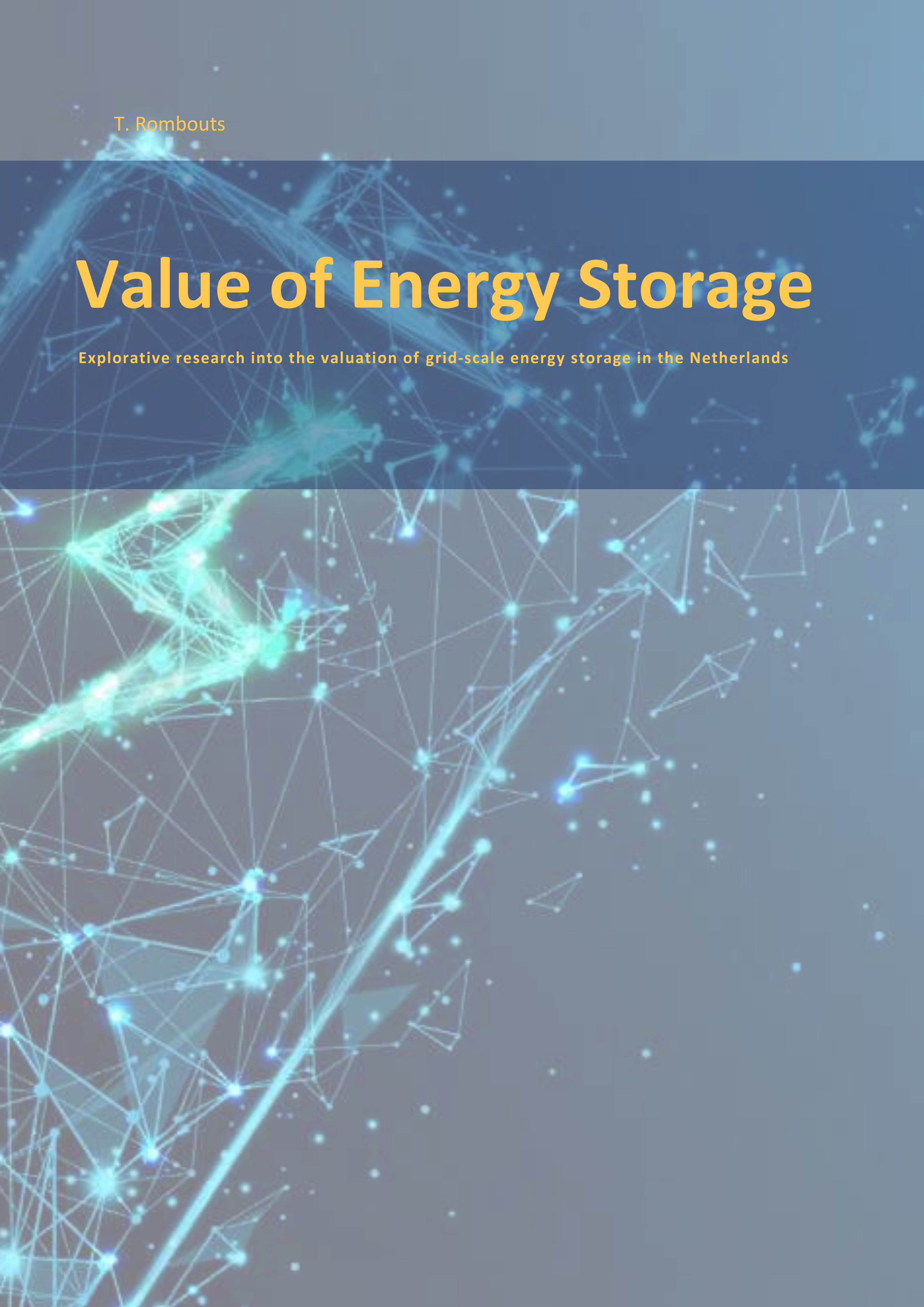

T. Rombouts

Value of Energy Storage

Explorative research into the valuation of grid-scale energy storage in the Netherlands

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Value of Energy Storage

Explorative research into the valuation of grid-scale energy storage in the Netherlands

By:

T. (Tessa) Rombouts

in partial fulfilment of the requirements for the degree of

Master of Science
in Industrial Ecology

at Delft University of Technology
and Leiden University
to be defended publicly on Tuesday October 13, 2020

Supervisor:	Dr. ir. G. Korevaar,	Delft University of Technology
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	I. Schjelderup MSc.,	RWE Corporation

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Preface

Dear Reader,

This thesis report is marks the end of my time as a student and is the result of my graduation research project of the Master Industrial Ecology at the Delft University of Technology and Leiden University. I am very grateful for all the things that I have learned in my time as a student both at the University as outside of the University. I am very grateful for all the help I received during my thesis and would like to thank some people in particular.

Starting with my graduation committee. Gijsbert Korevaar, I would like to thank you for all the support, interesting discussions and the questions to help me think critically about my work. I was really nervous on starting my thesis, but you helped me to make the process very enjoyable. Thank you also for being understanding and supportive when the writing part of the process did not go as I wanted to.

Enno Schöder, I would like to thank you for your feedback, direct questions and being critical on my research. You always provided me with enough food for thought on my work.

Ina Schjelderup, thank you for guiding me and providing me with a lot of information on how the energy markets work. Also thank you for your hospitality and letting me study at your home. I really liked working with you and felt very welcome at RWE.

Also a special thanks to the colleagues at RWE. Karolina, thank you for offering me the internship, welcoming me at RWE and providing a lot of information on storage value. Jan-Kees, thank you for your critical view and good questions. Jasper and Marjolein, thank you for the interesting conversations and enjoyable coffee moments. Also, thanks to all the other colleagues at RWE. You made me really feel at home and created a place in which I learned a lot and felt free to ask a lot of questions.

Furthermore I would like to thank Huub and Leen from Delta21 for letting me be part of the project. It was very interesting to see all the different parts and consideration of such an enormous project as Delta21. Your enthusiasm and focus is very admirable. Hopefully, this thesis will provide you with new insights on the energy storage part of the project.

Finally, I would like to thank my friends and family and some of them in particular. My boyfriend, Bas Druijf, thank you for being there for me during the whole process. You have provided me with enormous support. My study buddies, Niek, Joep, Yanniek and Gilliam, thank you for making working on my thesis a lot more fun. My best friend, Demi, thank you for being there for me, checking up on me and providing a lot of fun distractions. My parents, Coen and Hanneke, thank you for always supporting me and believing in me.

Enjoy reading this thesis!

Tessa Rombouts

Summary

Introduction

Climate change is a pressing issue and risk in our current society caused by greenhouse gas (GHG) emissions. To reduce the GHG-emissions more renewable energy is needed instead of electricity and energy production by fossil fuels, which are high in GHG-emissions. The electricity production by renewable sources has increased in the last couple of years in the Netherlands. However, renewable energy production via wind and solar energy is supply based, i.e. can only be supplied when wind and sun is available. Energy storage is needed to overcome the energy needs during low or no renewable energy in sustainable way. However, there barely seems to be any storage in the Netherlands. The market does currently not value all the services that storage can provide. Research into the value of storage is needed to understand the lack of energy storage and the current valuation of energy.

Energy storage can have different levels and services that it can provide. In this thesis the focus will be on grid-scale energy storage. In the Netherlands there are no grid-scale energy storages. In other countries there are grid-scale energy storages, often in the form of Pumped Hydro Storage. In the Netherlands there is a plan, called Delta21, that wants to expand the Delta Works and improve water safety by using pumps. In the plan the pumps can also be used for a Pumped Hydro Storage to store energy. It is important to understand the value of storages like Delta21 in the Dutch electricity system.

This leads to the main research question:

''How can the economic value of services provided by grid-scale energy storage in the Dutch electricity system be determined?''

Methodology

The services Arbitrage, Distribution Deferral and Carbon Abatement are selected as the services to be analysed. Furthermore, Delta21 is used as a case study to try methods and information found in literature on. Each service has its own approach or methodology to determine the value.

The value of Arbitrage, which is the value of selling and buying energy on the market, is determined by creating a strategy that uses historical data. The strategy determines the hours to buy and sell based on earlier years. The method explores the influence of efficiency and the amount of hours that the storage is used per day on the Arbitrage profit. Furthermore, the influence of the average price difference per day and average price in a year on the profit is explored.

The value of Distribution Deferral, which is the value of reduced investments in the distribution network, is approached by understanding the variables that have an influence on reduced distribution need. As there is no method for stand-alone grid-scale energy storage an approach of information gathering is taken. Experts are interviewed and literature is analysed to understand more about those variables and the value that Delta21 has in this service.

The value of Carbon Abatement, which is value of the reduction in carbon emissions, is determined in the short run by looking at the additional energy demand in the system induced by the efficiency losses of the storage.

Results

The most important findings show that the profit by Arbitrage is dependent on efficiency in two ways. The efficiency influences the losses in energy induced by the energy storage. Furthermore, the efficiency influences the amount of hours that the storage can be used per day to charge and discharge. There is an optimum in the amount of hours that the storage can be used which depends on the efficiency level.

Other important findings are that the price patterns also have an influence on the Arbitrage profit. The higher the price difference the more profit can be made. However, the higher the average the price the less profit can be made. This is due to Arbitrage having to overcome the energy losses, which are relative, while the price difference are absolute. So the average price and price difference together influence the Arbitrage profit possibilities.

The findings on Distribution Deferral are that the value depends on the location of the storage as it determines the amount grid deferral that can be done. A storage can provide value by storing energy during peak load and so defer the investments in the grid. The valuation of this aspect becomes more important as the pressure on the grid grows and the Transmission System Operator (TSO), TenneT, experiences more grid congestions. Furthermore, the realisation time of the storage becomes important as grid congestions issues increase. This is due to the fact that the TSO has to provide connections withing four years and storages can defer those investments in connections.

The findings on Carbon Abatement are that in the short term a storage increases the amount of carbon emissions by the energy system. Storage increases the electricity demand due to the efficiency losses and so the emissions of the electricity system increase. The higher the efficiency the higher the value of Carbon Abatement becomes or the lower the carbon emissions become. At the moment, Carbon Abatement has a negative value as the carbon emissions increase.

Conclusion

In this thesis is found that the economic value of a storage cannot easily be determined by the current market value only. The current market is represented by the Arbitrage value. It is shown that there is also value in Distribution Deferral and there is on the short term a negative value in Carbon Abatement. Arbitrage value can be assessed using historical market price data and using a strategy of buying and selling on this data. It became clear that determining the value of Distribution Deferral is hard, as currently there is no value in the economic system of reducing grid investments. This may change due to the congestion problem in the Netherland. The value of Carbon Abatement is depended on the approach takes and the value changes depending on the amount of renewable energy in the system and the price attributed to the carbon.

Table of Contents

1. Introduction

In the Introduction the background of the problem of the valuation of storage energy is given in Section 1.1. In Section 1.2 the problem definition and scope are presented by analysing literature about energy storage. In Section 1.3 the main research questions are presented. At last, in Section 1.4 a reading guide for this thesis is provided.

1.1 Background

Currently, climate change is one of the most pressing issues in our society. It poses risks to our life and society as we now know it (IPCC, 2014). To mitigate and reduce the risks associated with climate change, the greenhouse gas (GHG) emissions should be cut down (IPCC, 2014). To achieve this, the production of energy must change to more renewable sources (IPCC, 2014).

