actor will be able to influence these results, one by one, by operating a reversible energy storage. The outcome of the model should be operating profiles of the electrical energy storage. Finally the results will be researched by doing a statistical analysis of the outcomes of the simulations with respect to the input network imbalance.

Then, a discussion of the model and results will be presented and within the scope of this discussion, a fitting conclusion about changing operating responsibilities of electric energy storage based on the in-depth expert interviews and calculations will be presented.

2

The electricity system

2.1. History

The first ever electricity system can be identified in the UK in the 1880's where Edison sold electric lighting for households and streets. Since then, asset owners would work for city companies to provide the city with electric lighting. The city/municipality would then distribute the electricity. Such system would be called vertically integrated or even monopolised system.

In the 1980's, Chile and Argentina experimented with privatisation of electricity markets and a big step forward came when the UK privatised the electricity supply industry. Other Commonwealth countries started deregulating electricity sectors and this started wholesale and retail markets on electricity. The same happened to the Netherlands, wherein 1998, the liberalisation was ordered and consumers got to pick their own supplier. Finally, in 2010 the forced division of retailing and distribution makes up the landscape as it is at this point.

In 1996 the liberalisation of the Dutch electricity industry was announced. This was presented by the Dutch government in the Third White Paper on Energy Policy. With the introduction of the Electricity act in 1998, all customers with 2 MW connections were able to choose their supplier. Since 2007, every customer is able to choose their supplier. Next to this, the Electricity Act 1998 mandates an unbundling of the transportation activities and production or distribution. Presently, the Dutch distribution and production companies own the low voltage networks. The national high voltage network is owned by a company called Tennet. Any network operator is responsible for the safety and reliability of the network and is obliged to provide connections and transport services. The transport tariff is a non-distance related tariff and is set by the Dutch electricity regulator. This Electricity Act 1998 article 10b excludes network operators from trading energy on any market. These are the main regulations which form the Dutch electricity network but this landscape gets directions from the European legislation as well. The Directive on Energy Efficiency (2012/27/EU) is the main directive for improving the decrease in emissions. The directive states that the European Union should not overshoot the target of 1483 Mtoe primary energy [18]. The push for decarbonisation is governed by the highest office in our institutional system.

2.2. Framework

An investigation of the economic landscape is needed to find operation strategies of actors in this setting. The researched framework is a framework produced at this university by Laurens de Vries [1]. This framework captures the socio-technical landscape needed for the implementation of storage capacity.

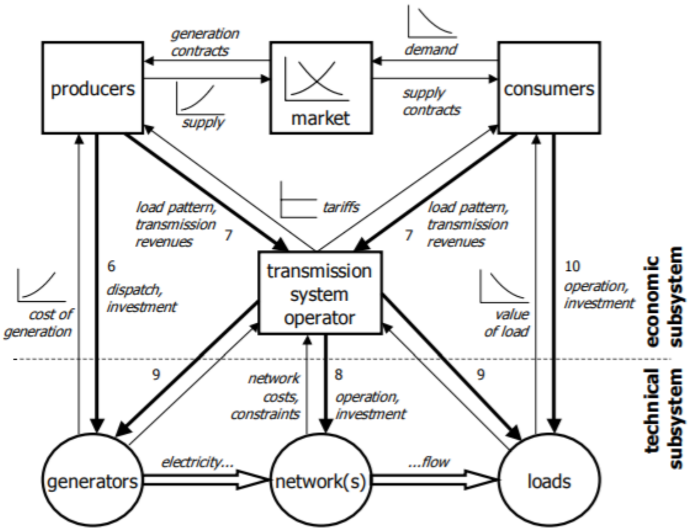


Figure 2.1: Framework of Dutch electricity system [1]

In figure 2.1, the Dutch electricity system is presented in two subsystem layers. The above layer is the economical or institutional layer and the lower layer is a technical or physical layer. The connection between each actor or asset are labelled and described. For details about this framework [1] can be referred to. This framework creates an overview for the system which needs to be researched. The black box (figure 1.1) gives a indication of where the specifications for this research is needed.

2.3. Markets

In the Netherlands, market design is well-developed and is one of the most liberalised designs of Europe [18]. It has multiple layers and each of these market layers will be explained in this paragraph. In this section, first bilateral contracts are discussed. Then the day ahead market, intraday market and balancing market are discussed. Next, auxiliary services are explained. Finally, the retail market is investigated.

Bilateral contracts

The settlement of the contracts is done on the EPEX market. During the open hours of the EPEX trading market, long-term contracts can be bought/sold on different granularities. In these periods, base and peak contracts are available. In some literature [19] buying off-peak is a possibility, in reality, this is buying base and selling peak. These different contracts are depicted in figure 2.2. From this figure, it can be seen that the closest block which can be bought is for a month ahead. After this the market closes and the positions are transferred to the day ahead market.

Day-ahead market

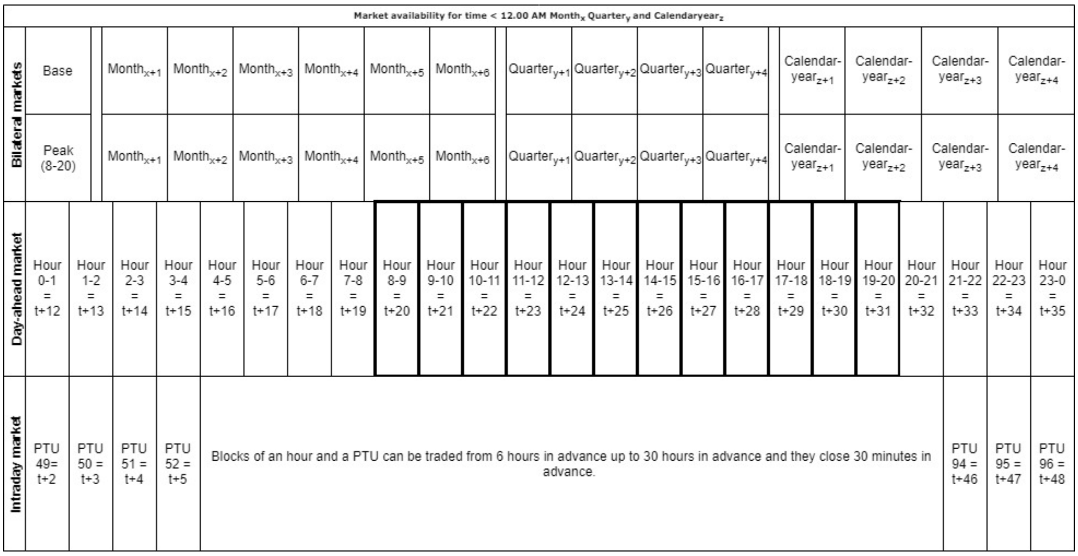
The day ahead market is a market auction system with a common price coupling algorithm (EUPHEMIA) [19] and is closed at noon where the day ahead is divided in 24, hour long, blocks. The day ahead is a forecast of demand and generation with a forecast between 12 and 36 hours ahead. Therefore a difference with reality might, especially for weather-dependent systems, be present. The hours from 8-9 until 19-20 are considered to be peak hours. The other hours are labelled ”off-peak”. Due to the size of the volumes traded on this market, it is assumed that the increase of 100 MW generation does not influence the cleared market prices.

Intraday market

The intraday market opens at the end of the working day for the complete next 24 hours. This means that the intraday has a forward trading moment of 7-30 hours and stops 30 minutes ahead. This intraday market and can be traded at hourly and quarterly granularity. The volume of this market is considered to be small and insignificant for this research based on ”The traded intraday volumes in EPEX Spot are equal to 4% of the traded day-ahead volumes in 2017 at EPEX Spot in the Netherlands”[20].

Therefore, this market will be ignored in the rest of this research.

To recap the market descriptions made, figure 2.2 is created to show the decision variables which electricity traders work with on a day to day basis.



Market availability for time < 12.00 AM Month$_x$ Quarter$_y$ and Calendaryear$_z$

Bilateral markets														
Base	Month$_{x+1}$	Month$_{x+2}$	Month$_{x+3}$	Month$_{x+4}$	Month$_{x+5}$	Month$_{x+6}$	Quarter$_{y+1}$	Quarter$_{y+2}$	Quarter$_{y+3}$	Quarter$_{y+4}$	Calendar-year$_{z+1}$	Calendar-year$_{z+2}$	Calendar-year$_{z+3}$	Calendar-year$_{z+4}$
Peak (8-20)	Month$_{x+1}$	Month$_{x+2}$	Month$_{x+3}$	Month$_{x+4}$	Month$_{x+5}$	Month$_{x+6}$	Quarter$_{y+1}$	Quarter$_{y+2}$	Quarter$_{y+3}$	Quarter$_{y+4}$	Calendar-year$_{z+1}$	Calendar-year$_{z+2}$	Calendar-year$_{z+3}$	Calendar-year$_{z+4}$

Day-ahead market											
Hour 0-1 = t+12	Hour 1-2 = t+13	Hour 2-3 = t+14	Hour 3-4 = t+15	Hour 4-5 = t+16	Hour 5-6 = t+17	Hour 6-7 = t+18	Hour 7-8 = t+19	Hour 8-9 = t+20	Hour 9-10 = t+21	Hour 10-11 = t+22	Hour 11-12 = t+23
Hour 12-13 = t+24	Hour 13-14 = t+25	Hour 14-15 = t+26	Hour 15-16 = t+27	Hour 16-17 = t+28	Hour 17-18 = t+29	Hour 18-19 = t+30	Hour 19-20 = t+31	Hour 20-21 = t+32	Hour 21-22 = t+33	Hour 22-23 = t+34	Hour 23-0 = t+35

Intraday market							
PTU 49= t+2	PTU 50 = t+3	PTU 51 = t+4	PTU 52 = t+5	Blocks of an hour and a PTU can be traded from 6 hours in advance up to 30 hours in advance and they close 30 minutes in advance.	PTU 94 = t+46	PTU 95 = t+47	PTU 96 = t+48

Figure 2.2: Markets daily choices

On a day to day basis, a lot of choices can be made for selling the commodity. To decrease the number of decision variables an abatement of markets is needed. Therefore, the day ahead market is taken as only viable market for storage capacity of the three above stated markets.

Balancing market

First of all, the balancing market consists of balancing responsibility of the sold position. This needs to be done by every Balancing Responsible Party (BRP). Also, the TSO offers service options to all BRP's. These services require the BRP's to withhold capacity with certain characteristics. These services are called auxiliary services. Below the services and connections between services are represented in a schematic way.

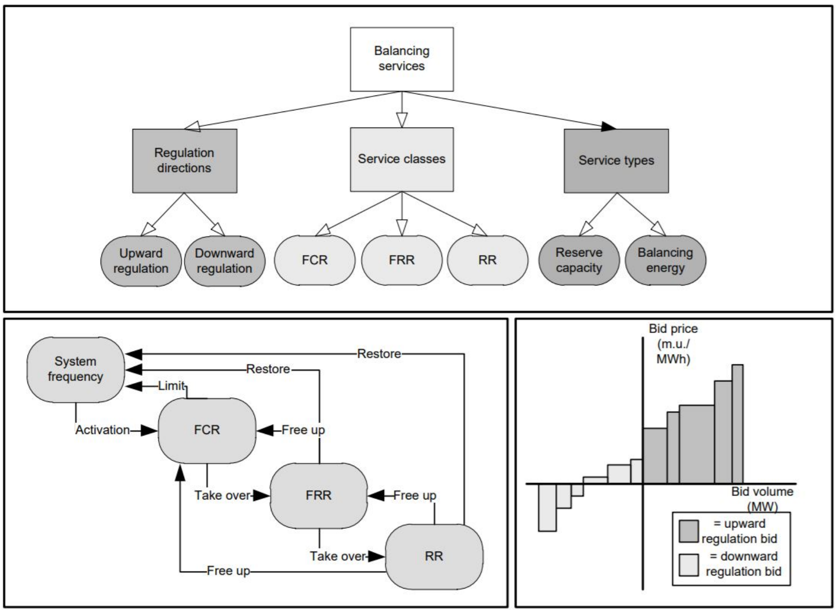


Figure 2.3: Balancing options and relations [2]

The lower right schematic in figure 2.3 shows the bid price merit order of the second reserve market. These merits are leading for the prices in the balancing market. On the website of the system operator, information is shared about these merits. Not all data is available but a total of 6 data points are shared. The data consists of prices of a total of 100 MW and 300 MW, positive or negative, imbalance and the maximum allowable imbalance. But the bids, themselves are actually for an auxiliary service. The creation of balancing market is due to the following process. Each generating party may have bid into the day ahead market which they are not able to deliver. The discrepancy with respect to their market sold power is called their balancing market position. Each party may choose to supply less or more than previously sold on the market. This position determines the settlement and profit/costs of the actor on the balancing market.

The Netherlands has a hybrid dual pricing system. This dual pricing system is best explained by (Redl,2016) [19]. Due to exposed trading, the dual pricing system can still be benefited from after realisation. BRP's are able to trade positions after it has taken place. The dual pricing system then provides at least two BRP's to get a better price for their position. For example, party A has a positive position of 10 MW at 20 €/MWh and party B has a negative position of 10 MW at 30 €/MWh. Party A and B are able to trade these positions with each other to get a better price. For example, party A can trade the 10 MW with Party B for 25 €/MWh. In this case, both parties have an increase of revenue of 5 €/MWh. The timing of the balancing market and reserve product are presented in figure 2.4.

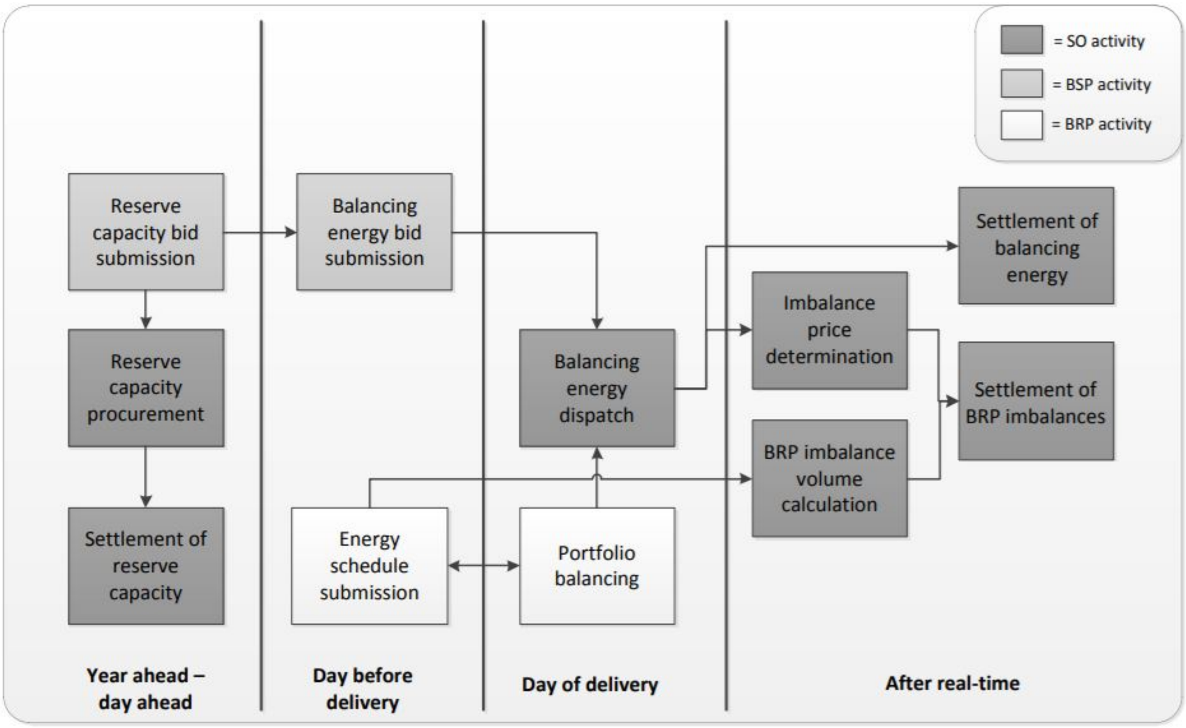


Figure 2.4: Timing of balancing products [2]

The result of the exposed trading is that a single pricing system can be approximated for actors by averaging out the two prices of the dual pricing system.

Auxiliary services

In the Netherlands, three auxiliary services are provided by the system operator. In this paragraph, the auxiliary services are described.

The first auxiliary service researched is the primary reserve. This is also called the frequency containment reserve (FCR). Every week the TSO tenders a predetermined volume needed to keep the frequency at 50 Hertz. This system does require a system to automatically adjust power output set points of generating parties.

The following auxiliary service is surprisingly called secondary reserve. This is a contract with the TSO which is tendered weekly/monthly. The contract obliges the contracted party to have an amount of power as a reserve (up and down). The contract does not entail the price for the amount of power which has to be kept as a reserve. This is the job of the contracted party which has to bid the reserved power into a merit order. This merit order is the primary pricing system for the balancing market.

The final auxiliary service is called tertiary reserve. This is also called incidental reserve. This is only used in periods of great imbalance. Also called RR, gets a separate price with respect to secondary and primary reserve. In practice, this price is always upward of 200 euros above the day-ahead market clearing price. [21]

Retail market

From consumer point of view, the electricity bill can be divided in three categories namely, energy production costs, energy taxes and network payments. These costs are divided by two parties, the energy retailer and the distribution network operator. [22]

The energy retailer collects the energy production bills and the energy tax bills. These bills are dependent on the amount of energy which is used. The energy production bill is created by the retailer by multiplying the used energy by a predetermined tariff agreed upon by the consumer. Additionally the energy retailer is allowed to bill a fixed costs for the connection. On top of the tariff for energy, the government bills a tax for energy consumption. Finally, the government gives a fixed amount of discount for every consumer. This amount will be €308,54 in 2018.

$$Bill_{energyretailer} = Consumption * (\lambda_{production} + \lambda_{tax}) - €308,54 \tag{2.1}$$

The energy retailer now has sold the consumer their energy but the transport of the energy is not accounted for. Since the landscape is liberalised, the bill for the connection to the electricity network is payed to a different actor in the landscape. This is a fixed bill with respect to the size of your connection.

Prosumer

The possibility for consumers to install decentralised generation creates a new actor with respect to figure 2.1. An additional generation circle could be added on the lower right side of this schematic.

Currently, prosumer costs are not differently calculated than consumer costs. The only difference is the consumption which is diminished by self generating of decentralised electricity. The bill for prosumers is defined by equation 2.2.

$$Bill_{energyretailer} = (Consumption - generation) * (\lambda_{production} + \lambda_{tax}) - €308,54 \tag{2.2}$$

This way of billing the prosumer will change in 2020 or 2023. Since the rules regarding the "salderingsregeling" will change. Despite receiving notice of the government, the new rules are not disclosed at this point.

2.4. Technical subsystem

2.4.1. Generators

Renewable production

Since the beginning of time until the mid 19th century, biomass has been the main energy resource for mankind. Then the rise of fossil fuel pushed biomass to the back ranks of energy production. Since 1990, the focus on renewable energy sources have been growing immensely. Below the technology and 2015 installed capacity will be specified for biomass, hydropower and newer variable renewable energy sources.

Biomass generators in the Netherlands mainly use the Rankine cycle to power a generator which produces electricity. This biomass can consist of wood shaving or compressed wood pellets. These wood based products are a waste product of industry processing wood. Next to this, solid garbage is also considered to be biomass. The burning of this solid waste produces enough heat to drive the generators. In 2015, a total of 87 MW installed capacity for bio-based electricity production could have been found in the Netherlands. [23]

The flow of water can be used to produce electricity which is called Hydropower. This hydropower can be used in two main principles. The first principle which can be used is an impulse based power conversion. The power production with impulse is done by a Pelton wheel. The conditions for using such a system is unfortunately not present in the Netherlands since this principle needs a large height difference from water input to water output. The other principle is based on mass flow which is converted by a Kaplan turbine. Since the Netherlands has multiple rivers flowing through it, seven of these systems could be found near these rivers in 2015 with a total installed capacity of 37 MW. [3]

Variable renewable energy sources can be divided into three categories namely solar dependent, wind dependent and tide dependent energy sources. For this research, the VRES which are solar and wind dependent are taken into account. Tidal power is considered to be negligible in the Dutch landscape. Next to this assumption, another dissection is needed to classify a certain technique to an owner. The dissection considered for this research is referred to in the literature as centralised and decentralised. The assumption is done that the onshore and offshore wind turbines are connected to the high voltage grid and are therefore 'centralised'. Wind power is produced by wind turbines. These turbines are propelled by moving air mass through the area covered by the turbine blades. The turbine blades translate about a third of the speed for which the air mass is travelling through this area into a rotating motion to actuate the generator.

On the other side, PV panels are smaller, easier to implement, power sources. The assumption is done that these PV panels are to be found in the consumer neighbourhoods and are therefore considered to be 'decentralised'. The PV panels convert photons hitting the surface of the panel into electric charges. Creating a collection of panels, connected in certain patterns, create enough electric flow to power household appliances.

Bron/Techniek	Perioden	Elektriciteitsproductie	Niet-genormaliseerde productie		Elektriciteitsproductie relatief	Niet-genormaliseerde productie		Opgestelde installaties	
		Genormaliseerde bruto productie	Bruto elektriciteitsproductie	Netto elektriciteitsproductie	Genormaliseerde bruto productie	Bruto elektriciteitsproductie	Netto elektriciteitsproductie	Aantal installaties	Elektrisch vermogen
		mln kWh			in % van het verbruik			aantal	MW-elektrisch
Totaal hernieuwbare energiebronnen	2014	11 793	11 707	11 039	9,98	9,91	9,73	.	.
	2015	13 168	13 694	12 998	11,05	11,49	11,39	.	.
	2016	15 039	14 735	14 061	12,52	12,27	12,13	.	.
	2017**	16 664	17 424	16 770	13,90	14,53	14,43	.	.
Waterkracht	2014	102	112	112	0,09	0,09	0,10	7	37
	2015	99	93	93	0,08	0,08	0,08	7	37
	2016	98	100	100	0,08	0,08	0,09	7	37
	2017**	94	61	61	0,08	0,05	0,05	7	37
Totaal windenergie	2014	5 810	5 797	5 797	4,92	4,91	5,11	2 124	2 865
	2015	6 917	7 550	7 550	5,81	6,34	6,61	2 171	3 391
	2016	8 364	8 170	8 170	6,97	6,80	7,05	2 331	4 257
	2017**	9 642	10 569	10 569	8,04	8,81	9,09	2 270	4 202
Windenergie op land	2014	5 060	5 049	5 049	4,28	4,27	4,45	2 028	2 637
	2015	5 882	6 420	6 420	4,94	5,39	5,62	2 032	3 034
	2016	6 041	5 901	5 901	5,03	4,91	5,09	2 042	3 300
	2017**	6 267	6 869	6 869	5,23	5,73	5,91	1 981	3 245
Windenergie op zee	2014	750	748	748	0,63	0,63	0,66	96	228
	2015	1 035	1 130	1 130	0,87	0,95	0,99	139	357
	2016	2 323	2 269	2 269	1,93	1,89	1,96	289	957
	2017**	3 375	3 700	3 700	2,81	3,09	3,18	289	957
Zonnestroom	2014	785	785	785	0,66	0,66	0,69	.	1 048
	2015	1 122	1 122	1 122	0,94	0,94	0,98	.	1 515
	2016	1 559	1 559	1 559	1,30	1,30	1,34	.	2 049
	2017**	2 149	2 149	2 149	1,79	1,79	1,85	.	2 864

Figure 2.5: Renewables installed capacities in Dutch electricity network [3]

For this research, the installed capacities in the setting are considered as an input. The table in figure 2.5 gives the installed capacities of each of these variable renewable energy sources in the years 2014 till 2017. This table is generated by an institution in the Netherlands which is called 'Centraal Bureau voor Statistieken'. [3]

Thermal production

Thermal production of electricity is the dominant method. This method is based either on a Rankine or Brayton cycle. Either way, a fuel is burned to produce heat or pressure. The side product of these processes are exhausts which as earlier said, would be rather prevented. To investigate how to decrease these emissions by adding storage capacity to the network, a specific research will be done for flexibility production methods which in the Dutch network will be mostly provided by gas-fired power plants. Next to this lignite, hard coal, oil and bio-based fuels are used to produce electricity.

Gas-fired turbines work on the Brayton cycle principle. This is very similar to jet engines because gas is mixed with air and ignited in a combustion chamber. The ignition changes the volume and temperature of the gas available in the turbines combustion chamber. The expanded gas then runs over turbine blades which are connected to a generator. [24] Newer turbines will consist of a combined cycle where the heat produced will also be used in a Rankine cycle to increase efficiency. For now this is left out of the scope of this research.

Gas-fired power plants have characteristics with regards of electricity production. These characteristics are researched for simulation purposes. Important characteristics for the balancing market are ramping rates, minimum stable generation, maximum generation, efficiency, efficiency decrease over power output and prices. These characteristics are displayed in the table below.

Table 2.1: Gas turbine characteristics

Gas-fired turbine	
Max power	<180 MW
MSG	50% of Max
Ramp up/PTU	25% of Max
Ramp down/PTU	25% of Max
Efficiency	38% - 31.74% [25]
Efficiency decrease	0.25% [24]
Price	52.63 - 63.24 €/MWh [19]

Other generation methods

Other methods are found to be insignificant with respect to the balancing market. The assumption is made that other generation actors can be abated from the scope established in previous sections since the added benefit of the EES is just the value of the storage itself. Therefore, a scenario will be taken with a stand alone party operating the storage capacity earlier defined as the base case for stand alone investors.

2.4.2. Load

Load is the term used for the usage of electricity. The load best known to the average person is a household appliance. But in the scope of this research load can mean everything from a light bulb up to a big server farm or a chemical industry heater. In either case, a collection of these electricity using machines can be used to create a portfolio of a consumer where portfolio is defined as a collection of assets and their positions to the commodity market. The portfolio started as a simple concept in the beginnings of the markets. Since the introduction of reversible storages in the electricity sector assets may now not only be positioned at either the production or consumption side.

2.4.3. Storage

In this section the possibility for storage capacity is investigated for the above described system. First of all, storage options are explored on technical specifics. Then a case study is chosen to implement in a model of the above described system.

One special option for flexibility is Electrical Energy Storage (EES). EES has several technical options. The main considered options are mechanical, electrostatical and electrochemical [26, 27].

Technology

Mechanical energy storage: Currently, 85% percent of storage is pumped hydroelectric storage (PHS) [26]. This is a good example of mechanical energy storage. This principle uses potential energy to store energy. A typical PHS has a rating of about 1000 MW and there is about 100 GW installed PHS capacity world wide. These storing facilities are geographically constraint since a large head (height difference) is needed to create capacity and power.

Other mechanical energy storages are flywheels which store energy in the form of angular momentum of a spinning mass. The total energy a flywheel is able to store is dependent on the size and speed of the rotor and the power rating of the generator. Flywheels are relatively efficient over a short period of storage time and have a long lifetime. To achieve maximum efficiency, the flywheel has to operate in a near vacuum and have a high rotational velocity.

The final mechanical energy storage which will be discussed in this paper is compressed air energy storage (CAES). This storage has also a geographically reliance since it is only economical feasible if it has a rock mine, salt cavern or depleted gas fields available to put under pressure. The depressurising of the natural tank can accelerate a turbine and therefore electrical energy can be harvested from this depressurising.

Electrostatical energy storage: Electrostatical energy storage can be found in capacitors. Currently, these applications are called supercapacitors or ultracapacitors based on their performance. These capacitors use a large surface area with molecule-thin layers of electrolyte. The electrolyte is able to separate charge over these surfaces and therefore store electrical energy. Many different materials are being used to produce these capacitors but are often made of porous carbon and aqueous electrolyte [26]. The occurrence of self discharging makes this technology more suitable for short period energy storage and therefore are mainly used in power quality applications.

Electrochemical energy storage: In this section, two different technologies will be discussed. These technologies are seen as high potential candidates for implementation in the current grid due to their respectively low levelized cost of energy.

The first energy storage technology discussed in this paragraph namely battery technology. ”Rechargeable battery is the oldest form of electric energy storage” [26]. A battery consist of one or more electrochemical cells. Each cells consists of an anode and cathode and an electrolyte. Due to an electrochemical reaction, a flow of electrons can be created in an external circuit. A form of a battery is the Lead-acid battery. Lead-acid batteries have been around since 1859 and they have are known to be very reliable and efficient. However, these batteries have drawbacks such as a short cycle life and poor energy density. Another example of battery technology is the lithium-ion battery. This battery form has been proposed a century later than the introduction of the lead-acid battery. The difference of the lithium-ion battery with respect to the lead acid battery is that it has an order of magnitude better cycle lifetime but a double as high levelized cost of energy. [26]

The final technology of electrochemical energy storage discussed in this paper is referred to as *Power to x*. For this technology the main working principle is the conversion of electric power to a chemical element. Currently, the best practical application of this principle is the electrolysis of water into hydrogen [27]. The main advantage of this system is the capability to store the energy for longer periods of time because little discharge of particles exist for chosen elements. This technology is mainly spoken of in the same sentence with a fuel cell technology since this is able to transform the element back into electricity.

Case study

For this case study, electrochemical technology is used. This technology is seen as the best fit for the Dutch electricity system since pumped hydro storage is not a possibility in the Dutch environment. The next best option is battery technology due to its fast ramp rates and rapidly decreasing levelized cost of energy.

As addressed in the introduction, a big electrochemical storage is introduced in the electricity system in Australia. This storage capacity is build by Tesla and has a reported power of 100 MW and a total of 129 MWh storage capacity. The Tesla Powerpack is able to ramp to its full capacity quickly and reliably.

This means it can support the South Australian electricity grid by providing Frequency control services with reaction times as low as 140 milliseconds. For this case study, the ramp limitations are neglected since the power pack is much faster than the market products discussed in the previous section.

3

Actor analysis

The goal of this chapter is to define the input variable of the ”blackbox” process. Then in the following chapter the operations within the black box will be defined.

3.1. Actors

In the framework (figure 2.1), the square boxes represent type of actors in the electricity sector. The different type of actors in the Dutch electricity sector can be classified as:

- Producers
- System operators
- Consumers

Within these classifications, a subcategory can be made. The producers can be divided into producers with controllable assets and variable assets. Figure 3.1 displays suggested operating responsible parties of EES.

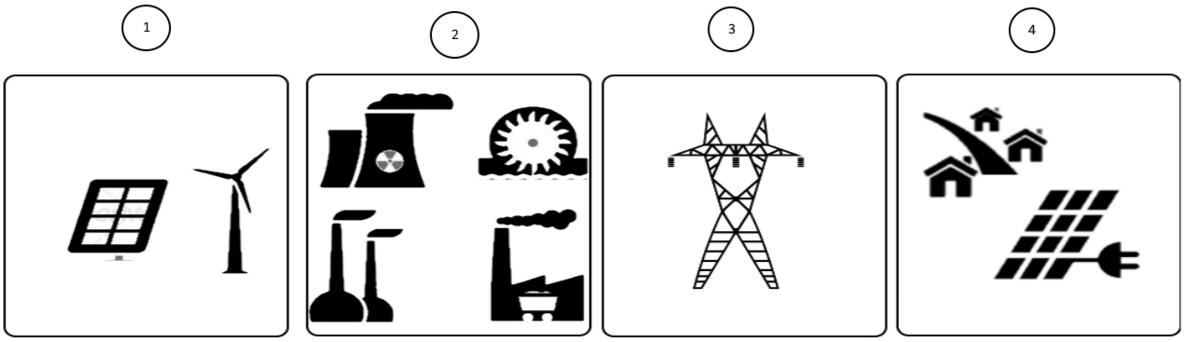


Figure 3.1: Possible actors for EES

To clarify the schematic above, the actors will be explained in this paragraph. The first actor identified is the operating responsible party of Variable Renewable Energy Sources (VRES). In the literature, these wind farms or centralised PV parks, are suggested to be the main cause of the imbalance certainly for the future. Due to the costs, the imbalance, which is created by the variability, will preferably be lowered by flexible capacity. This flexible capacity can be created by storage capacity.

The second actor which is identified is the current supplier of flexibility namely the fossil-fueled power plants. The owners of flexibility might use the storage capacity to maintain the market power position with respect to flexibility.

The third possible actor presented is the transmission system operator. This actor has the responsibility to operate a network safely and securely. The added storage can be operated to decrease the amount of imbalance forced on to the network.

Finally, consumers must be taken into account as possible users of storage capacity. Moral incentives have been created by the ”green” movement to become as energy independent as possible. Consumers are increasing their possibility to become prosumers and the possibility to store energy seems to be increasing by innovations such as electric vehicles and Tesla powerwalls.

These four actors have been found to may have different intentions of participating in electricity wholesale and balancing markets.

In the following section, the positioning of responsibility of operation of storage capacity and its differentiation are honed in on.

3.2. Operating responsibility

Only a few researchers have indicated that different objectives of the storage capacity are a possibility. While researching this subject, the keywords such as ownership EES, objectives of responsible parties storage and operation responsibility of storage capacity are used to find literature. The best differentiation is given by Brinsmead (2015)[28]. Although, noticing different objectives, this research does not conclude which parties would be connected to these objectives. The following objectives were suggested.

- portfolio imbalance minimisation - Any portfolio endures unpredictability and the result of delivering a different amount as nominated twenty four hours before results in imbalance volume. This imbalance might be helping or have negative effects on the network imbalance. Portfolio imbalance minimisation as an objective will result in the lowest absolute sum of imbalance volume.

- network load minimisation - Portfolios are connected to the network and must pay the network operator a fixed fee for the size of the connection. Lowering the maximum load on the network results in lower costs for the portfolio and a less volatile character of the connected network.

- profit maximisation - Portfolio’s often are owned by companies which have capitalistic incentives. Obtained options owned by the companies will be utilised in the most profitable manner.

These objectives were used to form a hypothesis for the identified actor types in this report. These hypothesis are presented in section 3.4. First a process will be developed to superintend this subsection of the research.

3.3. Actor research representation

The process for identifying all possible portfolio’s is presented in figure 3.2. The addition in this figure is the ”no actor” case which has been added. This case is added to investigate how a storage without a pre-existing asset portfolio, will react to the realised market situations.

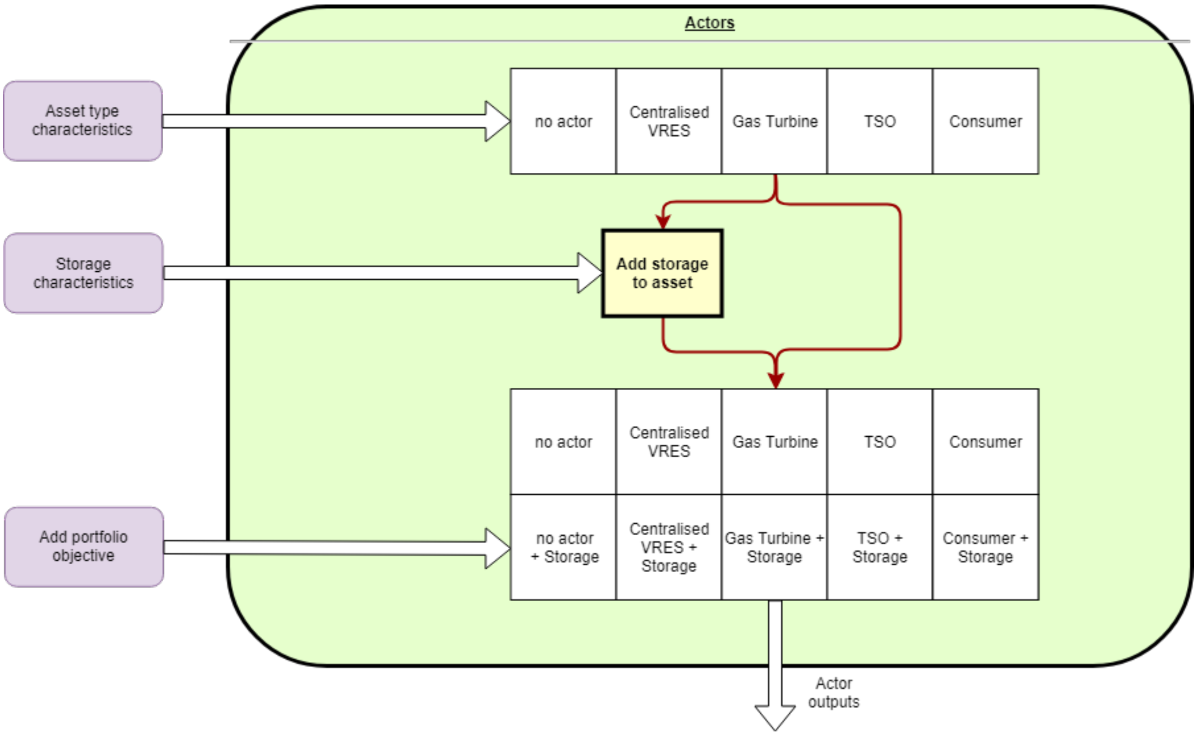


Figure 3.2: Actor input representation before validation

In figure 3.2, nine different possibilities of portfolio's can be seen because the no actor and no storage case does not change anything in the model. For the no actor + storage case, which later on in the research will be called "Base case", the objective has been assumed to optimise revenues. The other objectives will be researched in the following section

3.4. Objectives research

First a perspective is described. From there the possible objectives are coupled to the actors as an hypothesis. Finally, the objectives are validated by expert interviews.

3.4.1. Centralised VRES

- Perspective:

  Day-ahead market is cleared. The VRES has sold their forecasted power for an average of 40 €/MWh. Due to the changing weather the VRES is not able to deliver what was forecasted. Assuming this VRES has more likewise generating parties utilising the same principle in the same network, the power imbalance is significant for the balancing market (let us define to little generation as positive imbalance). The balancing market then gives a positive incentive to generating parties to produce more thus the balancing price is with respect to the Day-ahead market up for example 60 €/MWh. The portfolio of the centralised VRES would then be categorised as 'short' or to have a short position. This would mean that they pay the system operator 60 €/MWh which they did not deliver with respect to their day-ahead market sold power.

- Hypothesis:

  The centralised VRES balancing responsible party are seen as the creators of imbalance. They may be benefited from alleviating the disturbance they are responsible for. This alleviation could be done by an electric energy storage which is capable of redelivering power. The hypothesis is that the usage of this storage capacity would be done in a dampening fashion with respect to imbalance they create and therefore minimising costs they would have on the balancing market. The profit structure of the centralised VRES assumes the power generation has no additional costs. Therefore the marginal costs of power is zero and this results in the assumption of creating as much revenue on the market is equal to minimising costs.

- Validation:

  PZEM in the role of centralised VRES BRP and Gas turbine generator BRP: First of all, an introduction is done about the thesis and my background. After this, Jorim de Boks introduced himself and the company PZEM. The summary of this introduction concludes that PZEM is an electrical energy producer and a market party on the wholesale market of energy. While trading on the wholesale market, portfolio optimisation is used in order to produce electrical energy as efficient and profitable as possible. In the portfolio, a large amount of wind energy and gas power flexibility is present. Storage optimisation is largely dependent on technical specification for which on the one hand flywheels are used and on the other hand gas to power and pumped hydro-storage. More information has been given with respect to the research namely the case study implements an electrochemical storage in the Dutch setting. The interviewer now suggested that the party is the BRP of VRES production. While they do sell the power of the wind farms, the company suggest that it is not the owner for all the wind farms they provide services for. The agreement made with the wind farm could exist out of multiple forms. The agreement of the wind farm with the trader is not disclosed in the interview. The focus shifted to the owner of an asset where in this hypothetical case, it is responsible for their own energy trade. When this is the case, a few configurations are possible. The storage capacity could for example be used as balancing help. The position of the storage is in this case also a important factor. The first option is for example, behind the meter from the market point of view. The connection costs are possible to be combined and this is an interesting business case since the storage likely only want to deliver when the wind power is low since high wind power production lowers the price. But still in this case the storage capacity would mainly be used as risk mitigation because of opposing exposure.