Globally, our energy needs are mostly fulfilled with fossil fuels (IPCC, 2014). To reduce greenhouse gas emissions during production of electricity, renewable sources of energy have to be exploited instead of fossil fuel sources that have high carbon emission (IPCC, 2014). In the Netherlands the share of renewable energy of total energy use has grown from 1,64% in 2000 to 7,42% in 2018 (CBS, 2019a). The share of renewable electricity of the total supply of electricity in the Netherlands was 15% in 2018 (CBS, 2019b).

Due to the growing amount of renewable electricity in our electricity grid, new challenges arise. Solar and wind energy are supply driven. This means these techniques produce energy when wind or solar energy are available, as opposed to conventional techniques that produce energy when energy is needed. There is still a need for a baseload of electricity to provide electricity when it is demanded. Renewable energy cannot provide this baseload. However, storage of energy could provide this baseload electricity need.

At this moment there is barely any storage of electricity in the Netherlands. However, storage is considered as an important asset to become less fossil fuel dependent (Energy Storage NL & FME, 2019). The report of Energy Storage NL & FME (2019) explains that electricity and energy storage are important to make electricity and energy more renewable and less polluting. The report of Energy Storage NL & FME (2019) describes a few plans on grid-scale energy storage, among them Delta21. Delta21 is a plan to expand the current Delta Works, which are the constructions along the coast of the Netherlands that protect parts of the Netherlands from the sea . The Delta21 plan entails the use of water pumps for water safety and combines this with a water reservoir to store electricity (Berke & Lavooij, 2019b).

At the end of the report of Energy Storage NL & FME (2019) the different challenges are described for the energy system in the Netherlands. A part of the challenges are in the field of energy storage (Energy Storage NL & FME, 2019). Most of the challenges focus on the market models and business cases of energy storage (Energy Storage NL & FME, 2019). In the current market only the electricity delivered to the electricity network is financed (Energy Storage NL & FME, 2019). The backup capacity, that storage can provide, is not valued in the market (Energy Storage NL & FME, 2019). Also other functions, like flexibility provision and contributing to distribution networks, are discussed as services that are not valued in the current market (Energy Storage NL & FME, 2019). This shows that there is research needed into the value of energy storage.

1.2 Problem definition and scope

Storage level – Grid-scale energy storage

There are different types of storage levels. Ibrahim et al. (2008) provides an overview of different storage techniques and their magnitude. In Figure 1 the different storage techniques are presented and compared on power output and energy content (Ibrahim et al., 2008). These characteristics are related to the level of storage. Ibrahim et al. (2008) called it the categories of application and identifies the categories: local scale, regional scale, grid-scale and power-quality. In this thesis the grid-scale application of storage will be the focus, this means a high power and high energy capacity storage that is linked to the high voltage network.

Pumped Hydro Storage is a grid-scale application that is already widely used in the world. Worldwide, Pumped Hydro Storage is the most commonly used way of storing energy (“Energy Storage Exchange,” n.d.). This way of storing electricity utilises pumps to pump water to a higher reservoir and then releasing the water to a lower reservoir via turbines when the electricity is needed (Kose, Kaya, & Ozgoren, 2018).

There is an abundance of research papers looking into the combination of Wind Energy and Pumped Hydro Storage. Kose et al. (2018) researched the financial viability of a grid connected wind-pumped hydro power station. In their research the value of the combination of a wind park with pumped hydro storage is assessed. In the paper of Black & Strbac (2005), the value of pumped hydro storage was assessed in a generation system with substantial amount of wind energy production. The paper looked into the value of the storage providing an energy reserve (Black & Strbac, 2005). The value was estimated with the comparison to other energy storage solutions in fuel cost and CO_2 emissions (Black & Strbac, 2005).

Concluding, currently the value of pumped hydro is often looked at in combination with wind energy or in a high-wind energy system and not as an independent grid-scale energy storage.

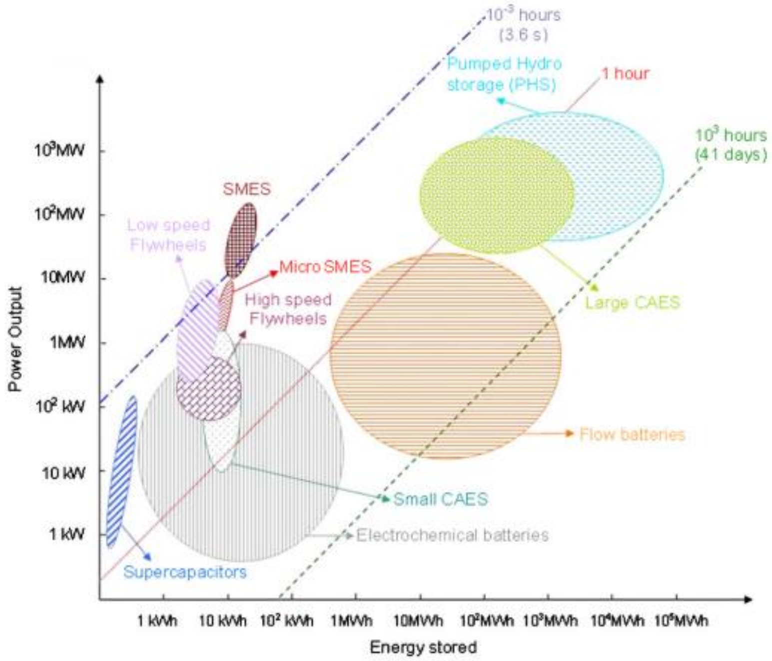

Figure 1 Storage techniques compared on power output and energy stored. Reprinted from: Ibrahim et al., 2008, p. 1241

Services of storage

Energy storage can provide different services to various actors in the energy system. Table 1 shows different services that can be provided by the grid-scale energy storage and a short description based on research (Lund, Lindgren, Mikkola, & Salpakari, 2015; Nikolaidis & Poullikkas, 2018; Sidhu, Pollitt, & Anaya, 2018; Spisto & Hrelja, 2016; Zafirakis, Chalvatzis, Baiocchi, & Daskalakis, 2016; Zakeri, Syri, & Wagner, 2017).

Table 1 Possible services of grid-scale energy storage

Service name	Description	References
Arbitrage	Buying of electricity when the price is low and selling of electricity when the price is high. Results in profit due to the difference in price, shaving the peaks and filling the valleys in the energy production.	(Nikolaidis & Poullikkas, 2018; Sidhu et al., 2018; Zafirakis et al., 2016; Zakeri et al., 2017)
Distribution Deferral	The storage of electricity during congestion or low grid capacity. It can lead to a reduction in cost of upgrading the distribution network.	(Lund et al., 2015; Nikolaidis & Poullikkas, 2018; Sidhu et al., 2018)
Seasonal storage	Long term storage of energy to overcome the difference in renewable energy production between seasons.	(Lund et al., 2015; Nikolaidis & Poullikkas, 2018)
Carbon Abatement	The reduction of carbon emissions with the total production of energy.	(Sidhu et al., 2018; Spisto & Hrelja, 2016)
Black start power	Power readily available to start the generators in the network in case of a grid black out.	(Lund et al., 2015; Nikolaidis & Poullikkas, 2018)
Frequency response	Power available to keep the frequency in the right range.	(Lund et al., 2015; Nikolaidis & Poullikkas, 2018; Sidhu et al., 2018)
Unit commitment	Managing of errors and uncertainties in the predicted wind and solar output by absorbing or discharging energy.	(Lund et al., 2015; Nikolaidis & Poullikkas, 2018)

One of the most discussed service or benefit is energy Arbitrage (Lund et al., 2015; Spisto & Hrelja, 2016; Zafirakis et al., 2016; Zakeri et al., 2017). This is the buying of electricity during low demand or high supply and selling of electricity during high demand or low supply. This provides the service of peak-shaving, which means that the peaks caused by renewable energy or demand patterns can be mitigated by storage. This service is most common because this is how storages can earn their money in the electricity market. The service uses the difference between peak and bottom price of the electricity market (Sidhu et al., 2018).

In the paper of Sidhu et al. (2018) the services that were identified are categorised per actor group to which the service provides a benefit. From Table 1, three services are selected that provide value to different actor groups. The three are Arbitrage, Distribution Deferral and Carbon Abatement. Arbitrage provides value to the owner or exploiter of the storage. Distribution Deferral provides value to the grid-owner. Carbon Abatement provides value to society and government.

The definition of the value is seen as the amount of benefit provided by a service to an actor, also called economic value. The value can be presented in a monetary value to use it for comparison. Determining the economic value of a service is not straightforward and there are different approaches which will be explored in this research.

1.3 Research design

Based on the previous information it is interesting to approach the value of a grid-scale energy storage by looking at different services that it can provide. This leads to the research questions that can be found in section 1.3.1 and the methodology to answer the research questions in sections 1.3.2.

1.3.1 Research questions

The main research question is:

"How can the economic value of services provided by grid-scale energy storage in the Dutch electricity system be determined?"

The corresponding sub-questions are:

1. *How can the economic value of Arbitrage provided by grid-scale energy storage in the Dutch electricity system be determined?*
2. *How can the economic value of Distribution Deferral provided by grid-scale energy storage in the Dutch electricity system be determined?*
3. *How can the economic value of Carbon Abatement provided by grid-scale energy storage in the Dutch electricity system be determined?*
4. *How do the values of Arbitrage, Distribution Deferral and Carbon Abatement relate to each other?*

1.3.2 Methodology

To answer the main question, three services will be used to get an indication on how to determine the value of a storage via the services it can provide. To test the methods a case study will be used, being Delta21, which is more elaborately introduced in section 3.1. Furthermore, this thesis research is performed in collaboration with RWE, who provided information, data and a lot of insight into the energy sector.

1.4 Reading guide

In Chapter 2 the background information on the value of energy storage is written. It contains the methodologies found in literature on how to determine the value of the services: Arbitrage, Distribution Deferral and Carbon Abatement. It also contains information on the functioning of the current energy system. In Chapter 3 the methodologies to approach the value of the services by the storage can be found. In Chapter 4 the results of the methodologies are presented. In Chapter 5 the approach, other insights, limitations and recommendations to RWE and Delta21 are discussed. At last, in Chapter 6 the conclusions and answers on the research questions can be found.

2. Background information

In this chapter the background information and relevant literature on the energy system and energy storage are discussed. In Section 2.1 the methodologies found in literature on the services Arbitrage, Distribution Deferral and Carbon Abatement are discussed. In Section 2.2 the relevant aspects of the energy system are discussed.

2.1 Methodologies in literature on valuation of services

The relevant literature of the services Arbitrage, Distribution Deferral and Carbon Abatement are discussed in respectively Subsection 2.1.1, Subsection 2.1.2 and Subsection 2.1.3. To represent the findings of the literature a system diagram is used.

A causal system diagram is a way to represent the variables and links of the system that is analysed. The system diagrams use boxes and arrows to represent, respectively, variables and links between the variables. The external variables have a striped background. External variables are the variables that cannot easily be influenced. Furthermore, the links can have a plus or minus to indicate the type of relationship between the variables. A plus indicates that if the one variable increases the other variable increases. A minus indicates that if the one variable increases the other variable decreases and vice versa.

2.1.1 Methods on valuation of Arbitrage

There are multiple researches done into the possible profit or revenue of Arbitrage by storage. There are different methods to approximate the value of Arbitrage.

The research of Sang Kang, Klein, & Zhao (2019) analyses the profit of Arbitrage with fast responding electric storage batteries on both the day-ahead market and the 5-min real time market from California. Dynamic programming and different models are used to simulate and optimize the value (Sang Kang et al., 2019). The method is designed for smaller storage units. Furthermore, the research uses an elaborate optimization model in which the amount of cycles is optimized due to one important characteristic of batteries: they have a limited amount of cycles per lifetime.