- Conclusion:

  The objective is to maximise revenue while subjected to market constraints.

3.4.2. Gas turbine

- Perspective:

  For these gas-fired power plants operators different conditions are significant so a different narrative is created for these actors. The day-ahead market will be cleared at a price which will in this case be in the range of the gas-fired power plant. We could even say it is a price setting party. Therefore this party is not running its power plant at full capacity. We could consider the remaining capacity as reserve capacity. Then, the wind drops and the balancing price rises as in the previous actor case. The gas-fired power plant now is able to run it's remaining capacity for a beneficial price. This portfolio position can then be categorised as long for which the system operator pays this owner the balancing market price of the extra delivered power.

- Hypothesis:

  the fossil fuelled power plant owners for which the hypothesis is that they want to create the biggest possible revenue with the storage. While, they already have reserve capacity calculated for average usage.

- Validation:

  The validation of the gas turbine BRP has been done with Jorim de Boks as well. A different hypothetical case, namely for the operating responsible party of a gas turbine, was suggested to discuss. For gas turbines, sometimes flexibility is needed to run a gas turbine, for example for a start up. Next to this, the auxiliary services could be an answer to the oversupply of their flexibility. This for example gives you the possibility to switch of a gas turbine while complying to the flexibility constraints of the auxiliary services. The storage capacity has variable shadow prices which is different for gas turbines which have a stable shadow price in relation with gas prices. The shadow price of a storage is dependable on when it is charged.

- Conclusion

The objective is to maximise revenue while the gas turbine is switched on and off on day ahead incentives.

3.4.3. System operator

- Perspective:

  The system responsible party does exceptionally interfere with the day-ahead auction only if congestion is suspected. In this research congestion is neglected. Therefore the SO will only operate with respect to the balancing market (which they own / lead / operate). The same situation is shown from the perspective of the SO. The SO will remark a drop in generation and/or frequency. Then the balancing market prices are automatically/synthetically positioned upwards. The responsibility of the SO is to maintain a stable 50 Hz on the network. A drop in delivery will offset this frequency. Therefore it is in their interest to minimise network imbalances.

- Hypothesis:

  the 'operator' or because the law prevents the operator to trade on the markets a third party in assignment of the operator. The hypothesis is that this party will try to plan for alleviating the total imbalance on the system and therefore influence the imbalance market but not with intent.

- Validation:

  A quick introduction about myself has been made, where after Joris Besseling introduced himself. After this, the vision of flexibility of Tennet is explained. The following conclusions could be subtracted from the interview; Flexibility need is growing, and current flexibility needs to be replaced due to carbon intensity. Still a lot of flexibility is present, even an overcapacity in some sense due to inter-connectivity and the insignificance of the spread of day-night demand. Therefore, the business case is not really positive at this moment. From there, portfolio balancing is also discussed to be a good policy against variability. Power plant tripping is a big problem for variability which Tennet needs to solve. Therefore they buy auxiliary services from asset owners. They are not allowed to own active assets. Possibilities may arise for storage for a new flexibility option which is referred to as referral of investments on the network through solving congestion problems or transport constraints problems. Mr Besseling also says that Tennet is not a market party and they definitely don't want to influence the market. Italy has invested in storage capacity but only for congestion management. The possible problem for storage capacity is that they pay an extra fee with respect to normal delivery because they need to pay the transport fee's. If the possibility arises that free storage is available to Tennet, the balancing will not be affected because the business case for other assets may not be influenced by the regulating party and they do not even want to. The battery would not even will be used in incidental cases because the same as balancing, the business case would be affected for example the price cap of incidental reserve products. Next, the emphasis is put on the fact that gas-fired power plants are as much a cause of imbalance on the system. This is the case of a trip of the power plant which is dimensioned on European standard. Therefore the reserve capacities are dimensioned on a trip of 2 big nuclear power plants in France. A clarification was made that a wind farm or a centralised PV park are also BRP's. This notation should be made correct in this report. Portfolio balancing is a nice tool, seen often, between 2 parties such as centralised VRES and Gas-fired power plants with a PPA (power purchase agreement). European systems are pushing towards making centralised VRES responsible for their imbalance. When looking at business cases the location of the storage capacity could be very beneficial. The price of the connection could be lower by storing peak power and releasing it later. There is still a difference in business case while operating a combination of wind farm and storage capacity since the location is possible factor in certain pricing such as connection fees or redispatching. Consumers are a possible balancing party as multiple sources are aggregated. Consumers will be incentivised to use as much decentralised produced electricity. DSO's will like this fact. Although big networks and power plants are trying to connect bigger networks together to become more efficient and to easier balance demand and supply. Suggested is that how bigger the network the more social welfare could be obtained. Decentralised local initiatives are incentives to continue developing programs but this does not ensure lowest society costs. The concept, utility death cycle as explained by [29], is not a problem in the Netherlands since the tariffs for network connection is a fixed rate per year instead of a fee on energy consumption. Finally, there is suggested that storage capacity is still not a viable business case in the Netherlands.

- Conclusion:

  This actor does not wish to optimise a storage capacity in the scope of this research.

3.4.4. Consumer

- Perspective:

  From a consumer point of view, these created imbalances on the electricity markets are not priorities. Consumers are used to consuming electricity whenever they need it and have a very low amount of hours, loss of power. The bill is not very insightful about usage at certain times. Smaller consumers such as households would even pay a fixed rate. So if it is considered that the consumer will pay a fixed rate of 50 €/MWh plus an additional fixed rate of 190€/MWh of taxes and even a fixed fee for connection. The biggest reason to use a storage capacity is to enable decentralised production and therefore decrease their usage of the network. The ability to store the energy from the produced decentralised VRES instead of reselling them on the balancing market or reselling them against the fixed energy costs, will save this party the costs of the network charges due to lower peak power connection fees.

- Hypothesis:

  The hypothesis is that the consumer would like to reduce the cost of their energy bill. Since there is a single pricing system for most consumers the storage is likely to use all electricity to minimise the peak power. The peak power is responsible for the connection which is needed to supply this peak. The bigger the connection the more the consumer needs to pay. Therefore, the storage capacity will be used as a peak-shaving option.

- Validation:

  First of all, an introduction is given, where after Silvana Iefel and Marcon De Vrede introduced themselves. Then, the interview went on to company characteristics. The main focus of the company is to be a telecom provider. The maintenance of the technical system regarding electricity is outsources but the planning and constraints will be managed by their company. Personal objectives have been guided by sustainability and these objectives are transferred to the company if there is possibility for it. Sustainability choices are suggested in the company and sometimes even accepted. Noted is that the core business is not to be an energy prosumer. The company delivers a service which costs electricity. This electricity consumption is therefore important but subservient from the security of service. Demand side management, is insignificant with respect to normal demand. A suggestion is given for cooling the server locations which could be extra cooled at low demand periods. The service itself could not be managed because the business case survives on a secure service. Therefore, at this point, no extra demand side management is used. Then, the representation of the landscape for this research is shown for which is asked to identify objectives for different actors. There was suggested that the system operator will like have the least amount of imbalance. Finally, the supply side of the electricity market are suggested to have only economical incentives.

- Conclusion:

  it is a economic based conclusion although the conditions are different. The biggest economic change can be by taking a smaller connection and therefore have a lower peak power. This will result in a smaller costs.

3.5. Conclusion of objectives

The TSO is dropped from the modelling of a case. To counteract, another case study is identified to be the prosumers. The four optimisation cases taken into account are now; Centralised VRES, Gas turbine, Consumer and Prosumer. The following objectives were identified for these actors.

- First for the centralised VRES owners, the objective is to optimise for minimal costs for imbalances created by forecast errors. While researching minimal costs, this has been found to be the same as maximising revenue on the balancing market since for zero marginal cost variable energy sources, the costs of electricity drop with the increased production and therefore sales of energy.
- Secondly, for the next owner which is flexible energy producers (gas-fired power plant operator), revenue maximisation is the objective for operating storage capacity.
- Finally, the objective is established that the consumer decreases its peak energy consumption to reduce connection costs which is the only way to reduce consumer costs with storage capacity at this point in time. The possibility to generate power itself changes operating behaviours therefore this will be taken as a separate scenario.

This changes the actor input representation into the following following figure.

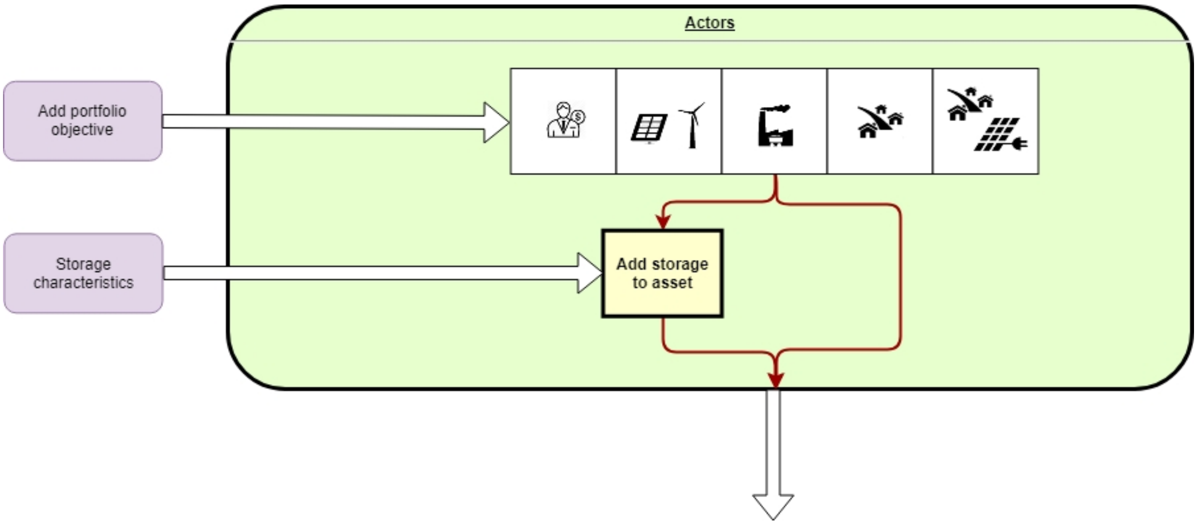


Figure 3.3: Actor input representation

In figure 3.3, the actors such as; Investor (base case), Centralised VRES (wind farm), Conservative BRP (gas turbine), Community (consumer) and Community with decentralised production (prosumer), are identified as input. To investigate the research question an important part is still needed to explain. This part is the performance metrics. This will be done in the following chapter.

4

Performance metrics

In this chapter, the performance metrics the model are investigated. This chapter aims to produce metrics for which the results can be easily compared. These metrics should be able to distinguish difference in operating a storage capacity and the influence on a network.

4.1. Operation profile

In the previous chapter, five individual actors are identified. These actors have objectives and conditions. With respect to the objective and conditions, a storage can be operated to create the best possible outcome for the objective which is defined in chapter 3. Therefore, one of the implied outcomes of the model is operating profile.

The markets which are evaluated have 35040 conditions per year in the smallest granularity. If a year is modelled a time series of 35040 data points is created. This is a large amount of numerical data and might be to specific to graph as a time series. If the numerical data is used to form a conclusion about operating profiles a different approach is needed to get a reasonable conclusion from the time series.

Suggested is that the time series are presented in a few different manners. First of all, a histogram can be used to represent the amount of output values during the year. A histogram plots the amount of reached values versus the value itself. Often uses of this technique can be found in statistical analysis of random variables. Second, the time series can be divided into a number of subsets. An example of the size of such a subset is, a operation profile is divided into daily cycles. These cycles then can look very different but averaging the outputs on certain time of days, gives an indication of the preferred output of this specific time of day. Finally, differences of operating profiles can be used to find the reaction towards different conditions. If a input variable such as a condition can be defined as a numerical value, this value can be used to create a linear regression of the output with respect to this value. Simply said, the value of the input is put against the difference of the output between two profiles.

4.2. Network imbalance

The operating profile of a storage capacity is able to influence the network imbalance. The network imbalance difference between before and after storage implementation, is inversely linear with respect to the storage output. For the measurement of the network imbalance of each of the experiments, the operating profile is used to add or subtract from the input network imbalance. For the input imbalance, the imbalance volumes can be used to create a histogram of the yearly market results. This histogram is shown in figure 4.1.

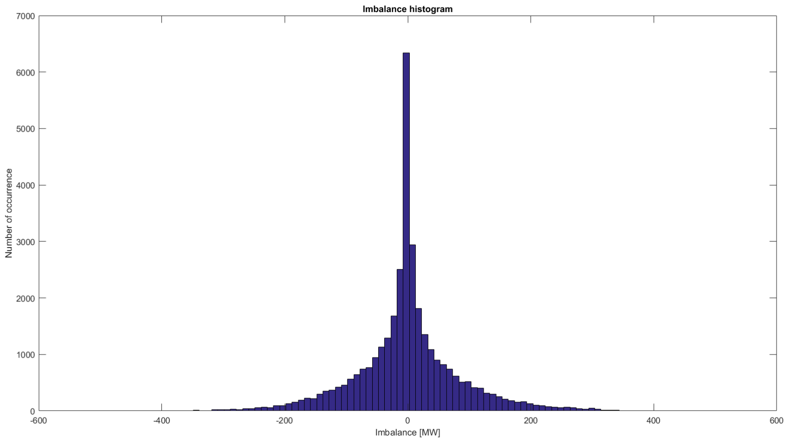


Figure 4.1: Network imbalance histogram

In figure 4.1, the number of occurrences are set out against the imbalance volumes. This gives a histogram of total imbalances over the year. This histogram of total imbalance volumes over a year clearly has a distribution. This distribution can be described as a double exponential distribution which is also known as a Laplace distribution [30]. The Laplace distribution is mathematically defined as

$$p(x; x_0, b) = \frac{1}{b} \exp\left(-\frac{|x - x_0|}{b}\right) \tag{4.1}$$

When fitted over this imbalance histogram, figure 4.2 is created.

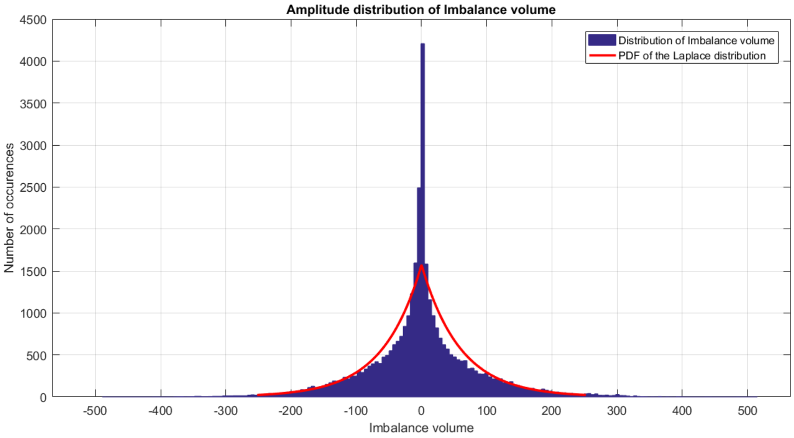


Figure 4.2: Imbalance histogram with fitted Laplace distribution

The values represented in equation 4.1, can be calculated. Since, for all distributions fitted in this research, the mean is within a small error of zero, the value b will be portrayed as the volatility of the imbalance volumes. This value for the above fitted distribution is 118,8. The closer this value gets to 0 the less volatile the imbalance will be. As imbalances induce extra costs for producers [31], the overall costs of production will rise as well. The assumption is taken that the social welfare of the electricity system is the inverse of the cost of generation plus the cost of the network [1]. Decreasing the total imbalance induced on the network will therefore decrease the cost of generation and increase the social welfare of the electricity system. [32]

5

Model synthesis

5.1. Objectives to mathematical expressions

From the written objectives, a mathematical definition of the objectives needs to be made. Below equations are created to describe the objective in the scope of this research. The optimisation of portfolio generation including storage is explained in [33].

$$Max : WindfarmPortfolioRevenue = portfoliorevenue_{DAM} + portfoliorevenue_{BAL} \tag{5.1}$$

$$Max : GasPortfolioRevenue = portfoliorevenue_{DAM} + portfoliorevenue_{BAL} \tag{5.2}$$

$$Min : ConsumerPeakPower = ConsumerDemand - Storageutilisation \tag{5.3}$$

$$Min : ProsumerPeakPower = ConsumerDemand - Decentralisedproduction - Storageutilisation \tag{5.4}$$

From these mathematical expressions a optimisation model can be made to calculate utilisation profile of a storage capacity integrated in the portfolio's of these actors. From these utilisation profiles, a new imbalance time series can be calculated and evaluated. This will be done in chapter 6.

5.2. Model specifics

As earlier assumed, a increase of 100 MW will not influence the Day ahead market price. Therefore for this simulation four additional portfolio's are added individually to the simulation to represent new imbalance. But first a base case for battery optimisation is run. Before doing so, a optimisation of the storage capacity is done for maximum revenue.

Base case

The optimisation of the storage capacity for maximum revenue is done step for step with respect to order of closing of markets. Therefore, the day ahead market is optimised with respect of revenue.

$$Max : Revenue_{DAM} = \sum_{t=1}^{T} P_{DAM,t} * \lambda_{DAM,t} \tag{5.5}$$

s.t.

$$P_{min} \leq P_{DAM,t} \leq P_{max} \tag{5.6}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} P_{DAM,t} * t \leq E_{max} \tag{5.7}$$

Next a jump in time is made to the following day where the optimisation is run to maximise revenue on the balancing market with keeping in mind the beforehand sold day-ahead market blocks.

$$Max : Revenue_{Bal} = \sum_{t=1}^{T} P_{Bal,t} * \lambda_{Bal,t} \tag{5.8}$$

where

$$\lambda_{Bal,t} = (Imb_t - P_{Bal,t}) * \frac{\delta P_{FRR,t}}{\delta \lambda_{FRR,t}} + \lambda_{0,FRR,t} \tag{5.9}$$

s.t.

$$P_{min} - P_{DAM,t} \leq P_{Bal,t} \leq P_{max} - P_{DAM,t} \tag{5.10}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} (P_{DAM,t} + P_{Bal,t}) * t \leq E_{max} \tag{5.11}$$

Combining the results from these optimisations, the maximised revenue profile for the storage capacity can be generated by adding the resulted profiles of the two above mentioned optimisations.

5.2.1. Centralised VRES

For the centralised VRES case, it has been decided to add a single wind farm with the installed capacity of 100 MW. The assumptions for the day-ahead market still holds specifically this means that the day-ahead market results will not be influenced by installing this wind farm. While assuming the day ahead market results being invariant with respect to this wind farm, the balancing market will be influenced by the imbalance this wind farm will present to it. To model wind farm forecasts and realisation, MERRA data is taken to represent forecasted power outputs. This MERRA data is published on the renewables ninja website [34]. Then, to create an imbalance profile a normal distribution for 20% deviation in wind power is used. [10]

For the following equations the following variables are introduced.

input:

$Pw_{for,t}$ [3, 34, 35]

$Pw_{real,t} = Pw_{for,t} * Dist_{Normal_{1,0.2}}$[10]

$Pw_{error,t} = Pw_{real,t} - Pw_{for,t}$

To optimise the actor case portfolio, the equations 5.12,5.13 and 5.14 are used.

$$Max : Revenue_{DAM} = \sum_{t=1}^{T} (P_{DAM,t} + Pw_{for,t}) * \lambda_{DAM,t} \tag{5.12}$$

s.t.

$$P_{min} \leq P_{DAM,t} \leq P_{max} \tag{5.13}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} P_{DAM,t} * t \leq E_{max} \tag{5.14}$$

Again, the time step on to the balancing market is made. The storage capacity will now be used to optimise the portfolio of the wind farm and storage combined. The added difficulty is the forecast error of the wind farm.

$$Max : Revenue_{Bal} = \sum_{t=1}^{T} (P_{Bal,t} + Pw_{error,t}) * \lambda_{Bal,t} \tag{5.15}$$

where

$$\lambda_{Bal,t} = (Imb_t - P_{Bal,t} + Pw_{error,t}) * \frac{\delta P_{FRR,t}}{\delta \lambda_{FRR,t}} + \lambda_{0,FRR,t} \tag{5.16}$$

s.t.

$$P_{min} - P_{DAM,t} \leq P_{Bal,t} \leq P_{max} - P_{DAM,t} \tag{5.17}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} (P_{DAM,t} + P_{Bal,t}) * t \leq E_{max} \tag{5.18}$$

The optimised portfolio storage capacity usage can now be isolated by adding the storage profiles of the day-ahead market and balancing market.

5.2.2. BRP with gas fired power plant

For the gas turbine case, some assumptions must be made. First of all, the day ahead market results are still not affected by the implementation of this gas generator. Secondly, a linear decreasing efficiency curve, which is a reasonable assumption according to Stoll(1989)[24], is assumed. Finally, for this case study the ramp rate of a open cycle gas turbine is assumed to be sufficient to ramp from minimal stable generation to maximum power in a single PTU. The gas turbine is modelled to run at marginal costs and can therefore be dispatched due to market results by optimising the equation 5.19 where a new variable u_t is introduced to create an "on/off" switch for the power output and therefore for the gas turbine. This is known in mathematics as the KKT-variable.

input:

Table 5.1: Gas turbine characteristics

Gas-fired turbine	
Max power	100 MW
MSG	50% of Max
Efficiency	38% - 31.74% [25]
Efficiency decrease	0.25% [24]
Price	52.63 - 63.24 €/MWh [19]

$$Max : GasRevenue_{DAM} = \sum_{t=1}^{T} u_t * Pg_{DAM,t} * (\lambda_{DAM,t} - \lambda_{Gas}) \tag{5.19}$$

where

$$\lambda_{Gas} = Pg_{DAM,t} * \frac{\delta P_{Gas}}{\delta \lambda_{Gas}} + \lambda_{0,Gas} \tag{5.20}$$

s.t.

$$u_t * Pg_{min} \leq Pg_{DAM,t} \leq u_t * Pg_{max} \tag{5.21}$$

After this, the storage capacity is optimised by revenue for the day ahead market just as the aforementioned optimisations.

$$Max : Revenue_{DAM} = \sum_{t=1}^{T} (P_{DAM,t} + Pg_{DAM,t}) * \lambda_{DAM,t} \tag{5.22}$$

s.t.

$$P_{min} \leq P_{DAM,t} \leq P_{max} \tag{5.23}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} P_{DAM,t} * t \leq E_{max} \tag{5.24}$$

A jump forward is again needed to arrive at the balancing market. A decision is made to optimise the gas turbine before the storage capacity. This results in the following optimisation 5.25.

$$Max : GasRevenue_{Bal} = \sum_{t=1}^{T} PG_{Bal,t} * (\lambda_{Bal,t} - \lambda_{Gas,t}) \tag{5.25}$$

where

$$\lambda_{Bal,t} = (Imb_t - Pg_{Bal,t}) * \frac{\delta P_{FRR,t}}{\delta \lambda_{FRR,t}} + \lambda_{0,FRR,t} \tag{5.26}$$

$$\lambda_{Gas} = Pg_{Bal,t} * \frac{\delta P_{Gas}}{\delta \lambda_{Gas}} + \lambda_{0,Gas} \tag{5.27}$$

s.t.

$$u_t(P_{min} - P_{DAM,t}) \leq P_{Bal,t} \leq u_t(P_{max} - P_{DAM,t}) \tag{5.28}$$

The resulted balancing profile of the gas turbine then is used as an input for equation 5.29.

$$Max : Revenue_{Bal} = \sum_{t=1}^{T} (P_{Bal,t} + Pg_{Bal,t}) * \lambda_{Bal,t} \tag{5.29}$$

where

$$\lambda_{Bal,t} = (Imb_t - P_{Bal,t} - Pg_{Bal,t}) * \frac{\delta P_{FRR,t}}{\delta \lambda_{FRR,t}} + \lambda_{0,FRR,t} \tag{5.30}$$

s.t.

$$P_{min} - P_{DAM,t} \leq P_{Bal,t} \leq P_{max} - P_{DAM,t} \tag{5.31}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} (P_{DAM,t} + P_{Bal,t}) * t \leq E_{max} \tag{5.32}$$

Finally as with the first two optimisations, the storage capacity balancing profile can be added by the storage capacity profile for the day ahead market and realised storage capacity positions can be simulated.

5.2.3. Consumer/prosumer

Another 100 MW is added for consumption. For this consumption a normal distribution with only a 2 percent deviation is used. [10]

Since consumers have different positions in the landscape the conditions have changed. Large scale consumers pay bills for energy described in section 2.3. The only way to save money for consumers (at this point) is minimising the connection capacity. Therefore the optimisation will minimise maximum power consumption.

Input: D_{cons} = consumer demand [34]

$$Min : P_{peak} = max(D_{cons,t} - P_{Bal,t}) \tag{5.33}$$

s.t.

$$P_{min} \leq P_{Bal,t} \leq P_{max} \tag{5.34}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} P_{Bal,t}) * t \leq E_{max} \tag{5.35}$$

Consumer storage capacity behaviour is suspected to be much different then the previous three cases. This is because of the changed conditions with respect to these three first cases.

For the prosumer the same optimisation is used but then with extra supply namely PV power. This PV power is again retreived from MERRA data on the renewables ninja website [34]. Assumed is that the installed capacity of these PV panels is 100 MW.

input: $Pv_{for,t}$ = PV power[3, 34, 36] $Pv_{real,t} = Pv_{for,t} * Dist_{Normal_{1,0.2}}$[10] $Pv_{error,t} = Pv_{real,t} - Pv_{for,t}$

$$Min : P_{peak} = max(D_{Pro,t} - P_{Bal,t}) \tag{5.36}$$

where

$$D_{Pro,t} = D_{cons,t} - Pv_t \tag{5.37}$$

s.t.

$$P_{min} \leq P_{Bal,t} \leq P_{max} \tag{5.38}$$

$$E_{min} \leq E_0 + \sum_{t=1}^{N} P_{Bal,t}) * t \leq E_{max} \tag{5.39}$$

The final storage capacity profile is created.

5.3. Model verification

For the model verification, a special case study is run for which the output of the model can be easily predicted.

The input for this case study is a synthetic price profile for the day ahead market and the balancing market. These prices are linear decreasing for every PTU in the timespan for the input in the model. Then the actor case, only a storage optimised for maximum revenue, is used. The mathematical approach for this case can be found in section as base case 5.2.

Since a reversible storage capacity is used, there is not a possibility to charge the storage for which more revenue can be created for discharging. For maximising revenue, the best profile is to not charge at all.

The same Laplace distribution analysis is used to investigate results of storage power output.

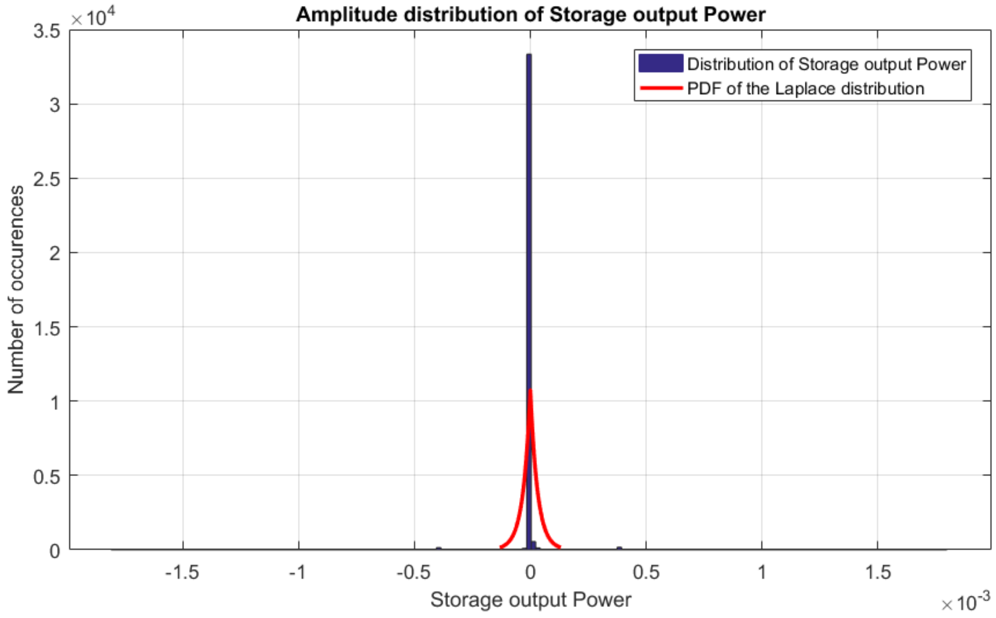


Figure 5.1: Storage output power of verification

The b factor of this analysis is $6.2 * 10^{-5}$. This result is within the range from zero including the expected accuracy of the model. Therefore the model can be assumed to operate as expected.

5.4. Model representation

The detailed model representation is presented in figure 5.2.

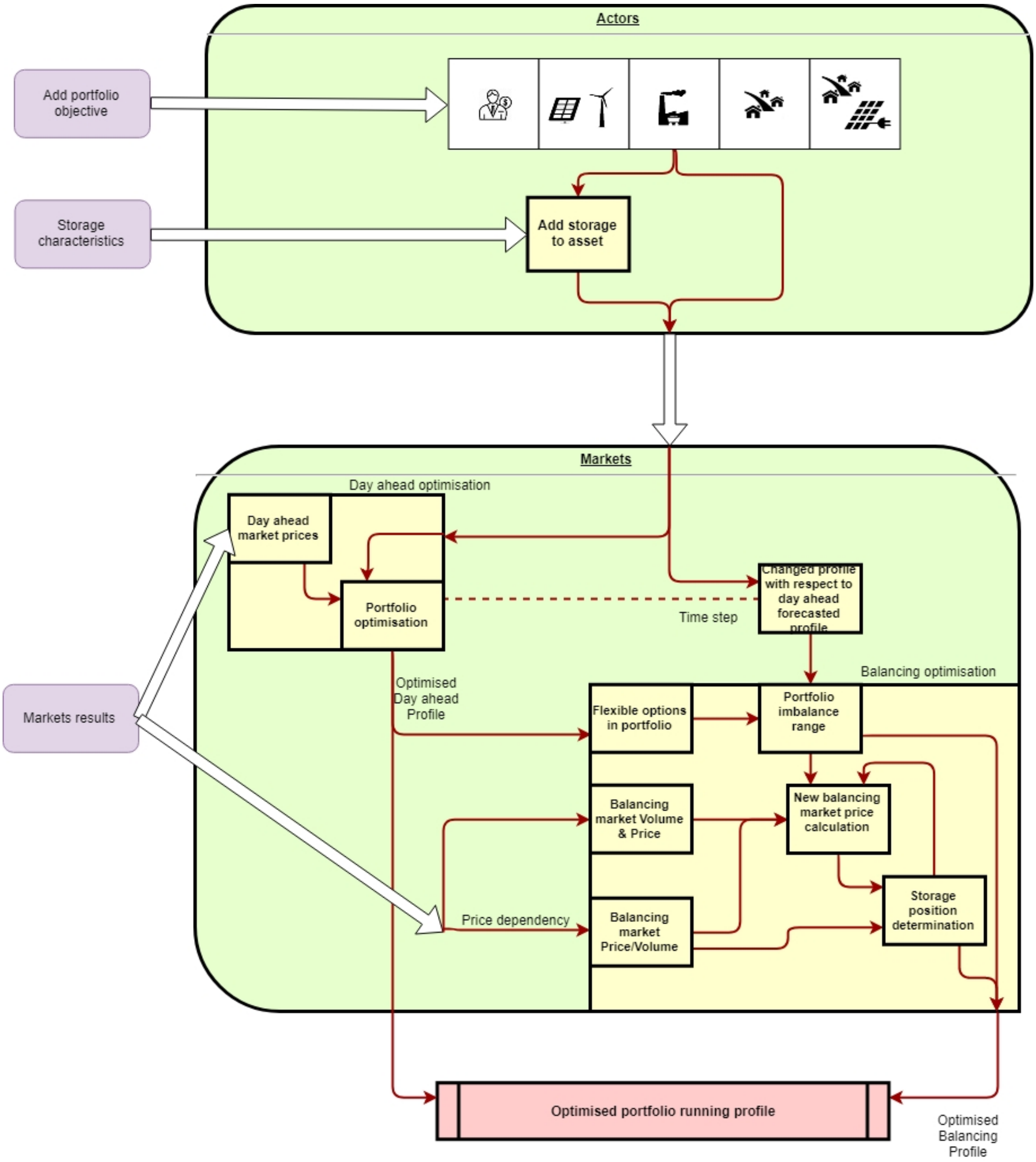


Figure 5.2: Model representation

With respect to the black box presented in figure 1.1, this process representation shows all steps taken from the possible actors until the operation profile. Then from this operation profile a new imbalance profile is created which is analysed in chapter 6.

5.5. Experiments

The experiments set up are 5 runs of ”Portfolio’s” which include one of each type of actor. For each of the actors which is not the new investor (base case), a new asset is added not larger than 100 MW. This asset creates a position for the actor. From this position, the storage is added to the portfolio and is operated optimally with respect to the objective. This calculation is done for each of the time steps in the data set. The outcome of the simulation is the optimised operation profile. From the optimised operation profile with the network imbalance input, a new imbalance profile can be calculated. These two profiles are saved and prepared for analysis.

A table is provided to present the experiments in a comprehensible overview.

	Base case	**VRES case**	**Gas case**	**Consumer**	**Prosumer**
Type actor	Before transmission	Before transmission	Before transmission	After transmission	After transmission
Optimisation	Revenue maximisation	Revenue maximisation	Revenue maximisation	Peak minimisation	Peak minimisation
Asset	-	Wind farm	Gas turbine	Demand profile	Demand profile + Pv panels
Source	-	[3, 10, 34, 35]	[19, 24, 25]	[34]	[3, 10, 34, 36]

6

Results

A total of 5 simulations have been executed. These simulations are optimisations with the objectives and conditions explained in chapter 3. From the calculations done by the computing tool, the resulting operational profiles are presented which are addressed in smaller granularity in appendix B. To recap, these optimisations are base case, VRES case, gas case, consumer case and prosumer case. The results are presented in two metrics namely difference in balancing profile and network imbalance. To be able to compare this data with the input data, the input data is also measured in these metrics.

6.1. Balancing profile differences

These differences are divided into before and after transmission systems. First the generation side of the system is discussed later the consumer side is hone in on. A linear regression is fitted between the difference in balancing profile and position on the balancing market of the portfolio for the parties before transmission. Behind transmission, a seasonal approximation is made to represent an average daily utilisation profile.

6.1.1. Before transmission analysis

Base case

The base case represents a new investor in the balancing market. The analysis of differences is done with respect to the base case to investigate possible synergies between preexisting portfolio's and new actors in the balancing market. Therefore the balancing profile positions for the base case during the year are presented in figure 6.1.

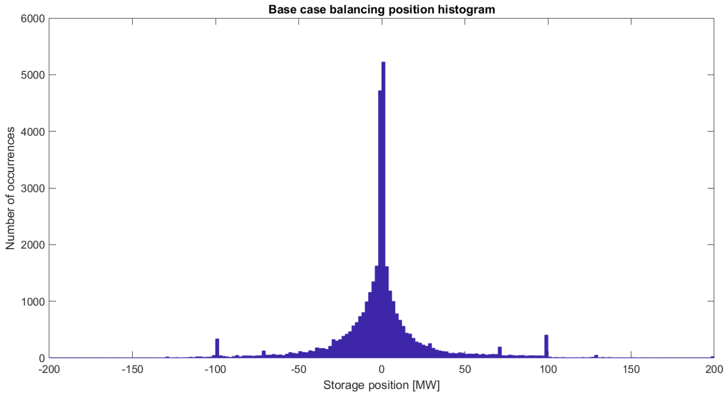


Figure 6.1: Balancing position histogram of the base case

Figure 6.1 represents the number of occurrences of balancing positions van the storage capacity when it is operated by an optimal new investor. The figure shows a laplace distribution with some peaks at trivial places such as 100 and -100 MW balancing power. These charges are found to be trivial because with a zero position on the day ahead market, these are the maximum charges possible and if the incentives are above or below a certain threshold the storage capacity will try to balance. Therefore these charges will occur more often than adjacent charges. Figure 6.1 shows the occurrences in a year but the time they occur might be as important as the count of occurrence. Therefore figure 6.2 present the average storage position over the length of a day.

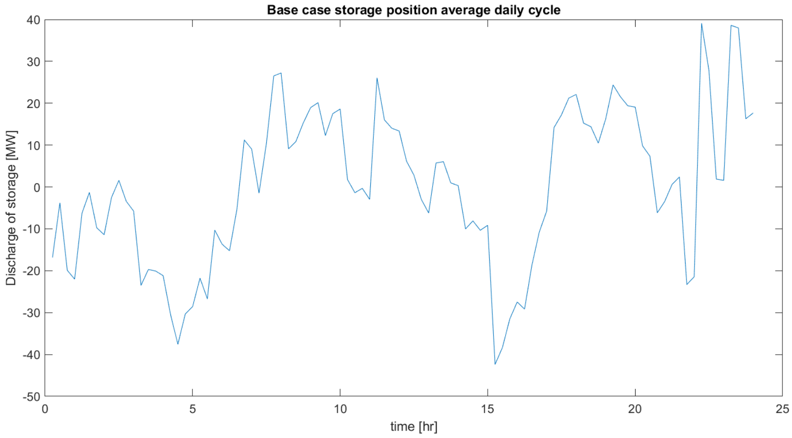


Figure 6.2: Average daily cycle of storage capacity for the base case

In figure 6.2 a volatile average cycle can be observed. Also, the averages do not exceed the 50 MW. This figure does not result in any conclusions for now. The next step regarding the research is to measure the difference of the other cases with respect to the results of the base case.

Centralised VRES case

To indicate added value of the storage capacity for portfolio optimisation, the VRES case is measured with respect to the base case. Therefore will the balance profile difference, which is defined as the balancing power of the wind farm case minus the balancing profile of the base case, be plotted against the wind power forecast. This scatter plot is presented in figure 6.3.

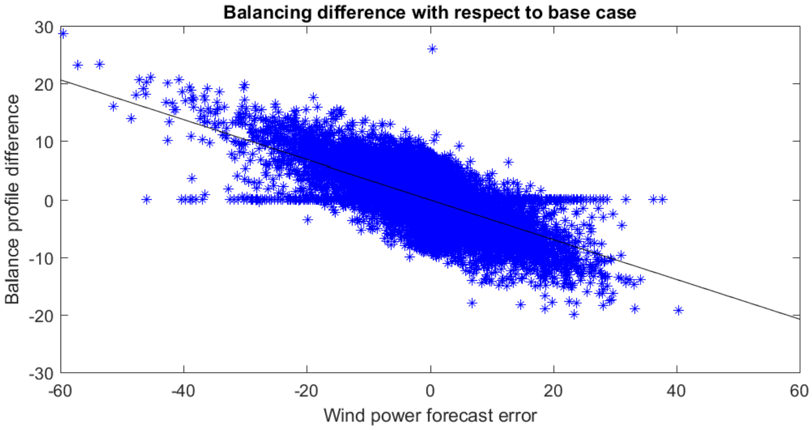


Figure 6.3: Wind power forecast error plotted versus the balancing profile of the storage difference with the base case

In figure 6.3, data points represent balancing difference for wind power forecast error on PTU level. The scatter plot shows a trend for preferred power output with respect to wind power forecast error. To represent this trend, a line is made by calculating the minimal mean squared error with respect to a linear equation. The minimised mean squared error is found for the following linear equation.

$$\Delta P_{bal,t} = -0.345 * Pw_{error,t} + -0.069 \tag{6.1}$$

The trend line is a inversely proportional with respect to forecasting error. This means that the storage is adjusted in the opposite direction with respect to the forecasting error. For example, if the wind forecasting error is -40 MW the storage adjusted to 20 MW more than the base case would. This is the expected result since the storage capacity will compensate for the created imbalance if the market prices are unfavourable with respect to this imbalance. The fit of the trend line is 83% of its variance calculated by linear least-squares.