The research of Zafirakis, Chalvatzis, Baiocchi, & Daskalakis (2016) analyses the value of Arbitrage for energy storage on the hourly prices of the spot markets of Nord Pool, EEX, UK, Spain and Greece. It can be assumed that this is the trading on the day-ahead market, because this is the hourly spot market of electricity. The research uses four strategies for Arbitrage, from which three are based on time signals and one is based on price signals (Zafirakis et al., 2016). In this research the energy storage is assumed to be a price-taker (Zafirakis et al., 2016). This means the production is too small to influence electricity price during its operation (Zafirakis et al., 2016). The strategy uses the previous day or week of the same year to determine the time signals for the next day and week (Zafirakis et al., 2016). This strategy is based on the price rhythm of the year and seasonality (Zafirakis et al., 2016).

The research of Sidhu, Pollitt, & Anaya (2018) takes two prices of the wholesale market that the price is supposed to vary between. The researchers approximate a number of charges and discharges and use a Monte Carlo simulation which incorporates a +/- 15% price fluctuation at the time of buying and selling (Sidhu et al., 2018). This is a really rough estimation based on averages and approximations that do not give clear insight into the value of Arbitrage of a project.

The research of Connolly, Lund, Finn, Mathiesen, & Leahy (2011) analyses the value of Arbitrage of a certain Pumped Hydro Energy Storage facility on 13 different electricity spot markets. The Dutch market is not part of these different spot markets. Connolly, Lund, Finn, Mathiesen, & Leahy (2011) compared three operation strategies on profit. The strategies are optimized over 24 hours (Connolly et al., 2011). However, they assume good prognoses of the prices by the storage executor (Connolly et al., 2011)

The research of Bolado, Ferreira, & Kling (2014) uses price forecasting with Artificial Neural Networks on the day-ahead market to value energy storage. They use a Dutch case study on the day-ahead market price data of 2008 to 2011. The storage is modelled in their research as a price-taker. In the research of Bolado et al. (2014) the influence of a 100 MW and 200 MW storage on the load curve of 2010 in the Netherlands was investigated.

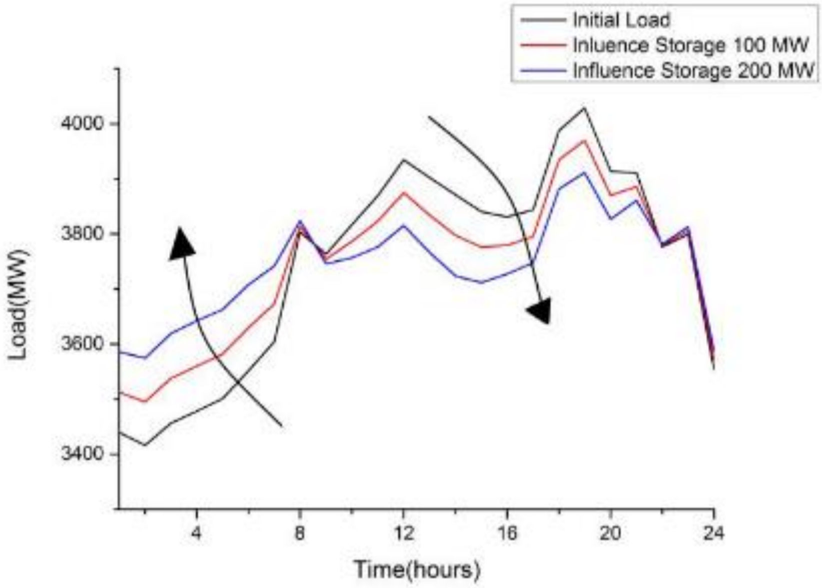

Figure 2 Influence of Arbitrage in the Load profile in 2010. Reprinted from "Energy storage market value - A Netherlands case study" by Bolado et al., 2014, Proceedings of the Universities Power Engineering Conference (UPEC), p. 5.

Most of these researches focus on Arbitrage on the day-ahead market. The research of Zafirakis et al. (2016) and Connolly et al. (2011) and Bolado et al. (2014) are used as a basis to form the methodology to value Arbitrage on the Dutch Energy market.

Conceptual system diagram on the value of Arbitrage

Based on the previously discussed research the system diagram of Figure 3 is constructed. It shows the variable influences on the value of Arbitrage, which is the Arbitrage profit in this research. Bolado et al. (2014) found a positive influence of the amount of hours that the storage can charge or discharge on the Arbitrage profit. In the system diagram it is called the amount of hours storage use. Connolly et al. (2011) found an optimum amount of hours to run a Pumped Hydro storage and discusses that there is an optimum storage capacity.

Bolado et al. (2014) also found a positive influence of the efficiency and the storage power on the Arbitrage profit. The efficiency and storage power are storage variables. There are also external variables, which can be seen in Figure 3 in the light blue striped box. Bolado et al. (2014) discusses the positive influence of absolute price difference of the day-ahead market on the Arbitrage profit. This is an external variable, represented in the box with the striped background, as a storage has no direct influence on the price difference. However, it could be expected that a grid-scale storage will influence the price pattern and so the price difference during the day.

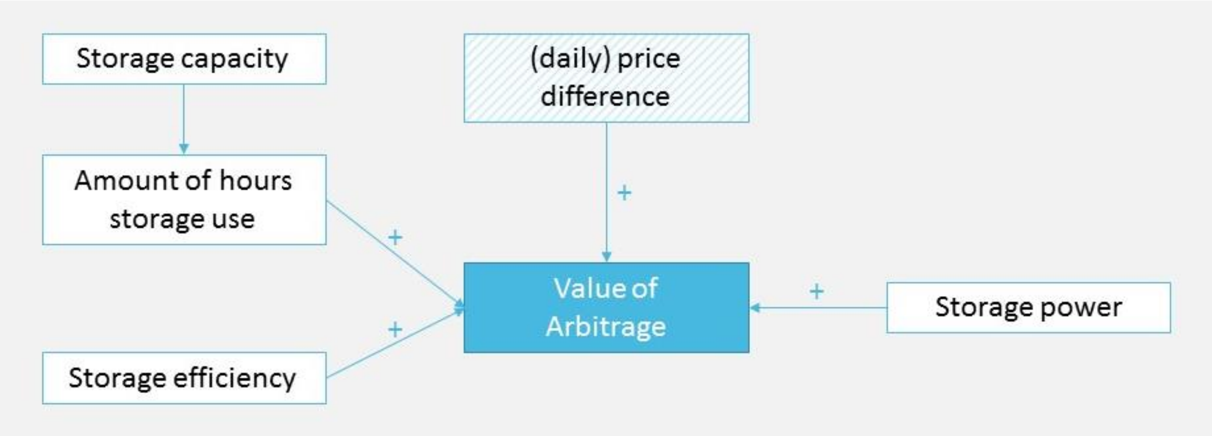

Figure 3 Conceptual system diagram on the value of Arbitrage

2.1.2 Methods on valuation of Distribution Deferral

In the literature found, which estimated the value of grid deferral or Distribution Deferral by storage, the value was often estimated by avoided cost of investments in a certain grid line.

Sidhu et al. (2018) calculated the benefit of the Distribution Deferral by a grid-scale storage using the avoided costs of investments in network reinforcement that are otherwise needed. This method can be used when the storage is an alternative for a planned network investment.

Klein Entink (2017) calculates the benefit of Distribution Deferral by storage on the low voltage network of Stedin in five different neighbourhoods in the Netherlands. Klein Entink (2017) used a thorough analysis of the load data of the different neighbourhoods to examine the future investments in transformers and cables that can be deferred by storage. In this analysis the storage characteristics, power and energy, are scaled based on the optimum for Distribution Deferral. This method is data intensive and on a small scale. The research shows that there is value in storage for Distribution Deferral.

Both Sidhu et al. (2018) and Klein Entink (2017) use present value and net present value respectively to calculate the current value of the investments. These methods calculate the total present value of future cashflows.

Conceptual system diagram on the value of Distribution Deferral

Based on the previously discussed research the system diagram in Figure 4 is constructed. It shows the variable influences on the value of Distribution Deferral, which is in this research the avoided grid investments. The literature does not describe the kind of relations between these variables and so no plusses or minuses are used in Figure 4.

In the method of Klein Entink (2017) different connections are described and used. As a starting point, the location of the storage dictates the load pattern in that location (Klein Entink, 2017). The load pattern has, among others, the following characteristics: the load peak demand and the duration of the load peak. Those characteristics are related to the storage power and the storage capacity. The amount of storage power determines the amount of peak load that the storage can reduce (Klein Entink, 2017). The amount of storage capacity determines the time in which the power can be used and so the duration of the peak that the storage can absorb (Klein Entink, 2017). The total grid load pattern influences the need of grid investment and together with the grid investment cost it determines the value that storage can have for Distribution Deferral.

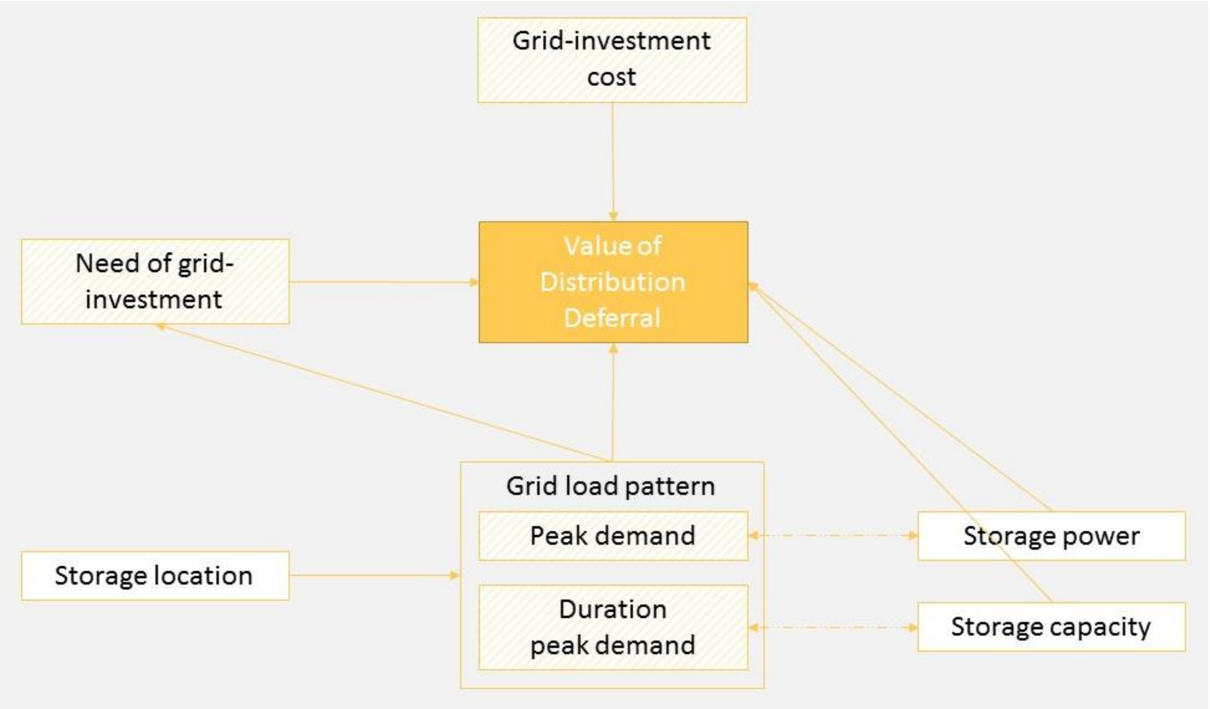

Figure 4 Conceptual system diagram on the value of Distribution Deferral

2.1.3 Methods on valuation of Carbon Abatement

The paper of Mckenna, Barton, & Thomson (2017) describes that a new storage can have two types of effects on carbon emission. The first one is described as the increase of the total electricity demand due to the losses induced by the efficiency losses (Mckenna et al., 2017). The second one is described as the change of the electricity demand pattern (Mckenna et al., 2017). The electricity demand pattern is changed by reducing the peak during the day and increasing the demand during the night. This change is also described and shown in Figure 2 in the part about Arbitrage methods in subsection 2.1.1. The method of Mckenna et al. (2017) focusses on the effect of storage on the amount of carbon emissions.