Gas case

The same analysis has been done for the gas turbine and storage optimisation case which results in figure 6.4.

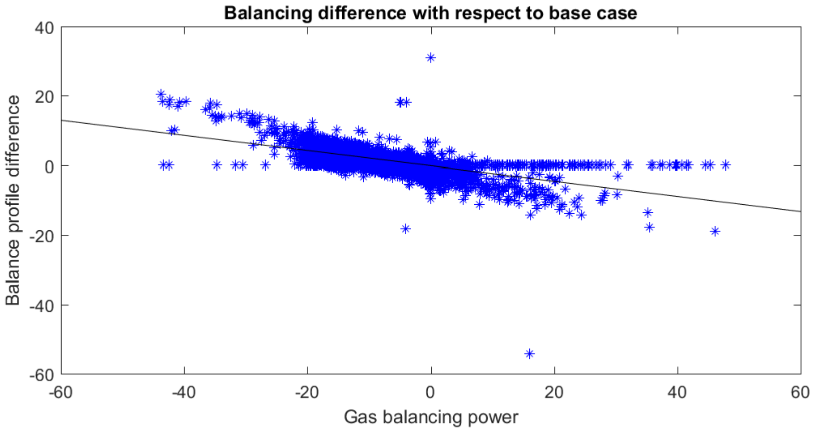


Figure 6.4: Gas turbine balancing positions plotted versus the balancing profile difference with the base case

The balance profile difference is defined as storage balancing profile in the gas case minus the balancing profile of the storage in the base case. This means that if the gas turbine is adjusted downwards the storage capacity will increase their sold power. On the side where the gas turbine is adjusted upwards the storage will shift downwards for sold power. The trend line is established by minimising mean square error. Equation 6.2 is the result of this calculation.

$$\Delta P_{bal,t} = -0.218 * Pg_{bal,t} + -0.142 \tag{6.2}$$

This trend line takes into account the data points for which the storage was not able to change its balancing profile. Therefore, the linear equation has an offset of the realised data. Still the trend seems to be that the storage will do the opposite of the gas turbine. A possibility is that the storage is used to maintain high power prices while the gas turbine has the bigger balancing volume on which the price is settled and therefore has more revenue. The fit of the trend line is 68% of its variance calculated by linear least-squares.

6.1.2. After transmission analysis

The difference in average profile of both suggested actors behind transmission can be observed in figure 6.5.

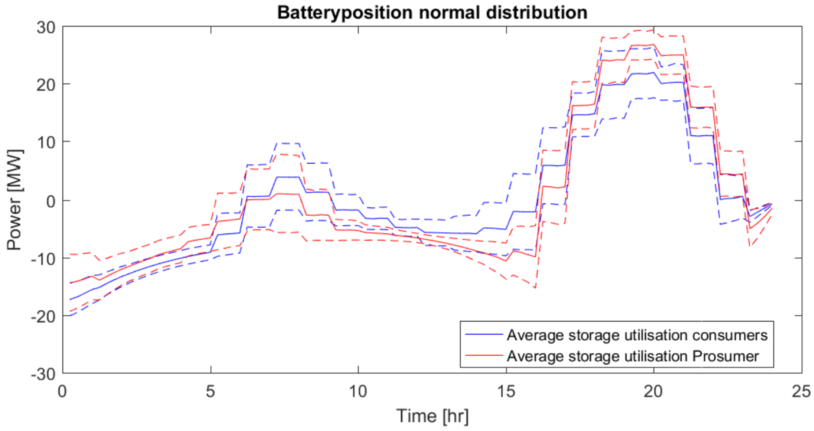


Figure 6.5: Average consumer versus Average Prosumer strategies

Figure 6.5 shows the average consumer balancing profile and the average prosumer balancing profile of the storage. The dotted lines corresponds to the line with the same colour and shows the first standard deviation from the measured average of the respective time. The hourly pattern of the data is seen in the figure. The standard deviations do not change significantly in size over the time span of the figure.

6.1.3. Difference in results interpretation

Before transmission

The objectives before transmission have been concluded to be both economic. Then portfolio balancing have been used to optimise the storage capacity. This results in the figures 6.3 and 6.4. When calculating the trend lines produced in figure 6.3 and 6.4, equations 6.3 and 6.4 are produced.

$$\Delta P_{bal,t} = -0.345 * Pw_{error,t} + -0.069 \tag{6.3}$$

$$\Delta P_{bal,t} = -0.218 * Pg_{bal,t} + -0.142 \tag{6.4}$$

The conclusion of the difference which can be observed between these equations is possibly that the incentive to store power decreases when power is delivered by a gas operated plant since this plant has marginal costs for the company. The biggest difference is that the gas plant is operating on an incentive of the market and the wind farm has a stochasticity which is not dependable on the market. It may even be described as an cause of imbalance prices. Therefore, the gas balancing powers are already beneficial for the company for which the wind power imbalances are sometimes beneficial and sometimes a burden. Therefore, more incentive is present when balancing the wind farm for the whole period of 2015 markets scenarios.

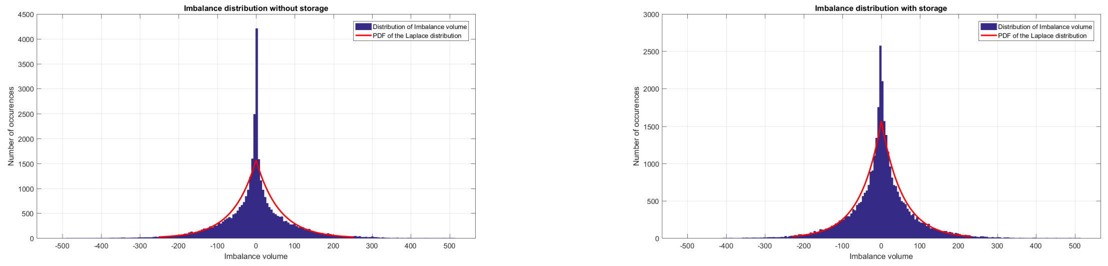
After transmission

After the transmission operator different incentives are present to operate the storage. The strategies are best captured by daily patterns. Therefore, figure 6.5 is consulted.

The biggest difference observed is the peak storage utilisation which is bigger for the prosumers. This is possible due to the lowered capacity needed in the afternoon due to the production of the PV panels. The numbers of lowered capacities under these circumstances are 75% for the consumer case and 65% for the prosumer case.

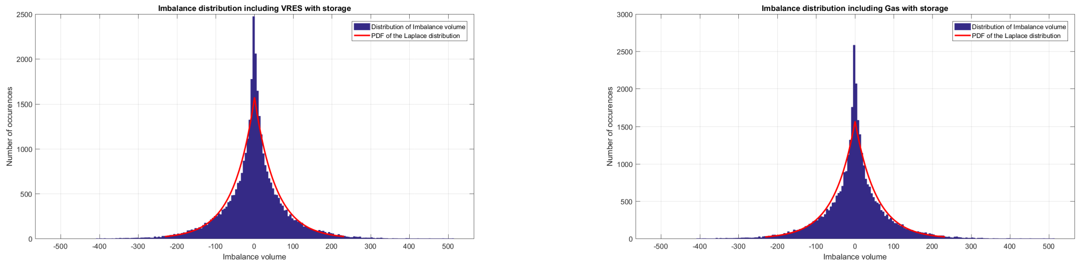
6.2. Network imbalance

The results of the simulation are shown in the following figures. The figures show the overall imbalance created by different portfolio's. By fitting a probability density function in these data sets, more detailed analysis of the imbalance can be made.



(a) Input imbalance distribution

(b) Base case imbalance distribution



(c) VRES case imbalance distribution

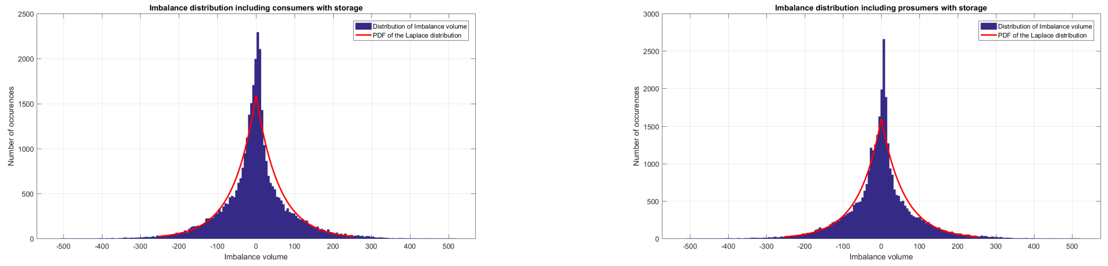
(d) Gas case balance distribution

Figure 6.6: Simulated imbalances with storage implementation at different operating responsible parties

The histograms represent the number of occurrences of balancing market results for each case. Figure 6.6a represents the realised market imbalances in 2015. Figure 6.6b shows the simulated market results for the optimisation of a stand-alone storage capacity with revenue optimisation as objective. Figure 6.6c represents the wind farm case including the storage optimisation. Figure 6.6d represents the gas turbine case including the storage optimisation.

These figures are shaped as Laplace distributions. Mind that the y-axes of the figures are not the same. The biggest difference which is observed is the difference in white area below the fitted laplace distribution. The input imbalance case seems to have a worse fit than the optimised results. Since the optical difference of these areas are not able to explain differences on scientific level the fitted laplace distributions are used to conclude differences on network imbalance levels. This is done later in this section.

For the consumer side, the results are shown in figure 6.7a and 6.7b.



(a) Histogram of imbalances with consumers

(b) Histogram of imbalances with prosumers

Figure 6.7: Simulated imbalances with storage implementation at different operating responsible parties behind transmission

The difference in figure 6.7a and 6.7b is observed to not be significant. Still the fitted distributions are added to the final analysis.

The optimisation of the consumer side is not incentivised by the balancing market prices therefore these figures show little difference. Since the differences are hard to see on the graphs the following table presents the fitted probability density function factors of the Laplace distribution fitting. As explained in chapter 3, the closer the number to zero the better it is for the network.

Table 6.1: Laplace b-factor per case

B factors	
Input Imbalance	118.79
Base case	109.23
VRES case	109.16
Gas case	109.37
Consumer case	119.37
Prosumer case	119.65

The numbers fitted to the distributions found before and after simulation, result in a negative effect for behind transmission implementation of storage for the overall imbalance in the system under 2015 conditions. While the optimisation of the storage capacity for the balancing market shows better overall performances with respect to network imbalance. At least one conclusion can be determined which is that the use of the balancing market has positive influence on balancing. Since it has been designed to do so, it is a working design for the scenario run of the year 2015.

The changes calculated between the before transmission cases seem to be insignificant with respect to the size of overall network imbalance. The complete difference in B-factor values is in total less one third of one percent therefore nothing concluding can be said about this difference.

7

Discussion

In this chapter, a discussion will be presented about the model, the result, the implications and the scientific value respectively. In these discussions the value and problems are explained.

7.1. Model level

First of all, a model is used to research a strategy. The first ever lesson given while learning about models is that every model is a representation of the view of the researcher of the subject. The conditions where these models are programmed in are important. In this section, the suspected significant uncertainties of the current model are presented.

- Normal distribution as stochastisity for wind, sun and demand.
  Variable renewable energy sources are known for the randomness of the realisation of the generation. Nowadays, a lot of money is invested in forecast models to be able to predict energy prices for even a few hours from now. While, this model has stochastic factors, these factors are still far from a real realisation profile. Often, profiles of higher wind or lower wind throughout the day can be found in realisation while the stochasticity used in this model has a greater randomness with peaks and valleys in sections for which in realisation just an offset would be created. A suggested improvement to the model would be to use Autoregressive Integrated Moving Average (ARIMA) models to create synthetic realisation data (as input for the balancing market) from an average wind profile. This application of an verified and validated ARIMA model can be a graduation thesis on it's own and is therefore neglected in this thesis.

- The normal distribution units.
  The normal distribution units used in this research all come from a single source. This source is an earlier master thesis of the Delft University of Technology. While trusting the research, the normal distribution units were not validated of verified in this research. Due to lack of realised data, the values of the normal distribution are assumed to be correct.

- Gas turbine optimisation should be iterated since the storage now influences the balancing price which could change the incentive for the gas turbine.
  Sequential optimisation for 2 factors which influence each other, has as drawback that lots of iterations are needed to find a stable output. In hindsight, these two factors were able to optimise in the same optimisation. This was not clear to the researcher in the moment of producing this model and is suggested as an improvement for the future research.

- 2015 input is dated data for energy research.
  The growth of variable renewable energy sources have been a big step for the electricity sector. The market results used as input of this model are therefore dated. The implementation of large quantities of VRES has made the wholesale market of electricity more volatile. When implementing the increased volatility, the business case of the storage capacity on its own will only become better. For the value of improved portfolio balancing will possibly increase as well.

- Assumption of price dependency of R2 market.
  As input, the dependency of the balancing market had to be assumed. At the point of model synthesis, the R2 market results seem to be the best available data to do so. While this is a indication, the real dependency will be very different since more companies than the companies which have bid into the R2 market will try to optimise their portfolio. Therefore the first derivative is expected to be higher. Since relative data of actors on the same market is used the price dependency of the R2 market is assumed to be a good estimator.

- Optimisation with all knowing perspective.
  Finally, optimisation in the form this research has done, has a major drawback of being all knowing. This means that 9 o'clock the prices of 12 o'clock are available and therefore the decision for charging can be made while in the moment the incentive was to discharge. In real life, the incentive at the moment will be leading while for the all knowing case the best option is chosen. As an earlier suggested, a new research with an ARIMA model would be able to create Monte Carlo simulations. These Monte Carlo simulations would be able to create an uncertainty with regards the future market prices. This would improve the research with respect of the all knowing perspective for the optimisation.

- Markets scoping as limits for options for EES.
  During the expert interviews, possible valuable options for actors have been uncovered. For example, a gas turbine starting cycle could be limiting the actor responsible of operating it in involving in the auction for auxiliary services. The instalment of an EES would create a freedom for to shut down the gas turbine where earlier the turbine would be forced to remain producing due to their commitment to the TSO. The operating profile for the portfolio included in the auxiliary services would be a significant addition to this research. Due to scoping in the conceptual phase of this research this synergy is neglected.

After summing up these uncertainties, the conclusion can be made that for calculating operating strategies or business cases the optimisations done is this report are too limiting. Since the outcomes of the model are used to compare profile differences, it can be assumed the model does represent real life operating profiles like the actors would have wanted to operate it. Therefore, the difference measured between the operating responsible cases could be used to explain the different significance of incentives and different effects on the overall network.

7.2. Results

7.2.1. Model results

Difference in operating profiles

As the results chapter suggests, the differences are only fair to compare within the same institutional position. The before transmission cases analysis are focusing on the differences due to portfolio changes. In this section, the differences of the portfolios are investigated.

The portfolios are build up from different assets. The base case portfolio only has the storage capacity to work with. Then, the VRES case has a wind farm and this modelled wind farm has an uncontrollable production. Therefore, the production is volatile but nearly always present. The model accounts for difference of production volume for every time step in the simulation. This creates a significant difference graph (figure 6.3). Due to the many a relative accurate linear regression can be created. This changes for the Gas case. The modelled gas turbine is a controllable generator. This adds a optimisation to the model since an operation profile is needed for this gas turbine. The added optimisation is a unit commitment problem and this results in the operation of the gas turbine only for profitable moments. The marginal costs of this gas turbine are relatively high and therefore the operation of this generator is limited. The total operational time is 11% of the total time. The linear regression graph (figure 6.4) therefore only presents 11% of the time steps (away from the y axis). Finally, the phenomena of the horizontal line in both graphs is discussed. This horizontal line created from data points, which do have different conditions but operate on the same power as the base case, must be explained. The horizontal line is created due to the limitations of the storage capacity. For example, in the day ahead market the storage is already nominated for the full 100 MW and the gas turbine is also utilised. The balancing power of the gas plant can be used to balance the balancing market but because the storage is already operating in full power the storage is not able to regulate upwards. This creates a data point on the x axis of the graph. If linear approximations of the differences are produced, these data points are considered in the minimisation of the mean square error. Therefore, the equation 6.1 and 6.2 approximation about the total usage and not only for the moments of imbalance or utilisation. The results must be used with respect to this realisation.

For the after transmission cases, the same consumption portfolio is used which is uncontrollable. During current day and age, the idea of demand response is researched extensively. Demand response is considered out of scope for this research but the results gotten from the simulations can be changed by demand response. Even if this is considered out of scope, the numbers gotten for peak demand after storage implementation are scenario sensitive. If any different input conditions would be given, the numbers of the maximum peak demand would be different. For example, the market conditions of 2016 could have been used and might have produced different numerical values for the same optimisation.

Network imbalance

The results of the network imbalance calculations are expressed in a 'b' factor. This 'b' factor is defined as the square root of two times the standard deviation squared. This give numbers in the order of magnitude of 10^2. Therefore is the standard deviation over 34560 entries is about 84 MWh for the input imbalance and about 77 MWh for the before transmission cases. At least it can be assumed that the lower imbalance is the better it is for the network. However, the increase of benefit can not be calculated by this difference.

7.2.2. Performance metrics

The previous section evaluated the results which are closely related with the performance metrics.

Before transmission difference of profile

As indicated in section 7.2.1, the trend line is created by fitting a linear equation in the data set created by the model. This linear equation is fitted by minimising the sum of error terms with respect to all data points. For the gas case these data points only represent 11 % of all time steps while for the VRES case this is 100 present of the time. Therefore, the trend line used to indicate added value of the storage with respect to the base case might be compromised due to this difference. The sensitivity of this difference is not researched in this thesis. The linear regression with respect to another operation profile is a self explored performance metric which should be researched more. Suggested is that the model produced in this report is adapted to calculate the added benefit for the portfolio with respect to the linear regression or the first derivative of the line.

After transmission difference of profile

The following problem can arise for the maximum peak demand. If, for example, a gas leak is detected in a residential area while the outside temperatures are low, the households in the neighbourhood will probably use electricity to heat water. This could create a higher peak demand. Because this peak is caused by a unpredictable event, the storage is likely not able to cover this big peak which then again causes a black out. This scenario would be dangerous for the inhabitants of this area since they will have no more means of creating heat for their house. Thus, the numbers created for these cases are for optimal and most predictable usage. No contingency planning is taken into account for these numbers. The average of a production profile might therefore not be a good indicator for performance.

Network imbalance

Assumed is that the imbalance over the year can be fitted by the laplace distribution. The 'b' factor of the laplace distribution function is assumed to be a good measurement for the imbalance. Next to this it is assumed that the minimisation of this 'b' factor is the best for the network and for the optimisation for social welfare. The minimisation of b factor is beneficial if the cost structure of the network imbalance is a exponential scale. For this research it is assumed that this is true. This assumption must be researched to use this performance metric in future studies.

7.3. System implications

As indicated in the problem introduction, the implementation of storage capacity is considered to be necessary and inevitable in scientific literature. As can be concluded from the results, the conditions of the operational responsible party are significant with respect to the operation of this storage capacity. Therefore, if recommendation could be made for, i.e. the ministry of economic affairs, the incentive for installation of storage capacity should be focused on the generation side instead of on local levels.

7.3.1. Actors

The results found in chapter 6 are beneficial for the energy producing companies and the energy retailers. The implementation of subsidies or support for instalment of electrical energy storage is an important subject for the current system. If this support is implemented, the system behaviour and the market power can shift towards the actor which is compensated. Therefore, truthfulness of actors is important since it could change the outcome of this research. If this research would be taken as recommendation for the government, the incentive to portray the company in another way can be present. One of the recommendations will be that support schemes should be investigated and before instalment of such support the outcome must be determined within a certain accuracy.

7.3.2. Technical subsystem

Early in this report it is assumed that the technical limitations of the network are omitted from this research. This results in little added value of this result with respect to the technical subsystem of the network. The only realisation gotten from the expert interviews is the positioning of the storage is important even if the technical limitation of the network is neglected. The positioning of the storage before or after measurement point of the markets can change the operational profile and strategy with respect to auxiliary services. The sensitivity of this change can be a subject for later research.

7.3.3. Markets

In section 2.3, the market description is given. The description suggests that the electricity market system in the Netherlands is rather complicated and the decision variables for the electricity traders is an extensive amount. The figures in this thesis are created to simplify the market structures. The current market structure does seem to work as designed for.

7.3.4. Framework

The framework used to superintend the desk research of chapter 2, is evaluated in this section. The framework created by de Vries (2004) [1], is a top level framework for the system. The first complication, while using this framework, is the implementation of production capacity on the after transmission side of the system. The Prosumers (defined as consumers with decentralised VRES) fit in the framework up to the point where they will produce more than consumed. The linear flow of electricity as a commodity is changing over time. In newer research (i.e. [37]), the flow of electricity is structured as a hub and spoke network. In the future, this might be a better structure but for the current system it will have to be somewhere in between. The next adaption needed for the framework is the implementation of storage. Storage (like the prosumers) can be categorised as either consumption and production. A new block can be added which controls these two controllable and uncontrollable reversible options which is neither exclusively consumption or production.

7.4. Scientific value

On a scientific level, the contribution of this report is the differentiation which is made in storage capacity operational responsibility, actor objective determination and a new performance metric for imbalance.

7.4.1. Sub results

During the desk research none of the actors incentives have been found. Therefore, expert interviews are used to establish these objectives. The hypotheses established before doing the interviews are based on the desk research which was performed but not all of them were concluded to be right. This new insight is reported and could contribute to the scientific knowledge of actor objectives. The new found validated knowledge is that economic incentives can be seen as most important but the conditions must be taken into account and that this is only not the case for the TSO.

As assumed in chapter 1, the operating responsible party is owner of the objective of operating the storage capacity. This assumption does not interfere with the cases described in this thesis up to the point where the operating responsible parties would have to share a storage capacity. In literature [38], asset responsibility is described as preferably split since this decreases the overall risks of owning such asset. For the results of the thesis, the possibility of sharing an asset is omitted from the scope. Therefore the results found are for single operating responsible party of an asset. The change with respect to multiple operating responsible parties is suggested to be researched in the future.

7.4.2. Results

Currently, storage implementation is suggested to have effects on the system without specifying operating responsibility or objectives in many researches. This report indicates that the objective difference of possible actors in a landscape is a significant change and this difference should be taken into account for storage application researches. Possibly the assumption can be made for application of storage capacity before transmission is equal to any other before transmission positions. The same assumption can be made for after transmission. The difference of before and after transmission however can not be denied.

7.4.3. Methods

The usage of laplace distributions for imbalance measurements is a novel method. In this research the correlation coefficient of the fit with respect to the histogram is 0.75. This is considered a sufficient fit but not an excellent fit. Probably a better fitted function can be constructed. The equation 4.1 can be changed to create a better fit by adding another factor such as in equation 7.1.

$$p(x; x_0, b, a) = \frac{1}{b} \exp\left(-\frac{|x - x_0|}{b}\right)^a \tag{7.1}$$

The added factor 'a' must be investigated to have influence on the assumption on the meaning of factor 'b'. In this report the 'b' factor is assumed to indicate the amount of imbalance. The minimisation of the b factor as being the best result for the network is also assuming that the costs for society are exponential with respect to imbalance. This assumption must be validated if this performance metric will be used in scientific literature.

8

Conclusion and recommendation

In this chapter, a conclusion will be produced by answering the sub-questions established in the first chapter. Then, recommendations will be presented. Finally, a reflection on the research will be given from the perspective of the researcher and the final learned lessons will be discussed.

8.1. Conclusion

Sub question one: What are the fundamentals of the Dutch electricity markets? And sub question two: What electrical energy storages are suitable for instalment in the Dutch electricity sector?

Multiple electrical energy storage technologies are suitable for instalment in a liberalised electricity market. Many of them are geographically constraint but one of the most promising technologies which is not geographically constraint is electrochemical battery technology. One example of instalment of such technology can be found in South Australia. The integration of the storage is possible in markets but since it is reversible electrical energy storage certain markets are more suitable for operation of the storage. The connection of the day ahead market and balancing market seems to be an interesting combination for the operation of the storage capacity. The portfolio position of different technologies are created by the differences from these markets and can serve as an input for a simulation of storage capacity utilisation.

Sub question three: Which actors are considered to operate electrical energy storage capacity?

For this research, possible operating responsible parties of electrical energy storage are divided in five categories namely; stand-alone storage users, centralised VRES owners, Gas-fired power plant owners, consumers and prosumers. These users of the storage all have a institutional position in the system. As actor conditions change due to different costs structures these actors are situated in, the objective functions of these possible operational responsible actors do differ. For the actors before the transmission network, the objective is found to be; to create as much revenue as possible on both markets evaluated. For the actors after the transmission network, the objective function is to minimise peak consumption. This results in decrease of connection fee (if this is applied for beforehand). The objective function together with the conditions are used as an input for the model created in this research.

Sub question four: How can there be a model developed to simulate the change of operating responsibilities as a variable in storage usage determination?

The objectives are translated into optimisation functions and the constraints and inputs are established. Constraints in this research are technical and institutional. The first constraint applied is the hourly sales of electricity on the day ahead market since the simulation is based on 15 minute increments. Second, the constraints of the storage capacity are added to the simulation. The constraints are maximum power constraints and energy content constraints. With the functions based on their individual objectives, optimisations for portfolios containing the chosen ”case study” storage unit is simulated. This is a simple version of an optimisation problem applied to the electricity system. Even though simplifications are made, this is considered to be a significant model for utilisation profile modelling.

Sub question five: How does the operational profile of the capacity of an electrical energy storage present itself under different operating responsibility?

Energy trading companies (actors before transmission) will optimise for the same goal with little difference in conditions. Centralised VRES owners have the incentive to regulate on imbalance they create to lower the portfolio imbalance and to lower the balancing market costs. This will be done on an average of 0.34 MW per Megawatt imbalance they create under 2015 conditions. For gas-fired power plant owners, incentive exists to discharge their storage when downward regulating power is asked for their gas balancing plant with an average of 0.21 MW per Megawatt downward regulated power. The suggested theory is that downward regulation of the gas-fired power plant saves money on gas costs with respect to the balancing price. This price seems to be high enough for the storage to discharge as well. This results in low balancing positions for these cases but it gives the opportunity to charge the storage on possible efficient moment.

Consumers and prosumers are in the market for different storage characteristics. The use of storage capacity for prosumers is very much more volatile then consumers when decreasing the maximum peak power. Household consumers/prosumers do still not benefit from having storage capacity since household peak power connection is fixed for household consumers. Big consumers with volatile demand do have an incentive to invest in storage since in optimally used the grid connection could be lowered to only 75 % of the current connection. This is conclusion is based on the 2015 weather conditions with a storage of which the power is exactly the peak consumption and the capacity is 1.29 times the peak power. If this consumer installs a capacity of the same magnitude as their peak consumption of PV panels, this connection could drop as low as 65% of their current peak under the same conditions. This will benefit the decrease of volatility in the day-ahead market while this is not their incentive. Still the incentive to invest in storage capacity will not be present in household consumers since the price of electricity is stable and there is no need for bigger connections because all household appliances work on the same voltage. Whenever the netting rule changes into a dual pricing system, the incentive for prosumers will be bigger to invest in storage capacity.

The network imbalance for the cases which are simulated, can be divided in two categories. The two categories identified are before and after transmission. The after transmission cases are at least not beneficial for the imbalance of the network. The difference in B-factor is less then 1 percent from the input imbalance. This difference is relatively small and can be assumed to be a model artefact for now. The before transmission cases on the other hand do show a significant improvement of the B-factor of the fitted laplace distribution. The conclusion is that the instalment of storage capacity on the before transmission side under 2015 conditions is beneficial with respect to the total imbalance of the network while the after transmission cases under the same conditions did not have this same beneficial effect.

Main research question

The research question is answered by concluding the following. The change of operating responsibility party does have influence on the usage of the storage. The biggest difference of storage usage is due to the fact that the cost structure of the owners change due to the institutional location in the system. The storage operating responsible position in the system has influence on the implications of network imbalance volume. To minimise societal costs, the focus on implementing storage capacity should be on the before transmission side of the institutional electricity system.

8.2. Recommendation

In the recommendation section, a few subsections will be created. These subsections are recommendation for this research and recommendations for future research respectively.

Recommendations for this research

As reported in the discussion, this research is dependable on the correctness of the data used as input. Therefore the first recommendation is to invest time in obtaining realised day-ahead market and balancing market results for gas turbine, wind farm and consumer data. This data is preferably as new as possible to represent the current investment incentives. Next to this, the results obtained should be validated. Currently these results, are as good as the model and as can be seen in the discussion, the model has sensitivities which should be quantified.

Recommendations for future research

The next step for evaluating strategies is to find out how these parties would bid on auxiliary services and if they would get cleared. Then this data can be used to evaluate the research of this report. The bigger question resulting from the auxiliary services is, what is the optimal ratio of using the storage for these services with respect to the balancing market. Finally a new research can be suggested to find the operational profiles for other countries, the obvious extra value would be to find the differences with the profiles from this report. Another suggested future research is presented in the discussion namely the application of ARIMA models with respect to variabilities in this research would increase the accuracy in which these models can operate.

8.3. Self reflection

In this section, I would like to reflect on the research from my own perspective. The first thing that comes to mind is a quote from the first lecture of Agent-based Modelling. A model is a representation of your skills to code your representation of the reality. The model which was built, is a representation of an asset optimisation for two markets. Because this model has the all knowing character, the simulation only reveals the best possible way of operating the storage capacity. The best way to operate an asset is not automatically a good strategy since it would have taken big risks to operate in this manner which I had to remind myself. To derive strategy from the optimum profile, the available information at certain time points must be looked at and then only assumptions can be made for the incentive to regulate up or down. Either way, having the preferred storage capacity usage profile could learn you a lot about the preferred states of a storage capacity. The conclusions produced from these profiles then again are only a representation of the capability for my head to write a text about my view on the problem. Eventually, a lot of steps needed to be made which could add significant amount of subjectivity into the research. At least, a detailed description was made to explain the steps taken and the repeatability should be high enough in my view. Still I learned a lot by doing this research such as ”do not take to big bites at once”. A proposal was handed in for computing the states of all generators in the markets discussed in this research. This was in hindsight indeed an overambitious goal. The overall workload was nicely distributed by the stable presence of myself at the university which took a lot of discipline and fortunately I was able to motivate myself.

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A

Appendix A

A.1. Creating interest

To address the suggested actors, interest must be produced to to enhance the opportunity to be able to hold this interview. Therefore the following text is carefully created to hopefully intrigue the company/actor.

Beste heer/mevrouw,

Laat me beginnen met mezelf voor te stellen, ik ben Rick Everaert en ben op dit moment mijn scriptie aan het schrijven aan de TU Delft over Energie opslag. Hierbij is mijn focus gericht op eigenaarschap van de mogelijke opslag capaciteit en wat het verschil zal zijn bij verschillende eigenaren. Voor dit onderzoek zou ik graag het bedrijf waarbij u werkt als één van de mogelijke eigenaren onderzoeken. Ik wil daarom graag een keer bij u of een van uw collega's langskomen om een gesprek te voeren over hoe u en uw bedrijf het gebruik van een opslag capaciteit voor ogen zien. De 'case' studie die ik zal gaan doen, zal gaan over 'the hornsdale power reserve' die ook wel beter bekend staat als de Tesla batterij in zuid Australië. Deze specifiek opslag mogelijkheid heeft een capaciteit van 129 MWh met een vermogen van 100 MW. Voor dit onderzoek is er specifiek gekozen voor deze (over)capaciteit. Voor uw medewerking zal het rapport, als dit is nagekeken, met u gedeeld worden.

Als u interesse heeft om mee te werken aan dit onderzoek, hoor ik graag van u. Ik ben te bereiken via mijn mobiele nummer; +31 6 4641 4xxx, of via mijn email adress; re@gmail.com. Ik zal heel de maand Juli beschikbaar zijn voor een gesprek.

Met vriendelijke groet,

Rick Everaert

A.2. Interview questions

First things first: Mag ik dit gesprek opnemen? Dit zal alleen gebruikt worden voor mijn onderzoek en alles wat hierover in het onderzoek komt zal ik bij moeten valideren. *Voorstelronde* Voorstellen: Rick – Energie(forze, circular energy). Ten eerste zou ik graag willen weten wie u bent wat uw functie is, en wat uw achtergrond is. *Kennis exploratie* Wat zijn volgens u de mogelijkheden van opslag van energie met betrekking tot balanceren en duurzaamheid over het algemeen *Bedrijf* Wat is de verhouding tot electriciteit van dit bedrijf? (welke catagorie; met overzicht erbij) Wat zijn de limitaties van het bedrijf? *Opslag* Hoe zal dit bedrijf gebruik kan maken van een Gratis energieopslag (onbeperkt vermogen en capaciteit) Wat denkt u dat andere partijen zullen doen met deze opslag zoals [centrale VRES, BRP's, SO's of consumers] en waarom. *Economisch* Economische haalbaarheid van opslag in het bedrijf Andere bedrijven? *RED FLAGS* Zijn er volgens u nog gevaren voor de implementatie van opslag?

A.3. Interviews

Tennet in the role of SO :

A quick introduction about myself has been made, whereafter Joris Besseling introduced himself. After this, the vision of flexibility of Tennet is explained. The following conclusions could be subtracted from the interview; Flexibility need is growing, and current flexibility needs to be replaced due to carbon intensity. Still a lot of flexibility is present, even an overcapacity in some sense due to inter-connectivity and the insignificance of the spread of day-night demand. Therefore, the business case is not really positive at this moment. From there, portfolio balancing is also discussed to be a good policy against variability. Power plant tripping is a big problem for variability which Tennet needs to solve. Therefore they buy auxiliary services from asset owners. They are not allowed to own active assets. Possibilities may arise for storage for a new flexibility option which is referred to as referral of investments on the network through solving congestion problems or transport constraints problems. Mr Besseling also says that Tennet is not a market party and they definitely don't want to influence the market. Italy has invested in storage capacity but only for congestion management. The possible problem for storage capacity is that they pay an extra fee with respect to normal delivery because they need to pay the transport fee's. If the possibility arises that free storage is available to Tennet, the balancing will not be affected because the business case for other assets may not be influenced by the regulating party and they do not even want to. The battery would not even will be used in incidental cases because the same as balancing, the business case would be affected for example the price cap of incidental reserve products. Next, the emphasis is put on the fact that gas-fired power plants are as much a cause of imbalance on the system. This is the case of a trip of the power plant which is dimensioned on European standard. Therefore the reserve capacities are dimensioned on a trip of 2 big nuclear power plants in France. A clarification was made that a wind farm or a centralised PV park are also BRP's. This notation should be made correct in this report. Portfolio balancing is a nice tool, seen often, between 2 parties such as centralised VRES and Gas-fired power plants with a PPA (power purchase agreement). European systems are pushing towards making centralised VRES responsible for their imbalance. When looking at business cases the location of the storage capacity could be very beneficial. The price of the connection could be lower by storing peak power and releasing it later. There is still a difference in business case while operating a combination of wind farm and storage capacity since the location is possible factor in certain pricing such as connection fees or redispatching. Consumers are a possible balancing party as multiple sources are aggregated. Consumers will be incentivised to use as much decentralised produced electricity. DSO's will like this fact. Although big networks and power plants are trying to connect bigger networks together to become more efficient and to easier balance demand and supply. Suggested is that how bigger the network the more social welfare could be obtained. Decentralised local initiatives are incentives to continue developing programs but this does not ensure lowest society costs. The concept, utility death cycle as explained by [29], is not a problem in the Netherlands since the tariffs for network connection is a fixed rate per year instead of a fee on energy consumption. Finally, there is suggested that storage capacity is still not a viable business case in the Netherlands.

KPN in the role of Consumer:

First of all, an introduction is given, where after Silvana Iefel and Marcon De Vrede introduced themselves. Then, the interview went on to company characteristics. The main focus of the company is to be a telecom provider. The maintenance of the technical system regarding electricity is outsources but the planning and constraints will be managed by their company. Personal objectives have been guided by sustainability and these objectives are transferred to the company if there is possibility for it. Sustainability choices are suggested in the company and sometimes even accepted. Noted is that the core business is not to be an energy consumer. The company delivers a service which costs electricity. This electricity consumption is therefore important but subservient from the security of service. Demand side management, is insignificant with respect to normal demand. A suggestion is given for cooling the server locations which could be extra cooled at low demand periods. The service itself could not be managed because the business case survives on a secure service. Therefore, at this point, no extra demand side management is used. Then, the representation of the landscape for this research is shown for which is asked to identify objectives for different actors. There was suggested that the system operator will like have the least amount of imbalance. Finally, the supply side of the electricity market are suggested to have only economical incentives.

PZEM in the role of centralised VRES owner and Gas turbine generator owner: First of all, an introduction is done about the thesis and my background. After this, Jorim de Boks introduced himself and PZEM. The summary of this introduction concludes that PZEM is an electrical energy producer and a market party on the wholesale market of energy. While trading on the wholesale market, portfolio optimisation is used in order to produce electrical energy as efficient and profitable as possible. In the portfolio, a large amount of wind energy and gas power flexibility is present. Storage optimisation is largely dependent on technical specification for which on the one hand flywheels are used and on the other hand gas to power and pumped hydro-storage. The interviewer now suggested that the party is the owner of VRES production. While they do sell the power of the wind farms, the company suggest that it is not the owner for all the wind farms they provide services for. The agreement made with the wind farm could exist out of multiple forms. The agreement of the wind farm with the trader is not disclosed in the interview. The focus shifted to the owner of an asset where in this hypothetical case, it is responsible for their own energy trade. When this is the case, a few configurations are possible. The storage capacity could for example be used as balancing help. The position of the storage is in this case also a important factor. The first option is for example, behind the meter from the market point of view. The connection costs are possible to be combined and this is an interesting business case since the storage likely only want to deliver when the wind power is low since high wind power production lowers the price. But still in this case the storage capacity would mainly be used as risk mitigation because of opposing exposure. For gas turbines, sometimes flexibility is needed to run a gas turbine, for example for a start up. Next to this, the auxiliary services could be an answer to the oversupply of their flexibility. This for example gives you the possibility to switch of a gas turbine while complying to the flexibility constraints of the auxiliary services. The storage capacity has variable shadow prices which is different for gas turbines which have a stable shadow price in relation with gas prices. The shadow price of a storage is dependable on when it is charged. For a TSO, the only business case is for redispatching and congestion since the institutions prevents them of influencing the market prices. Consumers have a different situation and for now the usage of a storage capacity is not changing any costs at this point. As soon as the netting agreement changes, this becomes a nice business case for prosumers since the taxes can be bypassed. This will only change for 2020 or 2023. For bigger consumers, the network costs can be lowered by making a smaller connection with having a storage capacity for the biggest peaks. This only works for volatile profiles. The dangers for example can already be found in the United Kingdom where capacity mechanism are implemented. The possibility that the price volatility will be decreased due to oversupply of storage capacity for which business cases for gas technologies will decrease as well, the security of supply will be lowered in high demand periods as in the Dunkelflaute in Germany.

B

Appendix B

The model described in chapter 3, is used to run simulations of the electricity system and network. The additions of respectively small assets gives the chance to simulate different behaviour of a storage capacity on the balancing market.

B.1. Base case

For the base case, a 100 MW storage is optimised to create as much revenue as possible. To review the strategy, a day is chosen to represent the data on a short time span and verify the short term behaviour. For this case day the following prices are used as input.