To value the amount of carbon emissions the EU Emissions Trading System (ETS) price can be used. In section 2.2.3 a more elaborate explanation of the carbon market in Europe and the ETS price can be found. In Figure 5 the connections found in the method and paper about the method are presented. The storage power, amount of hours that the storage is used and the efficiency determine the amount of additional electricity that will be used by the storage facility. The carbon emissions of the production of electricity together with the additional demand of the storage facility influences the amount of additionally emitted carbon. The value of additional carbon is determined by the ETS price.

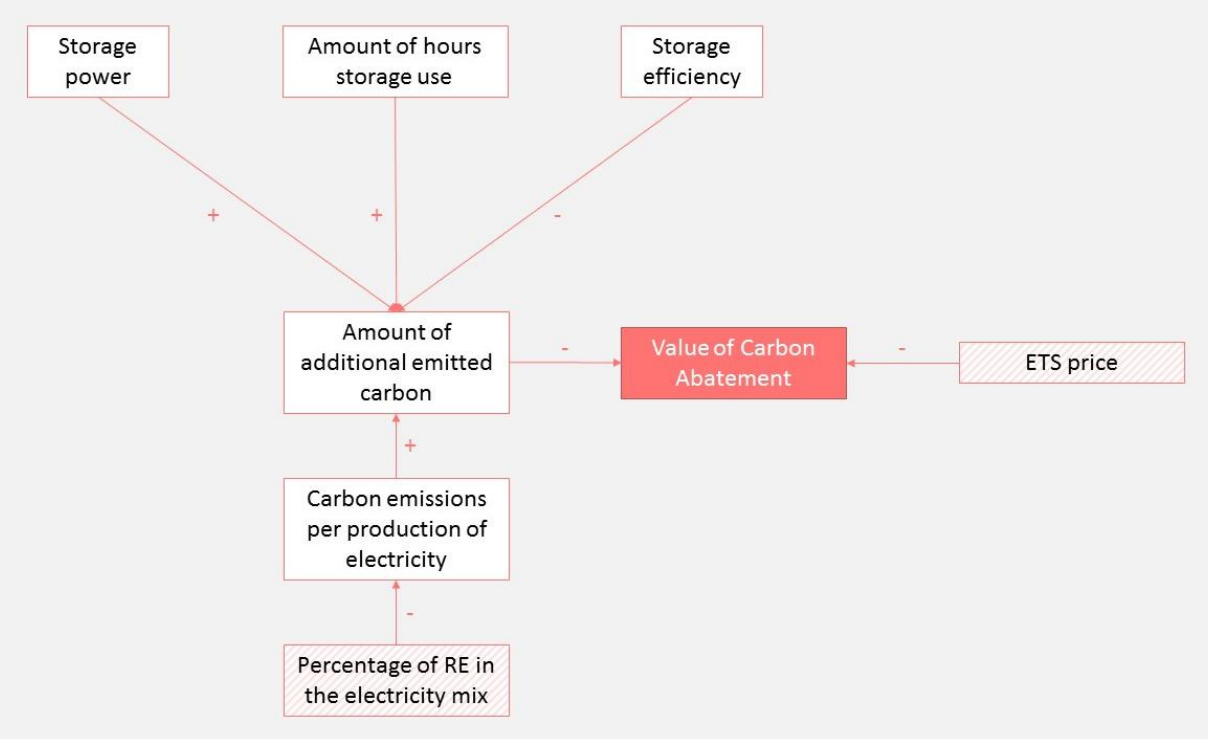

Figure 5 Conceptual system diagram on the value of Carbon Abatement

2.2 Energy system

2.2.1 Dutch Electricity Markets

In this subsection the different energy markets of the Netherlands are discussed. In Figure 6 the different markets are shown in a short overview (TenneT, 2020a). The different sections will discuss the different markets, followed by a conclusion regarding the markets on which a grid scale storage could be active.

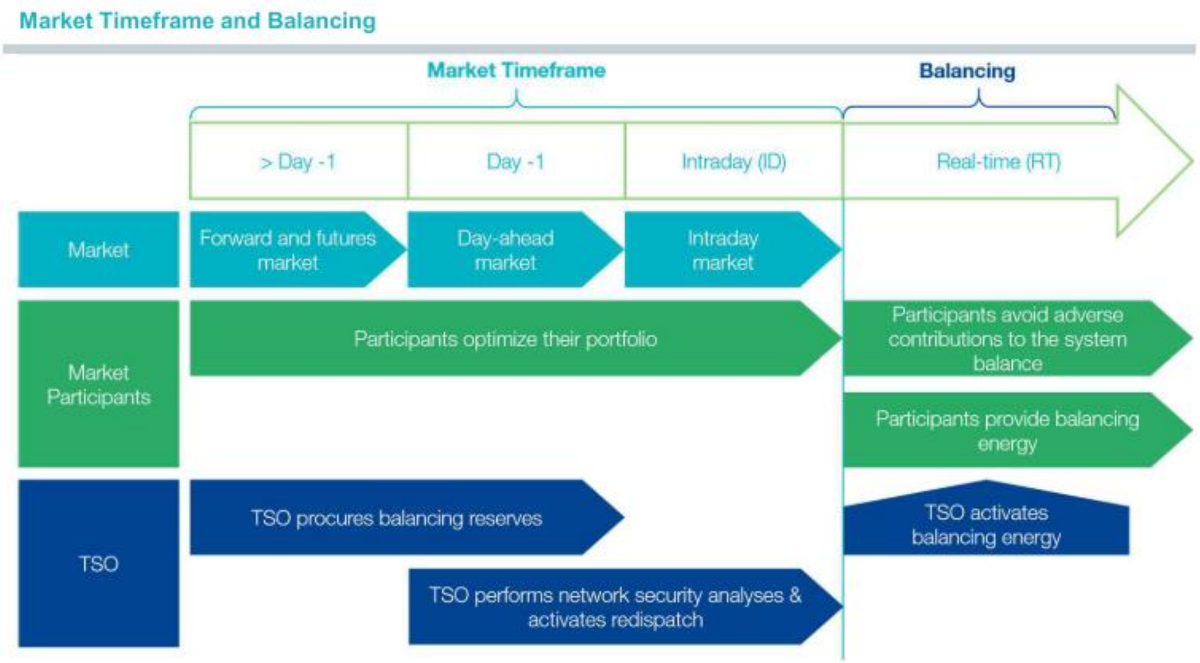

Figure 6 Market Timeframe and Balancing. Reprinted from "Annual Market Update 2019", TenneT, 2020, p. 7

Forward and Futures market

The timeframe of the forward and futures market is years before until up to the day before the delivery of the electricity (TenneT, 2018a). The product is a contract which entails the amount of electricity delivered/consumed at a certain time in the future and the price of this electricity (TenneT, 2018a). Futures are standardized contracts on power exchanges and forwards are non-standardized contracts, which are concluded between producer and consumer (TenneT, 2018a). These contracts are used by electricity generation companies to reduce risk and so vulnerability to electricity price fluctuations (TenneT, 2018a) (I. Schjelderup, RWE, personal communication, March 2020). The prices in these contracts are related to the futures for the fuel prices (TenneT, 2018a). Storage does not generally participate in this market. Therefore, these markets will not be considered in this thesis.

Day-ahead market

In the day-ahead market the electricity is traded one day before the delivery of the electricity (TenneT, 2018a). In this market the highest volume is traded (TenneT, 2018a). Because of this, the price from the day-ahead market is often referred to as the electricity price (TenneT, 2018a). In 2017 the total energy volume that was traded on the day-ahead market was approximately 34 TWh based on TenneT (2018a).

Intraday market

In the intraday market the electricity is traded on the day of delivery (TenneT, 2018a). The market enables producers and consumers to improve their position based on more precise renewable forecasts and unexpected production or demand changes (TenneT, 2018a).

The last few years the intraday market is growing in volume of energy (TenneT, 2020a). In 2017 the total energy volume traded on the intraday market was approximately 1,5 TWh (TenneT, 2018a). The last two years the intraday market increased hugely with a growth of more than 50% as can be seen in Figure 7 (TenneT, 2020a).

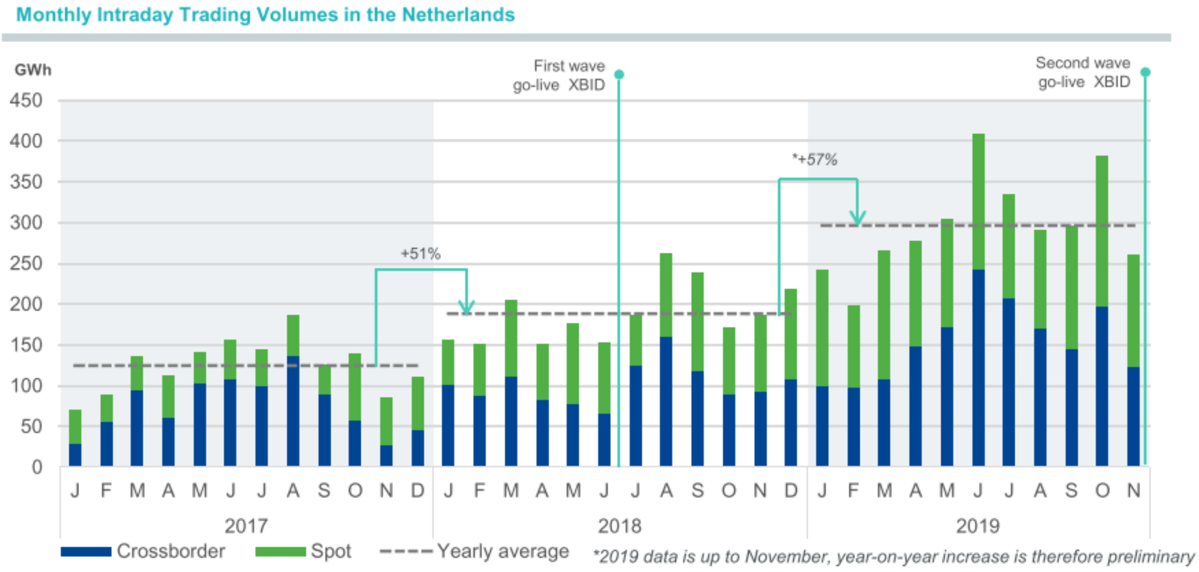

Figure 7 Monthly Intraday Trading Volumes in the Netherlands. Reprinted from "Annual Market Update 2019", TenneT, 2020, p. 13

Balancing market

The Balancing market is the name for the market where reserves are contracted by the Transmission System Operator (TSO), TenneT, to use during imbalance (TenneT, 2018a). There are three types of reserves: Frequency Containment Reserves (FCR), automatic activated reserves (aFFR), manually activated reserves (mFFR) (TenneT, 2018a). These reserves are auctioned ahead of time.