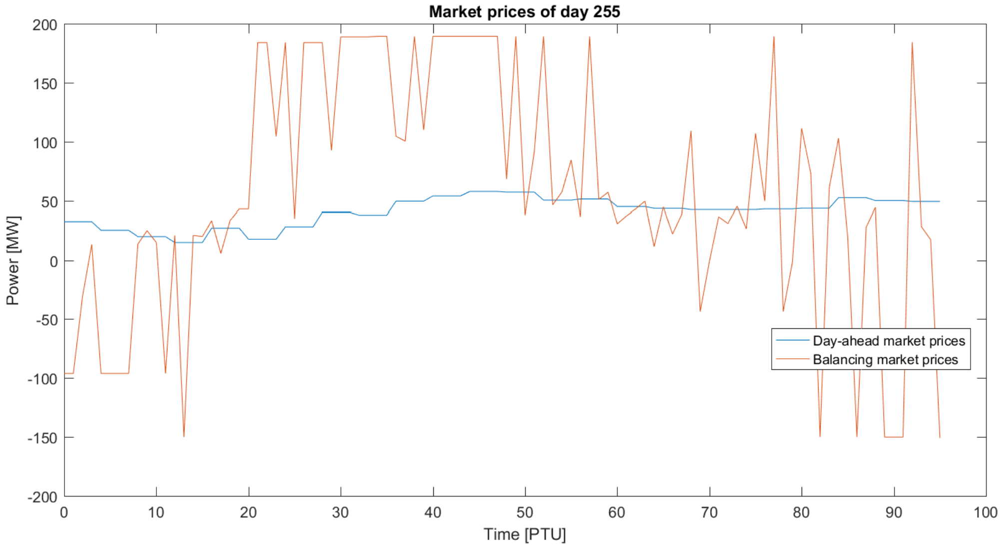


Figure B.1: Prices day case

In figure B.1, two different price courses can be identified. The blue line represents the day-ahead market prices which are established for hour long periods. The red line represents the balancing market price course which is much more volatile. The balancing market is shallower than the day-ahead market. It is assumed that the operation in the balancing market affects the price. When optimising the storage capacity with these assumptions for this day, the following results are generated.

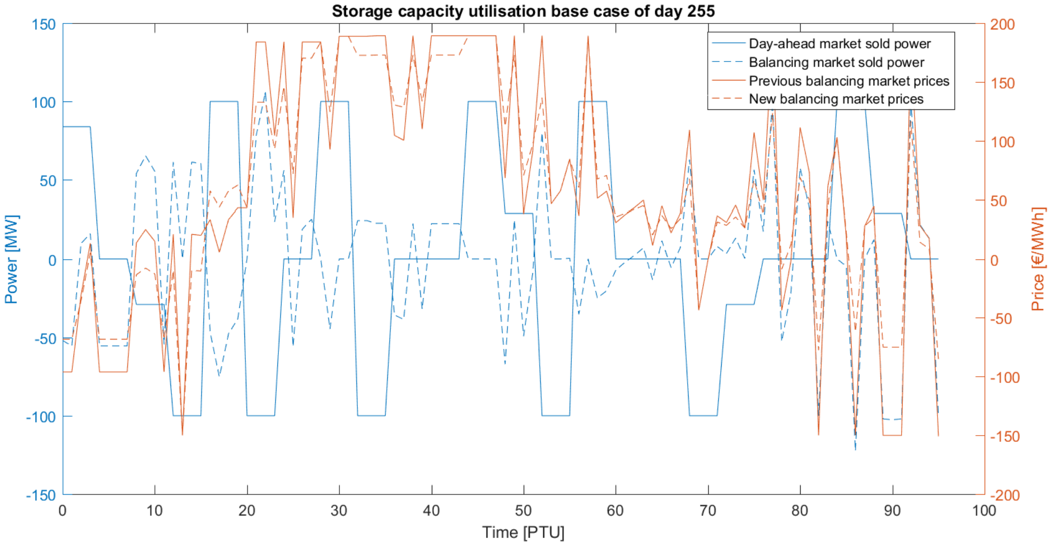
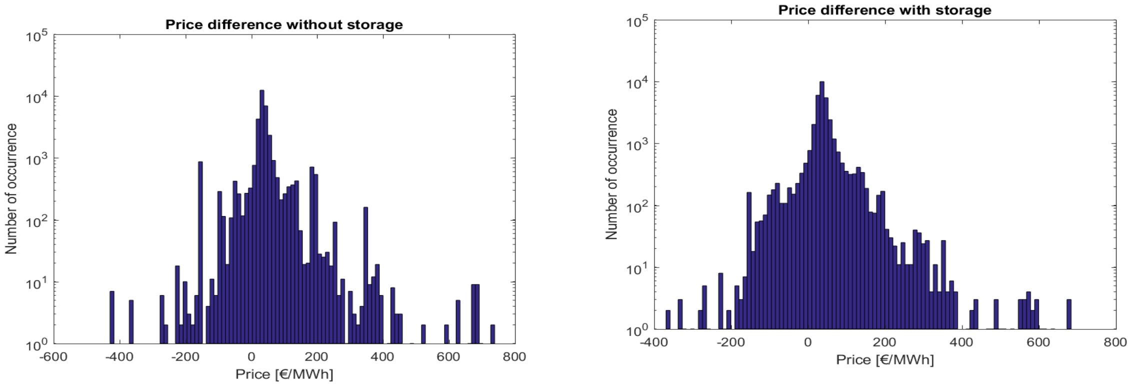


Figure B.2: Day case storage optimisation

The blue lines represent positions, which has it values on the left y-axis, in the markets. The blue lines added will result in the storage realised power profile. The change in balancing market prices, represented in the red lines which has there value plotted on the right y-axis, over all days will represent the implication of the generalised strategy of the storage capacity. The decrease of prices when delivering power on the balancing market verifies the correct price dependency implementation.

Figure B.3a shows the balancing price for the realised balancing market results and in figure B.3b the simulated balancing prices when the storage is implemented are displayed.



(a) Balancing prices occurrence for balancing market

(b) Balancing prices occurrence for the simulated balancing market with storage

Figure B.3: Base case balancing market prices

These images are bar plots of the number of occurrences of a price during the period which is simulated. This is also called a histogram. The important detail which should be noticed for these figures is that the y-axis of these graphs are on a logarithmic scale. For the peaks on the high prices of figure B.3a, which is the realised balancing prices, can be explained by a occurrence of an incident in the Dutch landscape. This resulted in a power loss for a whole province for 4 hours and high prices in the balancing market.

For the results presented in figure B.3, the following can be concluded. The extremities have been decreased with the implementation of storage and the overall histogram has been cleared from noise. This is due to the best price seeking algorithm of the optimisation. As the storage can charge for a certain price (which is dependent on the amount of consumed power that PTU) it will sell that power for any price above the charging price and therefore bringing those prices further together. The limitations of the storage such as power and capacity are the explanation of the remaining odd peaks on the graph.

B.2. Centralised VRES case

The input for the centralised VRES case is represented in figure B.4 for the particular day which is used to verify the model.

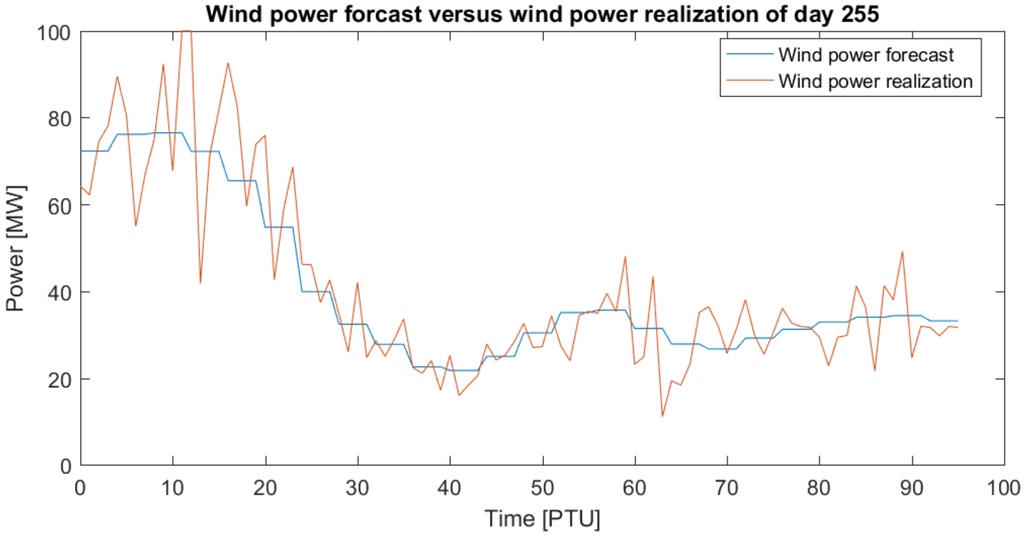


Figure B.4: Wind farm case

In figure B.4, the blue line represents the power expected from the wind farm for the day ahead market. This power is assumed to be sold as forecasted. This means that strategic bidding for the wind farm is neglected. The red line in figure B.4 is the realisation of power of the wind farm which calculated by multiplying the forecasted wind farm production by a stochastic factor defined by [10].

The addition of this stochastic factor results in a change of balancing market prices. In figure B.5 the change of the forecast power error is shown

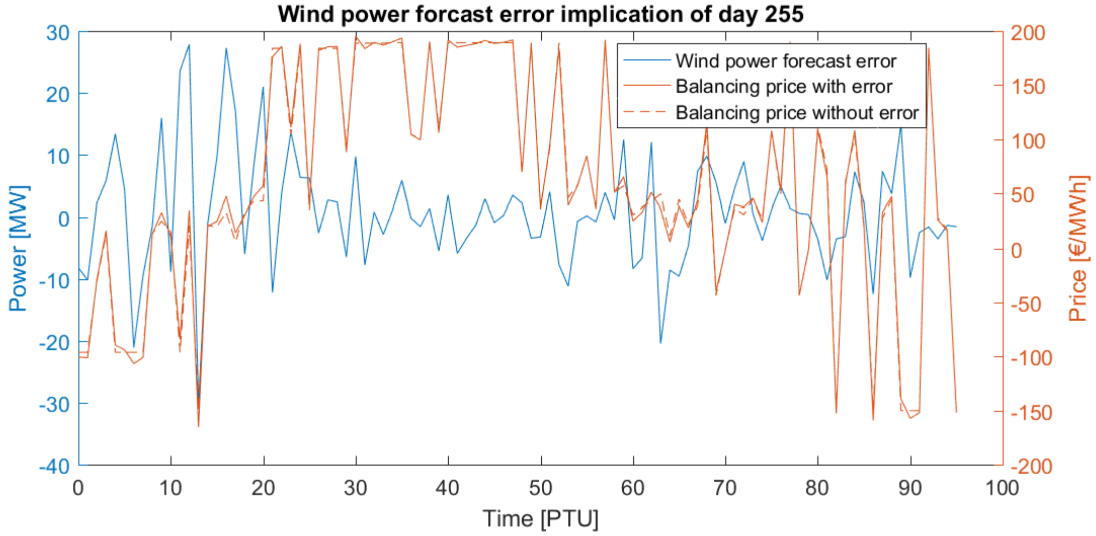


Figure B.5: Wind forecast error implication

In this graph the wind power forecast error is defined as the realisation minus the forecasted power.

This shows that the balancing price does not change significantly but to verify the correct dependency of the price with respect to imbalance. PTU 16 is suggested to hone in on were could be seen that positive forecast error drops the balancing market prices which is the correct influence as is expected.

This new simulated balancing market price is taken as input for optimising the storage capacity. With this new imbalance price and wind forecast error the balancing profile of the storage capacity is presented in figure B.6.

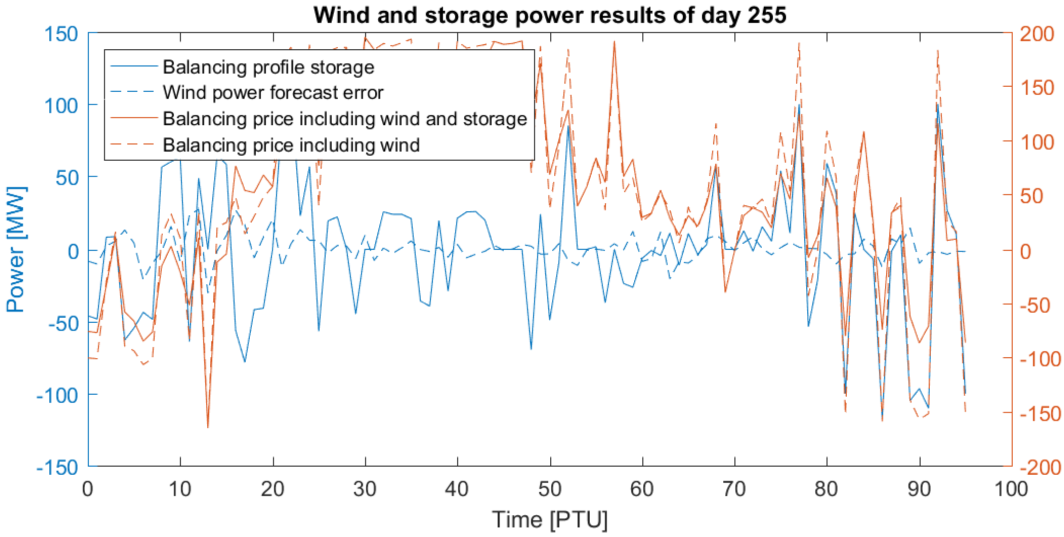
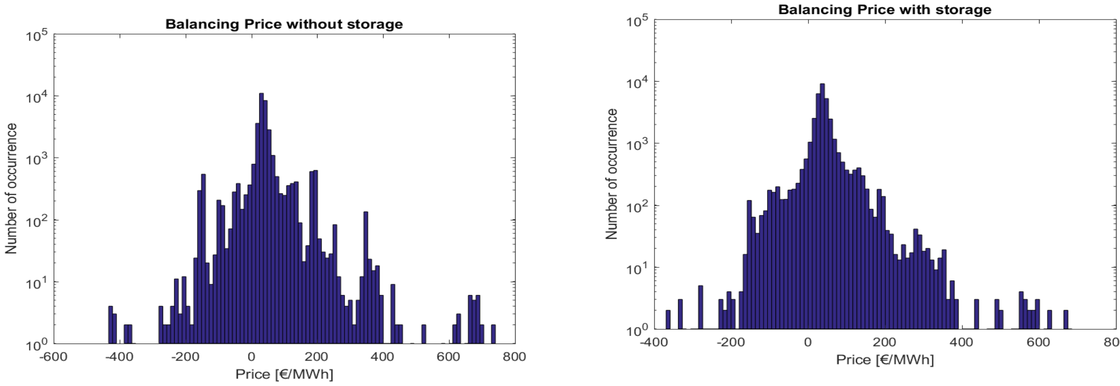


Figure B.6: Wind and storage

Figure B.6, represents two steps in the optimisation tool. For the first step, the wind power forecast error is added to the realised market result prices to create new synthetic balancing market prices, represented in the red dotted line. Then this is used as the input for the optimisation of the portfolio imbalance of the wind farm including the storage capacity. This results in the storage balancing profile represented by the blue line and the balancing market prices after storage capacity balancing by the red line.

Then based on the day case we know that the balancing prices over the year change represented in figure B.7.



(a) Balancing market prices including wind forecast error

(b) Balancing market prices including wind forecast error and storage balancing

Figure B.7: Balancing market prices development in the wind farm case

In the graphs B.7a and B.7b, the occurrence of balancing market prices for the realised plus wind forecast error case and the implemented optimised storage for the wind farm case are shown. Again the overall prices of imbalance are smoothed by the revenue seeking algorithm.

B.3. Gas turbine case

The implementation of the gas turbine in the realised market as described in chapter 3, has been simulated. The simulation of this gas turbine has resulted in a volatile utilisation profile. In figure B.8, the running profile of day 255 is displayed.

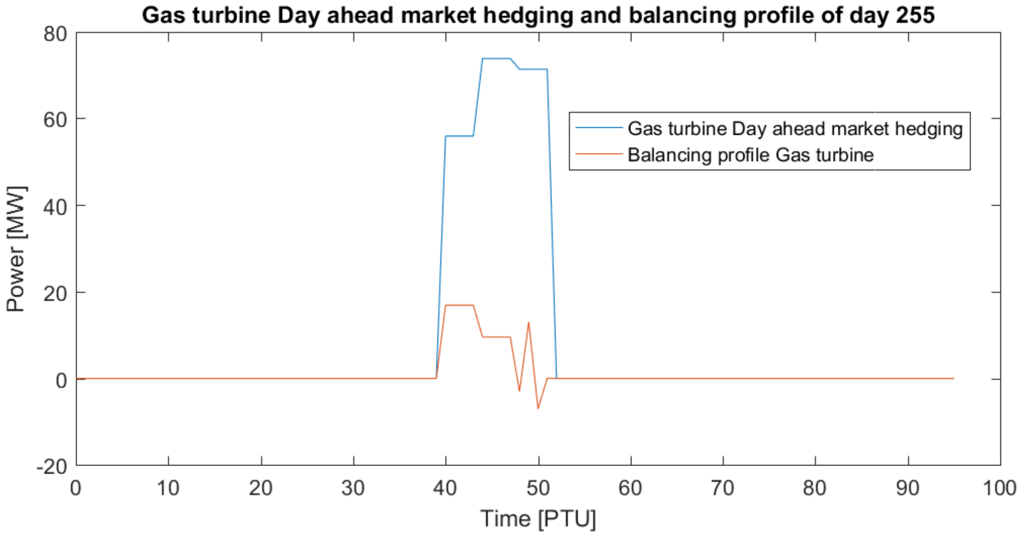


Figure B.8: Gas turbine case input

Figure B.8 shows a running profile of three hours from nine o'clock in the morning to midday. The output is between the minimal stable generation and maximum power. The difference between the sold power on the day ahead market and the minimum stable generation of maximum power is the total flexibility range. Then, the market balancing profile is shown as the red line in the graph. As can be seen, the balancing power is within the range of flexibility.

The balancing power has influence on the balancing market prices. Therefore, figure B.9 shows the change of the prices.

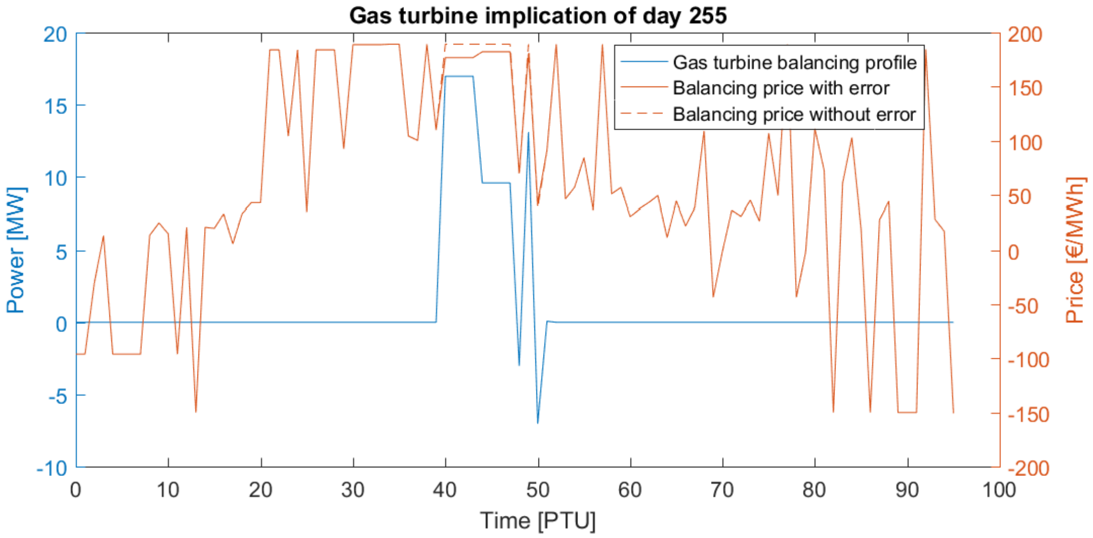


Figure B.9: Gas turbine price implication

This new imbalance price, indicated by the solid red line in figure B.9, is taken into account while optimising the storage capacity. Clearly can be seen that the solid blue line has a direct impact on the price, as was expected. With this new imbalance price and Gas turbine balancing, the balancing profile of the storage capacity can be calculated. These results are shown in figure B.10.

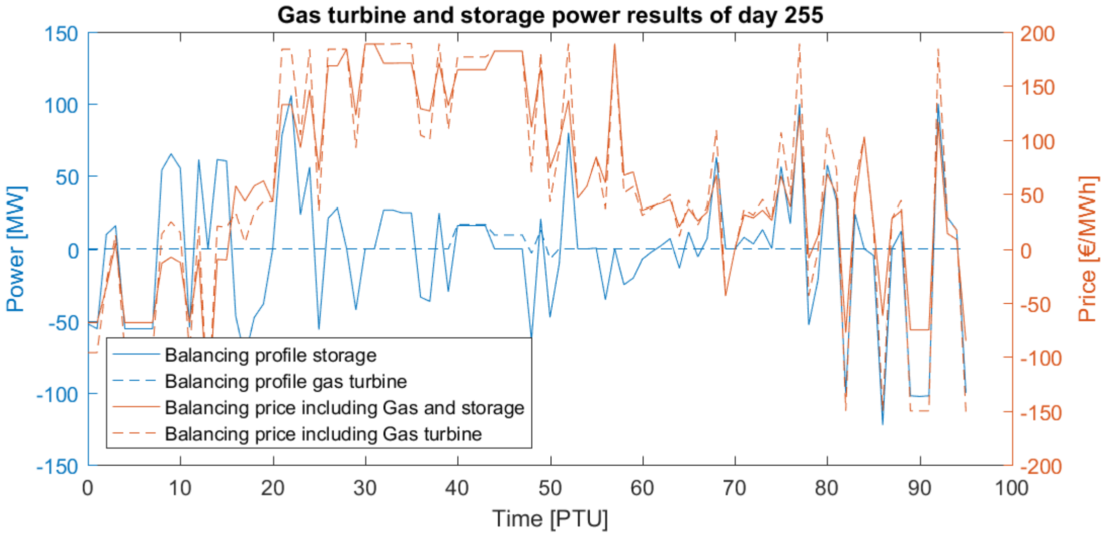
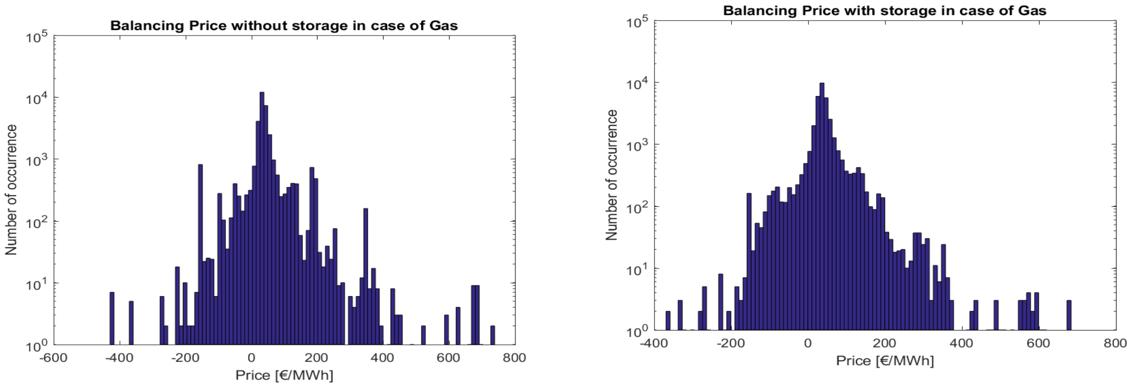


Figure B.10: Gas turbine and storage

The solid blue line in figure B.10 indicates the balancing profile of the storage. This affects the prices which are indicated by the red solid line after the balancing of the storage and the dotted line before implementing the storage balancing profile. This indicates that the prices again drop with respect to positive balancing of the storage capacity. Therefore, the implication of balancing is correctly added to the equation.

To investigate the effects of the gas balancing and storage balancing in this portfolio, on the total balancing price histogram, figure B.3 is replicated in figureB.11 for the gas balancing data.



(a) Histogram of balancing prices with extra gas turbine

(b) Histogram of balancing prices including gas and storage

Figure B.11: Gas turbine case balancing market prices

With respect of figure B.3a, figure B.11a shows a little price smoothing over all data point. Meanwhile, figure B.11b shows nearly the same figure as figure B.3b but a real trained eye could see some little differences in favour of figure B.11b.

B.4. Consumer

Consumer behaviour as explained in chapter 3, has different implications on price and storage behaviour. In this section, the simulation results will be verified and the total influence of the consumer behaviour will be analysed. First, the input for the day case is shown in figure B.12.

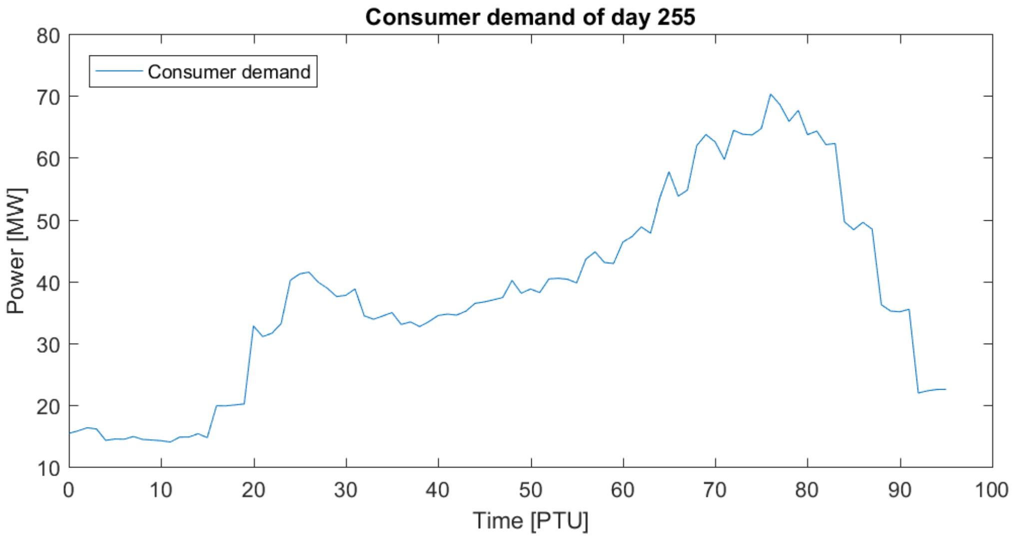


Figure B.12: Gas turbine case input

This consumer demand is an average demand of a domestic neighbourhood with a 2% stochastic factor over it. This will be treated as the input for an portfolio but this portfolio does have the condition of fixed pricing. The 2% of stochasticity is used to feed into the balancing market since the consumption is forecasted by previous results with good accuracy. In figure B.13, the price implication is reflected.

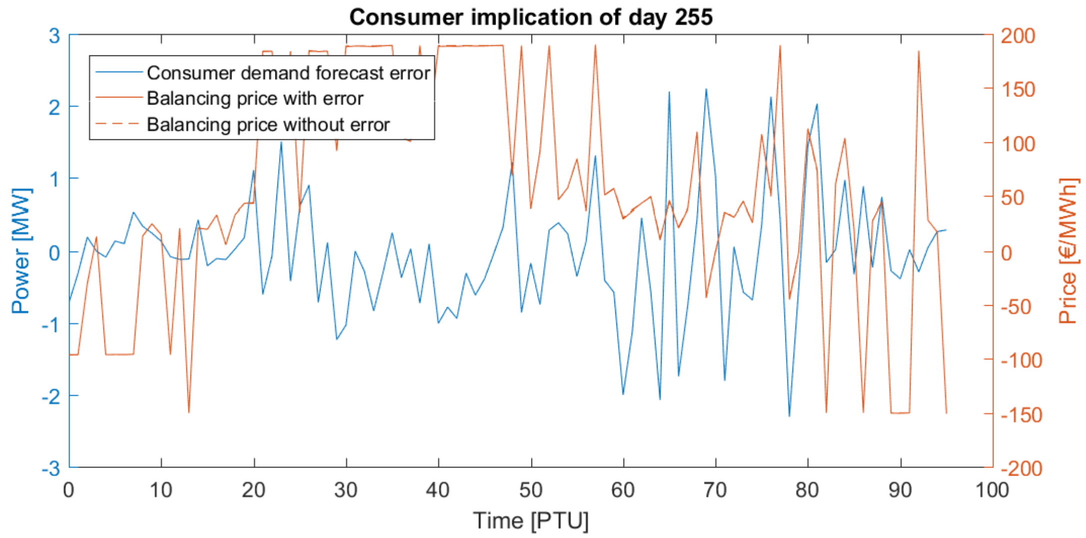


Figure B.13: Consumer stochasticity affect on balancing market

This shows that the balancing price does not change significantly which is as expected since the consumers are not affected by this price and therefore are not trying to influence this pricing system.

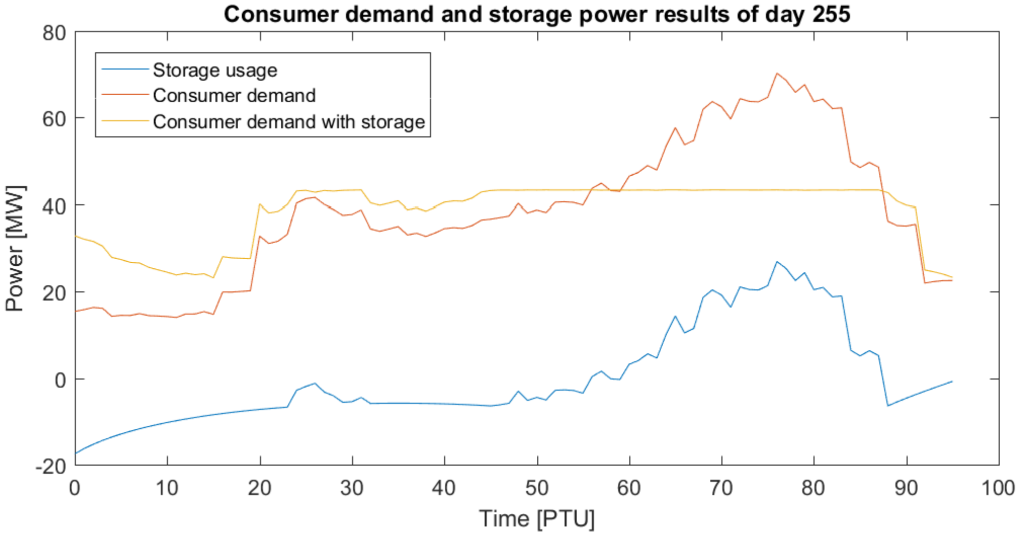
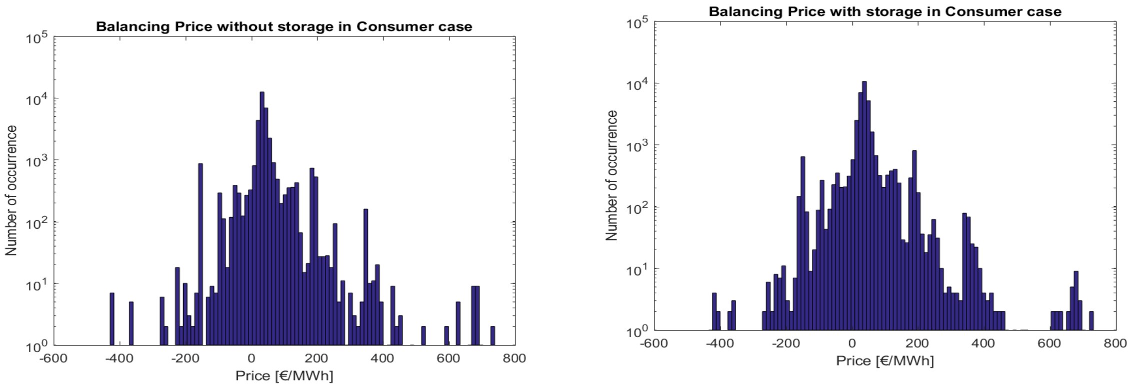


Figure B.14: Storage utilisation for a day, consumer case

The consumer demand will be capped due to the storage optimisation. While consumer will get the best price since their connection is smallest as possible, the DSO will benefit from this optimisation since their network will not be burdened with peak loads which gives the DSO the possibility to defer investments.

The total influence over the year is again shown in a histogram. Even though, the consumers are not influenced by the prices created by imbalance the prices do change by balancing with the storage capacity. The volatility seems to be dropped a little but no clear conclusion could be created by these differences.



(a) Consumer influence on balancing prices

(b) Consumer storage balancing influence on balancing prices

Figure B.15: Balancing prices histogram in the consumer case

No relation could be found with respect to the base case. Therefore, no additional figure is shown which was the case with the previous two case simulations.

B.5. Prosumer

From the consumer case, an additional 100 MW of solar panels are added to the consumer portfolio. This results in a demand profile shown in figure B.16.

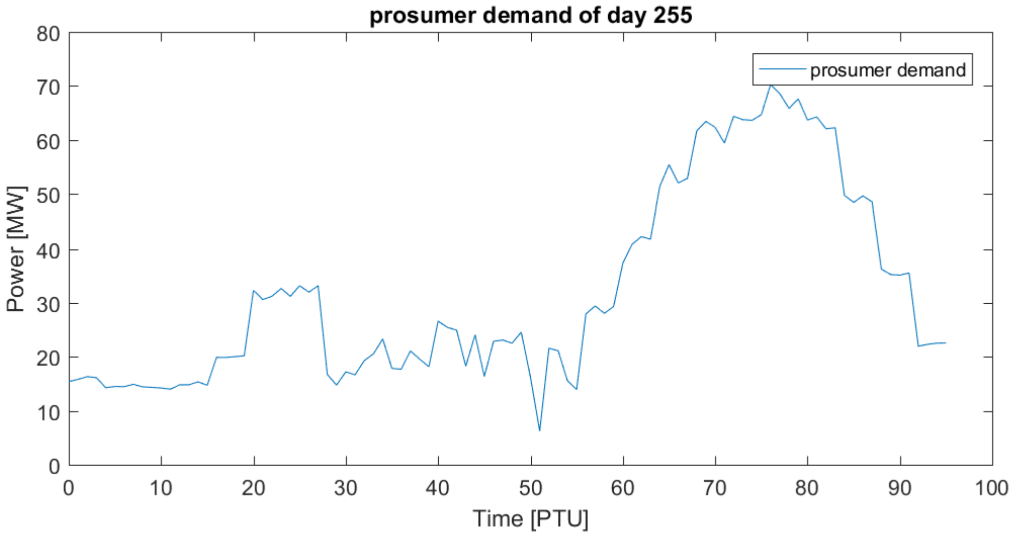


Figure B.16: Prosumer demand day case

When adding the consumer demand stochasticity with the forecast error of the solar power, the influence on the balancing market can be modelled. In figure B.17 the result of this modelling can be seen.

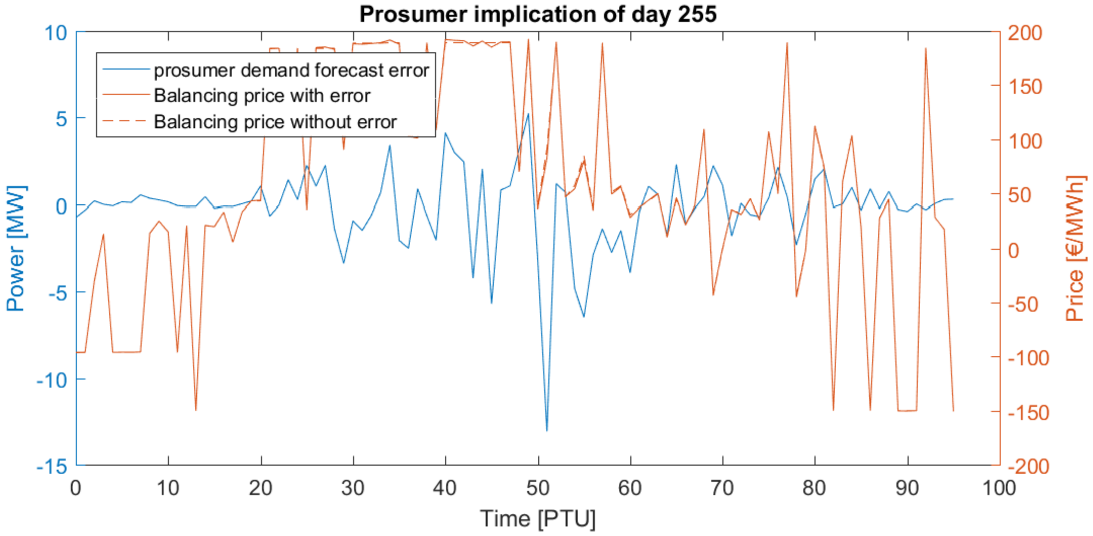


Figure B.17: Gas turbine price implication

The balancing market prices are influenced by this summed forecast error term. Since the prosumer is not influenced by this change in prices. The storage will optimise for minimum peak demand. This results in the prosumer demand with storage presented in figure B.18.

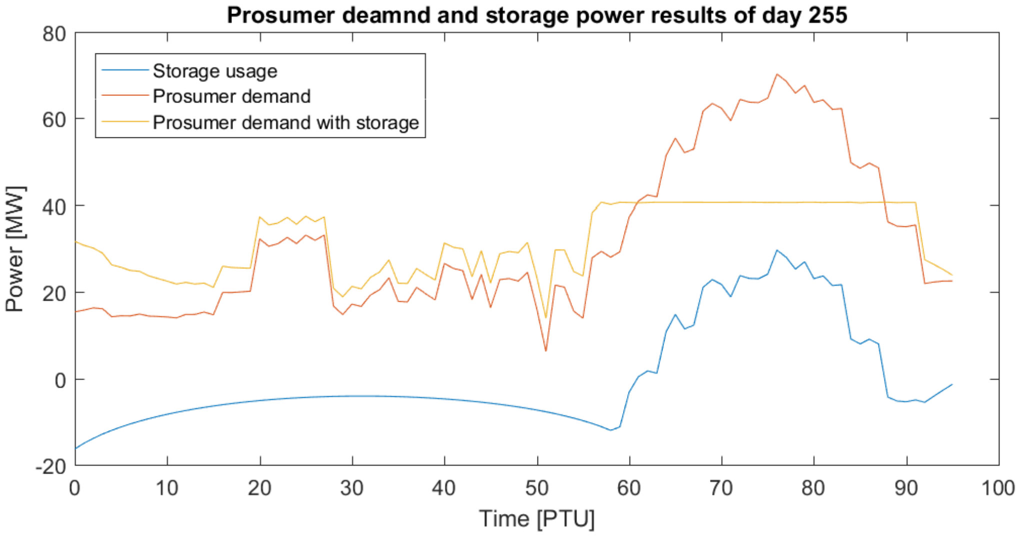
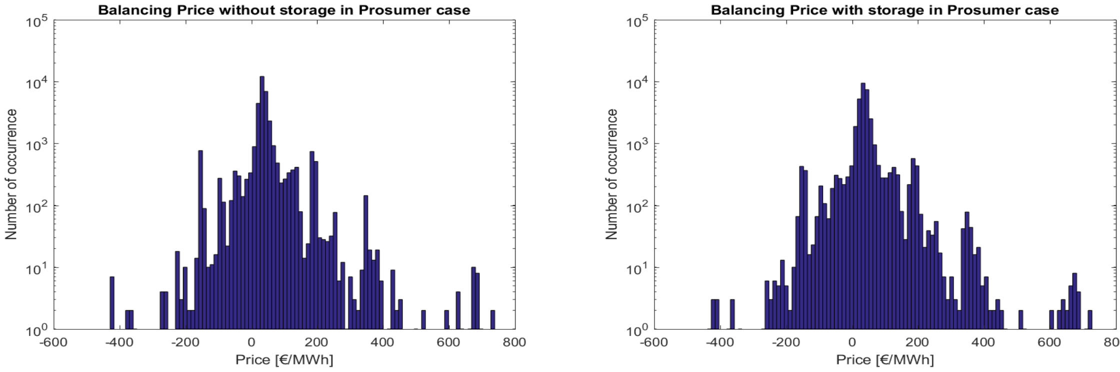


Figure B.18: Prosumer demand and storage utilisation

The storage capacity utilisation represented in the blue line clearly shows a relation to the prosumer demand profile represented in the red line. Subtracting the storage utilisation from the demand will result in prosumer demand with storage, this is represented in the yellow line.



(a) Balancing market prices including Prosumer case

(b) Balancing market prices for Prosumer storage case