Imbalance market

The imbalance market is a settlement of the imbalance price executed by the TSO (TenneT, 2020a). An imbalance occurs when the real-time generation and/or consumption deviates from the scheduled generation and/or consumption of the market parties (TenneT, 2018a). Market parties can be in imbalance. They will have to pay a price for being in imbalance when they contribute to the systems imbalance. This means when the system is short and the market party is short, the market party will have to pay the imbalance price. However, if the system is short and the market party can provide extra electricity, the market party receives the imbalance price. The imbalance price is determined by the balancing market using the merit order (*see textbox marginal pricing and merit order).

Ancillary services markets

The ancillary services are used to support the transmission and distribution system. These services are delivered by companies to the TSO (TenneT, n.d.-b). The Balancing market is part of these ancillary services. The other services are the delivery of Reactive Power (blindvermogen), the delivery of redispatch, the availability of Black start power and provision (herstelvoorziening) (TenneT, n.d.-b). These ancillary services are small parts of the whole energy system and cannot be used to buy and sell energy for storage. They play a small role in the business model of grid-scale storage.

Grid-scale energy storage on markets

A grid-scale energy storage is probably mostly active on the day-ahead market, intraday market and balancing market. According to RWE Storage experts 60 to 70% of the revenue streams of the pumped hydro storages in Germany are on the day-ahead market.

2.2.2 Marginal cost, Merit Order and Merit Order effects

Marginal cost and the merit order are two important aspects of the electricity market to understand the pricing of the markets. Often, when marginal cost are discussed in relation to the electricity market, the short run marginal cost are meant. Both short and long run marginal cost and the merit order are discussed in this subsection.

Short Run Marginal cost

The definition of marginal costs is the costs that are made to produce one unit extra. In case of electricity production, short run marginal cost are the costs related to the production of one kWh extra, given an existing production unit (Blumsack, n.d.). The short run marginal cost of conventional power plants mostly consist of the fuel cost and the emission allowance price. The marginal cost of wind and solar energy are close to zero due to the low variable cost.

Long run marginal cost

These are the cost related to producing one unit of energy extra, not given an existing production unit (Blumsack, n.d.). These cost are used for the investment decision in another production unit.

Merit order

The merit order is used to determine the price of electricity. The (short run) marginal prices and volumes of electricity producers are bid in and set in order from lowest to highest. The electricity consumption determines which electricity production units are used and the highest price is payed to everyone, a principle called single price clearing. Due to the merit order and single price clearing, electricity producers ask the short-run marginal cost.

Merit order effect

The merit order effect is the effect of increasing wind and solar energy on the merit order and is shown in Figure 8 (Next Kraftwerke, n.d.). The merit order effect reduces the average electricity price, as the short run marginal cost are almost zero (Next Kraftwerke, n.d.).

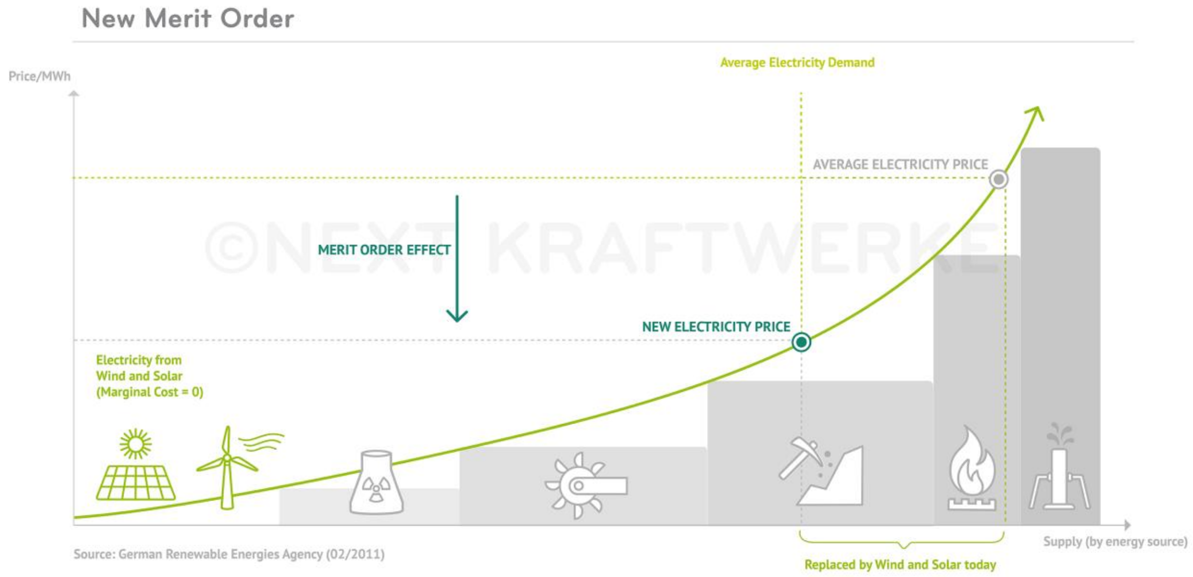

Figure 8 Merit order and merit order effect of renewable energy. Reprinted from: ''Merit order: What does merit order mean?'', Next Kraftwerke, retrieved from: https://www.next-kraftwerke.com/knowledge/what-does-merit-order-mean

2.2.3 Carbon Market - ETS

In Europe a market is used to give carbon emissions a value, it is called the EU Emissions Trading System (ETS). This market is a tool to reduce the emissions in a cost effective way. There is a cap on the amount of greenhouse gases that can be emitted by power stations and industry ("EU Emissions Trading System (EU ETS) | Climate Action," n.d.). This cap is reduced every year to decrease the amount of emissions ("EU Emissions Trading System (EU ETS) | Climate Action," n.d.). In Figure 9 the ETS price and the increase of the ETS price for the years 2017 to 2019 is shown. The last years the ETS price increased with steps of more than 60%. This is likely due to the decreasing amount of emissions that can be emitted.

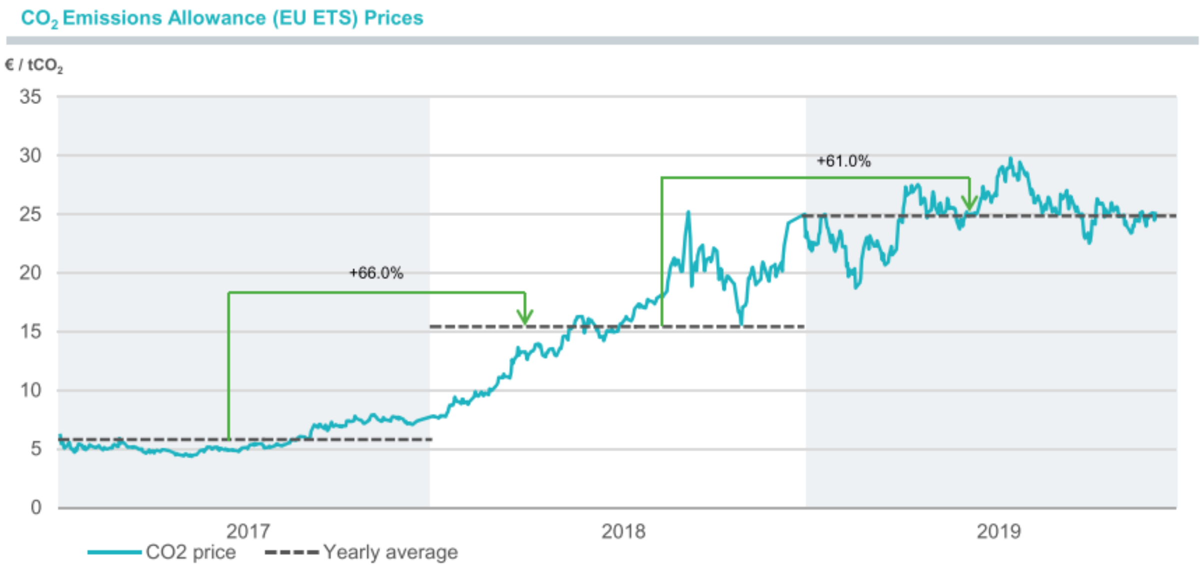

Figure 9 CO_2 Emissions Allowance (EU ETS) Prices. Reprinted from: ''Annual Market Update 2019'' by TenneT, 2020, p. 17

2.2.4 Future Energy Scenario

There are multiple scenario’s available in the literature and the reports of energy sector companies and institutions. One of the important ones is the predictions of PBL (in Dutch: Planbureau voor de Leefomgeving), which is a Dutch research institute on the topics of environment and spatial planning. According to Ina Schjelderup (Personal Communication, June 2020) PBL is a reliable source of information for the energy sector.

Figure 10 shows two figures from the report of PBL on climate and energy (Schoots & Hammingh, 2019). The figure shows the prognosis of PBL on the amount of power and energy of the different sources of energy (Schoots & Hammingh, 2019). The figures show that the amount of coal will be reduced to zero and that the electricity production will consist of mostly solar and wind energy. The other part will mostly be produced by gas powerplants.

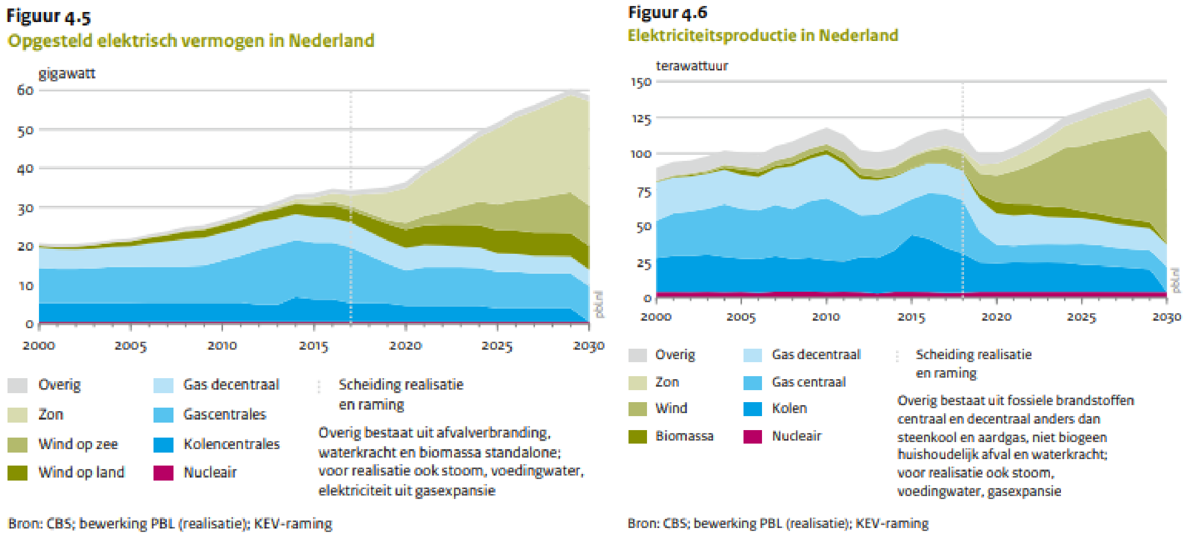

Figure 10 Power and energy mix predictions of PBL. Adapted from ‘’Klimaat- en Energieverkenning 2019’’, Schoots & Hammingh, 2019, p. 92 & 93

3. Methodology and approach

The methodology and approach to determine the value of energy storage will be discussed per service of the storage. First the case study of Delta21 is explained in section 3.1. Then the methodology to analyse the services Arbitrage, Distribution Deferral and Carbon Abatement are explained in the sections 3.2, 3.3 and 3.4 respectively.

3.1 Case study: Delta21

Delta21 is a plan to expand the Delta Works in the Netherlands. The main focus of Delta21 is to provide water safety by using pumps (Berke & Lavooij, 2019b). The pumps are used to lower the water level of the rivers during storms and high river water discharge (Berke & Lavooij, 2019b). According to their plans, the pumps are needed for water safety once in five to ten years for three to five days (Berke & Lavooij, 2019b). To secure the working of the pumps and have secondary benefits from the investment, Delta21 includes a water reservoir that uses the pumps to store electricity (Berke & Lavooij, 2019b).

In Figure 11 the most current plan of Delta21 is presented. The figure shows the port of Rotterdam, Rotterdam itself and part of Zeeland. The plan of Delta21 is to build a reservoir next to the Maasvlakte. The pumps will be placed between the reservoir and the sea and there will be a dam between the Haringvliet and the energy lake. This dam will be used for water security and opens when the pumps are needed for water safety.

Figure 11 Delta21 energy lake plan. Adapted from ''Update 2019: DELTA21 Een actualisering van het plan'', Berke & Lavooij, 2019, p. 20

From this case the focus will be on the energy storage in the water reservoir. This way of storing energy is the same as Pumped Hydro Storage. The higher reservoir is in this case the sea and the lower reservoir is the created energy lake. In this way electricity can be (re)created by filling the energy lake. The latest estimate is that the energy storage will have a power of 1,85 GW and a capacity that allows the pumps to pump water for 12 hours (Berke & Lavooij, 2019a, 2019b).

In the Netherlands the operational power is around 30 GW (TenneT, 2018b). This means that 1,85 GW power is around 6% of the total amount of operational power. This is high and a lot of power for one storage, as for example Centrale Eemshaven (RWE) has a power of 1,56 GW and Pumped Hydro Storage Vianden (RWE) has a power of 1,291 GW (RWE, n.d.-b, n.d.-a). The technique of pumped hydro storage is widely used in the rest of the world. Due to the scale of this grid scale storage and the wide availability of data on pumped hydro storage the Delta21 case can be properly tested against this data and the available research.

SWOT analysis of Delta21

Based on the previous information from chapter 2 and the case information the following SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis can be distilled.

Table 2 SWOT analysis Delta21

SWOT analysis	Helpful	Harmful
Internal	**Strengths:** - High Technology Readiness Level - High power and capacity - Beneficial to multiple stakeholders for different purposes	**Weaknesses:** - Low efficiency (for PHS)
External	**Opportunities:** - Wind park connections - Expected growth of Renewable Energy	**Threats:** - Other storage projects that enter the market - Connection costs

This SWOT analysis will be used to apply the results found on the different services to the case of Delta21. In the Discussion in Section 5 there will be recommendations based on the results which will be applied to this SWOT analysis.

3.2 Method to assess the value of Arbitrage

To get an indication of the value of Arbitrage, the possible profit of the Delta21 storage lake on the market is determined. As Arbitrage is the buying and selling of energy, a strategy is formed to buy and sell electricity on the market. There are different markets on which electricity is traded, all discussed in subsection 2.2.1 . The day-ahead market is chosen to analyse, as it is the market with high trading volumes. The day-ahead market is often also referred to as “the electricity price”. The influence of efficiency and amount of hours usage of the pumps on the amount of Arbitrage profit is analysed to get an indication of how important those storage properties are for the value of the storage.

Data gathering and description

The price data from the day-ahead market was gathered from the years 2010 to 2019. This data was made available by RWE (Leonard van den Hoek, RWE, Personal Communication, 5 February 2020). The data consists of the day-ahead price in €/MWh and the date and hour of the price. There are 87.648 data points of prices per hour. There are 3 missing values in the data. The missing data are the prices of the following dates and hours: 9-9-2014 17:00, 29-11-2014 12:00 and 13:00. This small amount of missing data is deemed insignificant to such an extent that it will not influence the accuracy of the analysis.

Programmed buying and selling strategy

The strategy that is programmed will be shortly explained and can be seen in the flowchart in Figure 12. The strategy determines when to buy and sell electricity on the market. This done based on the month and the weekday, taking seasonality and daily patterns into account. For each month and weekday the hours with high prices are determined. This determination is done by taking a set of hours from each date with the highest prices and the lowest prices. Then for each combination of weekday and month, the hours of the day that are most often within this combination are chosen as the most likely to have a high price. The same is done for the hours with the lowest prices. This results in a list of hours to buy and a list of hours to sell for the combination of each weekday and month.

The hours to buy and sell are applied on the execution year. The prices corresponding to the hour lists are selected. The prices from the high price hours are the selling price and the prices from the low price hours are the buying prices. The Arbitrage profit is calculated by the sum of selling prices multiplied by the efficiency minus the sum of the buying prices as shown in the formula 3.1.

$$Arbitrage\ profit = efficiency * sum(selling\ prices) - sum(buying\ prices) \tag{3.1}$$

Arbitrage profit is defined as the difference between cost of buying and the income of selling on the electricity market. The selling prices are reduced with the round-trip efficiency losses. This assumes that the round-trip efficiency is stable over time and not dependent on how full or empty the storage is.

This is how the strategy is programmed. As an example, the strategy is explained using the strategy on one day in textbox 3.2.1 for clarification. The strategy uses the 24 hours of one day to determine the hours to buy and sell based on the price distribution in the day of the previous years. Both Connolly et al. (2011) and Bolado et al. (2014) use 24 hours for their strategy. Bolado et al. (2014) describes that in the Netherlands on the day-ahead market the electricity is traded for 24 hours a day ahead. The developed strategy buys and sells the same amount of hours on each day. This simplification makes sure the strategy stays within the limitations of the energy lake.

This strategy is programmed in Python, so the code of the strategy can be re-used. The code can be found in Appendix A. As there was, in the literature found and described in subsection 2.1.1, no direct code available to apply, the code and strategy were developed for this research.

Textbox 3.2.1 Example of strategy application

In this textbox an example of calculating the profit for one day is explained. This is to further explain the used strategy.

To calculate the Arbitrage profit for the 3rd of March 2019, calibrated on the years 2014 to 2018, charging the storage for 4 hours the following steps happen. First, the 3rd of March 2019 is a Tuesday. To know which hours to buy electricity that day all the Tuesdays in March of the years 2014 to 2018 are selected. For each of these days the 4 hours with the lowest price are selected of each Tuesday. Those hours are combined in one list and the 4 hours that are the most often in that list are selected as the hours that are likely to have the lowest prices. These 4 hours are used to buy on the 3rd of March 2019 and the corresponding prices are selected from that year. Then the prices to sell the electricity are selected in a similar manner as the prices to buy. However, then the 4 hours with the highest prices of each Tuesday are selected and combined in a list and then the 4 hours that are the most often in that list are selected. Those 4 hours are applied to the price data of the 3rd of March 2019 and added to the amount for which the electricity is sold. The profit that is then made, with this strategy, is the electricity selling sum multiplied by the round-trip-efficiency to account for losses minus the electricity buying sum.

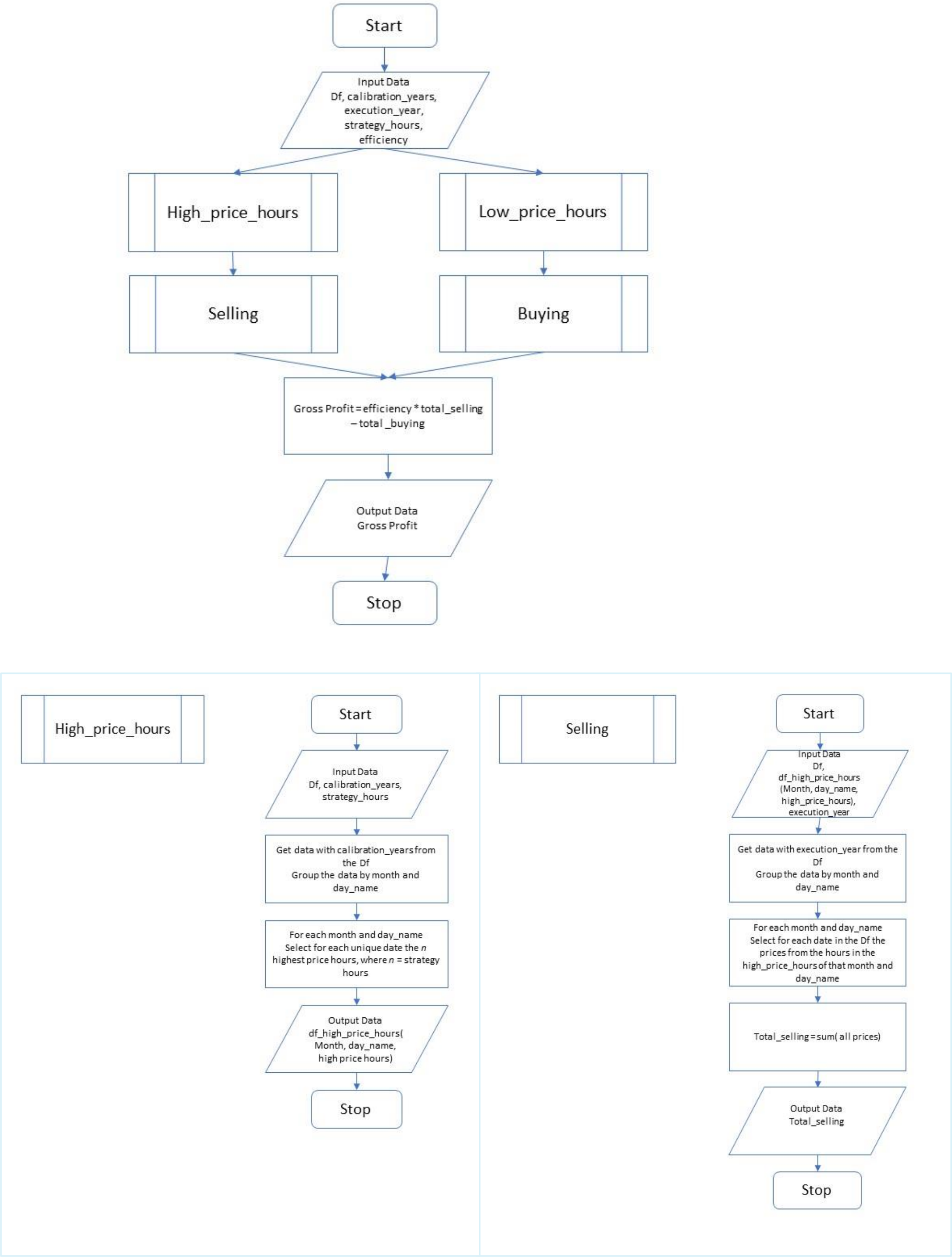

Figure 12 Arbitrage strategy program flowchart

Dependent and independent variables

The strategy uses the inputs the amount of hours to buy and sell energy and the efficiency of the storage. The result of the strategy, the dependent variable, is the Arbitrage profit in Euros per MW (of power). The assumption is that if it is likely to buy or sell it is likely to use all the power allocated for Arbitrage because of the expected profit. This means that the results can be multiplied by the amount of power used for Arbitrage to calculate the total amount of profit.

The levels of efficiency used to analyse are 70%, 75%, 80% and 85%. These levels are based on the information in the report of World Energy Council (2019) that report a 70 to 85% efficiency for pumped hydro storage.

The amount of hours that the storage is used a day to charge or discharge is set on an integer from 1 to 12. When the variable is set at 1, it means that the storage is charging 1 full hour and is discharging 1 full hour a day.

These influences on the combinations of these variables on the Arbitrage profit will be analysed in graphs. Each efficiency level will have its own graph in which the influence of the amount of hours is presented on the Arbitrage profit. Comparing the four resulting graphs indicates the influence of the efficiency level.

Application of the strategy

First, the influence of calibration years will be investigated by using five different randomized calibration year combinations on the year 2019. The influence of the efficiency level, the amount of hours and the pattern of the different calibrations is determined visually.

Second, the strategy is applied to the case of Delta21. In this case the efficiency is set on 72,5% as this is the round-trip efficiency. There is one calibration combination used of the years 2010 to 2014 and applicated to the years 2015 to 2019.

Third, the strategy is applied to grid-scale energy storage. The different efficiency levels and amount of hours are used in the analysis, comparing the Arbitrage profit of the years 2015 to 2019 under different storage variables. The strategy is calibrated on the years 2010 to 2014.

Influence of average price and price difference on the Arbitrage profit

The average price and the price difference for the years 2015 to 2019 are calculated. The price difference is calculated as the average of the maximum price difference of each day for that year following the formula presented below.

$$average \max price\ difference = \frac{\sum_{i=1}^{n}(\max(pi) - \min(pi))}{n} \qquad (3.2)$$

$$where\ p_i = prices\ on\ day\ i$$

The average price and average maximum price difference will be presented together with the profits for the case of Delta21 for four hours of charging and discharging for the years 2015 to 2019. This method is used to find the influence of the price difference on the Arbitrage profit and see how the average price and the price difference is connected to the profit.

3.3 Approach to assess the value of Distribution Deferral

In the literature and method section, described in subsection 2.1.2, there is no method found on Distribution Deferral valuation that is applicable to a grid-scale standalone storage, like Delta21. The method from Sidhu et al. (2018) is only applicable if the storage is an alternative for investments in the grid and the costs for these investments are known. The method from Klein Entink (2017) is applicable if the storage can be scaled to optimize for Distribution Deferral. The method of Klein Entink (2017) uses load pattern data which is not publicly available.

To understand more about the Distribution Deferral, the recent developments in the Netherlands related to storage and grid capacity problems are analysed and experts from TenneT and RWE were interviewed. The information is translated to a causal system diagram to make the system clear, which is an update from Figure 4 in subsection 2.1.2.

3.4 Method to assess the value of Carbon Abatement

As seen in the literature review, in Subsection 2.1.3, there are different approaches to determine Carbon Abatement. The approach taken is one that can be applied to a stand-alone storage. The approach of taking emissions of the electricity production and then calculating the additional electricity produced due to the efficiency losses of the storage is used.

CBS (Centraal Bureau voor de Statistiek, or Central Agency for Statistics) yearly publishes data on the average emissions of the electricity production in the Netherlands of a year (CBS, 2020). The most recent data is used, which includes the years 2000 to 2018. The CO_2 emission factor that is used is from the integral method of the CBS, as this factor method includes the renewable electricity production (CBS, 2020). The integral method includes the emissions from total electricity production (renewable and non-renewable), but excludes the electricity from waste incineration plants and residual gasses from the industry (CBS, 2020; Gerdes, Segers, Bosselaar, Verdonk, & Harmelink, 2012).

The value of emissions is based on the ETS price. The price information of the ETS is extracted from Ember (2020) in xls format. The ETS price is extracted in a daily format and is averaged to a yearly number using Microsoft Excel. The averages from the years 2015 to 2019 are compared to the averages in the graphs published by TenneT to check the accuracy of the data (TenneT, 2018a, 2020a). The data from Ember corresponds to the publications of TenneT. Therefore, the data from Ember (2020) is assumed to be reliable.

The amount of additional electricity production on a yearly basis is calculated based on the results from the analysis of Arbitrage on the day-ahead market. The optimum amount of hours of the corresponding efficiency and year is selected from the results of the analysis of Arbitrage on the day-ahead market. The amount of electricity stored in a year is calculated by the formula shown below. It is assumed that the storage is used on full power. Subsequently, the amount of additional electricity asked from the electricity system is calculated by multiplying with one minus the efficiency. Those calculations are shown in the formulas 3.3 and 3.4.

$$Electricity\ stored\ \left[\frac{MWh}{year}\right] = Power\ [MW] * Amount\ of\ hours\ per\ day\ [\frac{h}{days}] * 365\ [\frac{days}{year}] \tag{3.3}$$

$$\begin{aligned} &Additional\ Electricity\ production\ needed\ \left[\frac{MWh}{year}\right] \\ &\quad = Electricity\ stored\ \left[\frac{MWh}{year}\right] * (1 - Efficiency\ [\%]) \end{aligned} \tag{3.4}$$

To calculate the amount of carbon emissions induced by the storage, the additional electricity production that is needed due to the losses in efficiency, is multiplied with the emission factor of the year analysed. The formula for this calculation is shown in formula 3.5. The carbon emission value can be calculated by multiplying it with the carbon price, which is shown in formula 3.6.

$$\begin{aligned} &Amount\ of\ carbon\ emissions\ \left[\frac{t\ CO2}{year}\right] \\ &\quad = Electricity\ stored\ \left[\frac{MWh}{year}\right] * (1 - Efficiency\ [\%]) \\ &\quad * Emission\ factor\ \left[\frac{t\ CO2}{MWh}\right] \end{aligned} \tag{3.5}$$

$$Carbon\ emissions\ value\ \left[\frac{€}{year}\right] = Amount\ of\ carbon\ emissions\ \left[\frac{CO2}{year}\right] * Carbon\ price\ [\frac{€}{t\ CO2}] \tag{3.6}$$

This analysis will result in a negative value for Carbon Abatement, because it calculates the carbon emissions induced by the storage in short time. However, the influence of storage properties, such as efficiency can be analysed.

4. Results

The results of the research will be discussed per service of the storage. Section 4.1 discusses the results of the analysis on the value of Arbitrage on the day-ahead market. Section 4.2 shows the findings of the expert interviews, literature and data search on Distribution Deferral. Section 4.3 shows the results of the methodology of the calculation on carbon emissions that are emitted or abated and what the corresponding value is.

4.1 The value of Arbitrage

The value of Arbitrage is determined using a strategy of buying and selling energy on the day-ahead market on a daily basis. First, the calibration of the strategy and its results are shown in Subsection 4.1.1. Then the strategy and the results of the strategy are applied to the case of Delta21 and are shown in Subsection 4.1.2. The research was performed on a broader aspect of the value of Arbitrage of a pumped hydro storage in the Netherlands and the results are discussed in Subsection 4.1.3. After that, the influence of the price level and the price difference on the Arbitrage profit are discussed in Subsection 4.1.4. A causal diagram is used to visually represent the results in Subsection 4.1.5. Finally, the valuation of storage is discussed in the perspective of the predictions on the future energy production in Subsection 4.1.6.

4.1.1 Calibration of the strategy of buying and selling electricity

The strategy of charging and discharging the storage is calibrated on the hours with the highest and lowest electricity prices of former years. The impact of different calibrations on the year 2019 are studied to know if the calibration has an influence on the results and the behaviour of the results. Table 3 shows the different calibration combinations of years chosen via randomized choice in Python that are used for the calibration.

Table 3 Calibration years combinations

Calibration name	Calibration years
A	2014, 2015, 2016, 2017, 2018
B	2010, 2011, 2013, 2014, 2018
C	2010, 2013, 2014, 2016, 2017
D	2013, 2014, 2015, 2016, 2018
E	2011, 2013, 2015, 2017, 2018

In the results the influence of the amount of charging and discharge hours per day and the influence of efficiency is inspected. Figure 13 shows four graphs with different efficiency levels and each graph shows the influence of charging and discharging hours on the Arbitrage profit per MW of power per year. The different calibrations are represented by the different coloured lines and the names in Figure 13 and Table 3. Figure 13 shows the influence of these different calibrations on the strategy applicated to the 2019 day-ahead market.

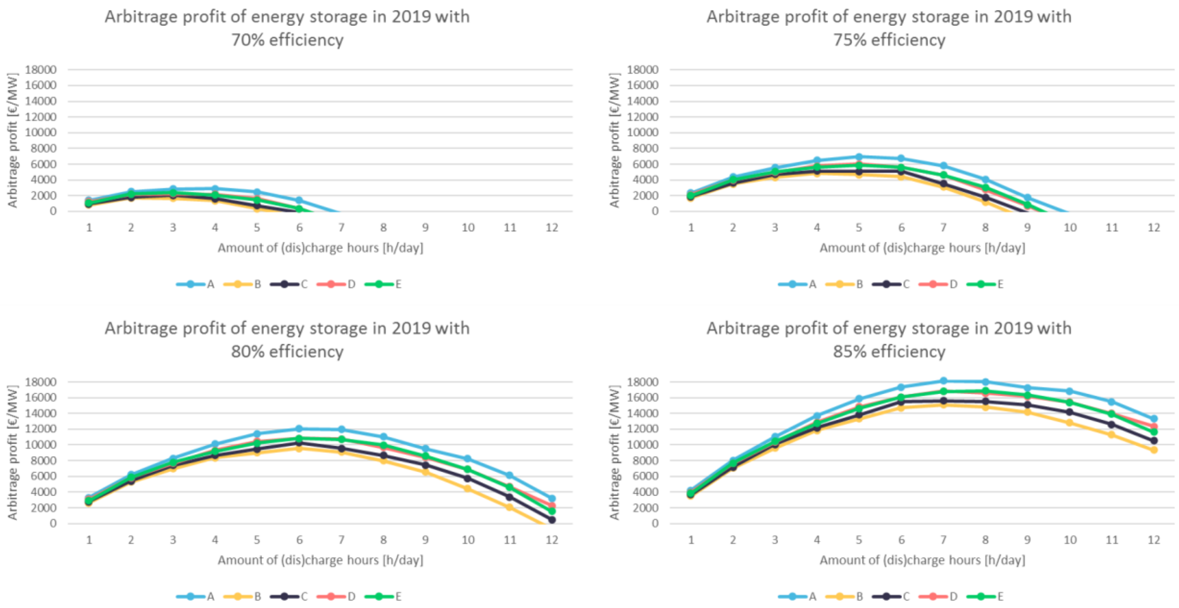

Figure 13 Arbitrage profit of energy storage in 2019 with different calibrations

The influence of different calibrations on the amount of gross profit that can be made is rather minimal. The pattern of influence of the amount of charging and discharging hours on the amount of gross profit is similar. The influence of efficiency on these patterns appears to be the same for each calibration combination as well.

It seems that the more recent calibration years give a slightly higher amount of gross profit. However, the choice is made to use the same calibration for the analysis. So, in the rest of the results the years 2010 to 2014 are used to calibrate the strategy. In such a manner the same strategy can be applied to the years 2015 to 2019.

4.1.2 The value of Arbitrage of Delta21

The value of Arbitrage of Delta21 is determined by using a strategy of buying and selling energy every day on the day-ahead market. The method and exact strategy is elaborately described in section 3.2. In the developed strategy a few variables can be entered. To determine the value of Arbitrage of Delta21 the following variables are used: a round-trip efficiency of 72,5% and a consistent power of 1,8 GW.

The possible value of Arbitrage of Delta21, based on the programmed strategy applied on 2019 and calibrated on the years 2010 to 2014, is shown in Figure 14. The graph in Figure 14 shows the influence of the amount of hours that the storage charges and discharges a day on the amount of Arbitrage profit that can be made per MW of power. This assumes a constant power of the storage lake.

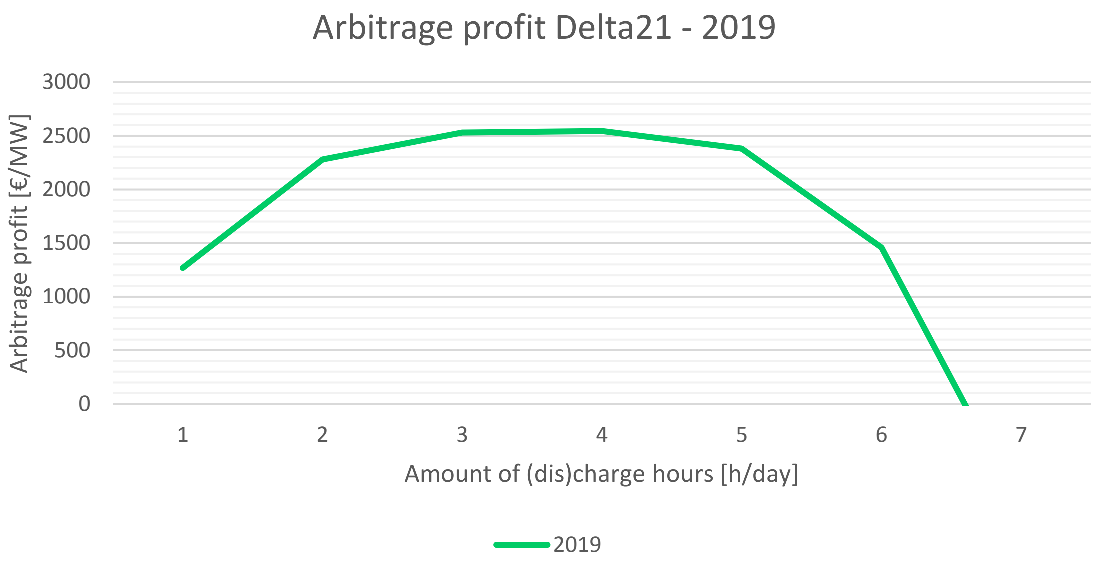

Figure 14 Possible Arbitrage profit of Delta21 in 2019 based on strategy calibrated on the years 2010-2014

The graph in Figure 14 shows that there is a certain optimum of amount of hours that the storage should be used on the day-ahead market. If Delta21 were active on the market of 2019, it would have an optimum amount of hours around three or four hours of charging and three or four hours of discharging the storage to buy and sell electricity on the day-ahead market. That would mean that the storage would only be used for 25% to 33% of the capacity, as it can be used for 12 hours for charging or discharging.

The Arbitrage strategy calibrated on the years 2010 to 2014 was applied to more years. In Figure 15 different years are plotted in different coloured lines. This represents how different years influence the possible Arbitrage profit that can be made on the day-ahead market and how this relates to the influence of the amount of hours to charge and discharge per day on the Arbitrage profit.

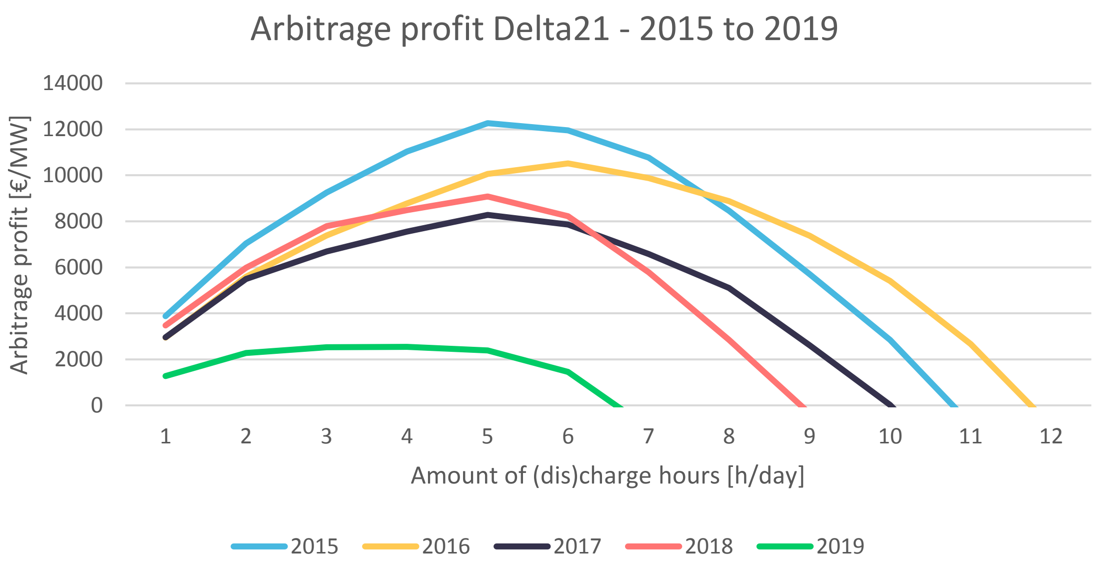

Figure 15 Arbitrage profit by Delta21 in the years 2015 to 2019

Figure 15 shows that the possible Arbitrage profit can differ greatly per year. The optimum of the amount of hours to charge and discharge even differs, but is around five hours each year for the Delta21 project. This would mean that the capacity of the storage will only be used for approximately 40 % of the capacity.

In Figure 16 the Arbitrage profit for Delta21 on the day-ahead market is calculated and shown for the year 2015 to 2019 based on the calibration on 2010 to 2014. It is the same figure as Figure 15 but multiplied by 1,8 GW to show the Arbitrage profit for the full power storage. The Arbitrage profit in Figure 16 is in million euros.

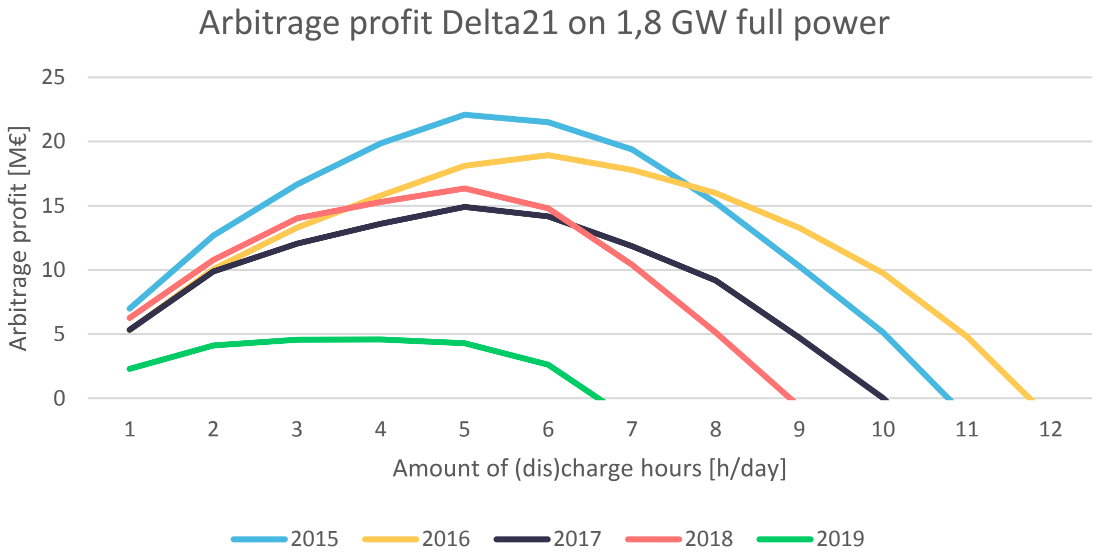

Figure 16 Arbitrage profit by Delta21 in 2015 to 2019 with full power

Figure 16 shows that with the current Delta21 specifics, the 2 billion (2 x 10^9 €) of profit over 50 years that they presented on the 24th of September is highly unlikely to be earned (Berke & Lavooij, 2019a). Even if the year 2015 would repeat itself with around 22 million euros per year for 50 years, it would be 60% of this anticipated income. In this scenario the profit of the storage would approach, without discount rate, around € 1,8 billion. However, as it shows in Figure 16, the Arbitrage profit can differ greatly per year.

4.1.3 The value of Arbitrage on the day-ahead market of grid-scale storage

As Pumped Hydro Storage, like the one from Delta21, often have an efficiency between 70 and 85% (World Energy Council, 2019), this efficiency range is used as an input for the model. In Figure 17 there are four graphs shown with each its own efficiency level, the levels 70%, 75%, 80% and 85% are used. The individual graphs show, just like the graphs above, the influence of the amount of hours to charge and discharge on the Arbitrage profit and the differences between the years on which the strategy is applied. By showing the graphs for each efficiency level also the influence of efficiency on the Arbitrage profit is shown. The same calibration years, 2010 to 2014, are used to make the same comparison.

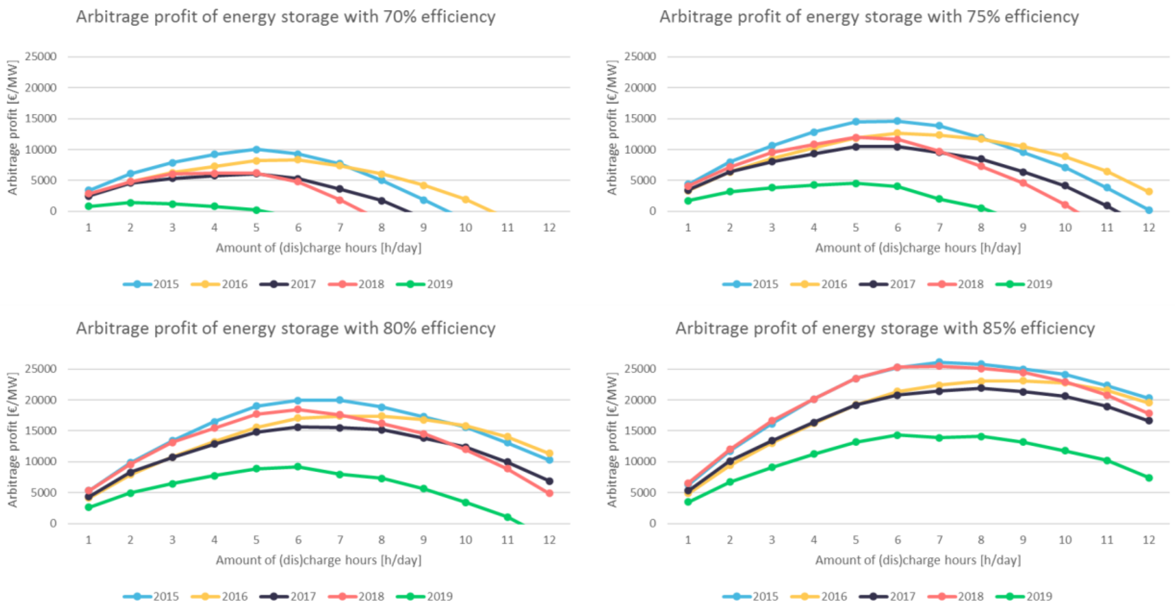

Figure 17 Arbitrage profit of energy storage in 2015 to 2019 calibrated on the years 2010 to 2014

Figure 17 shows the high impact of efficiency on the possible Arbitrage profit of the storage. Furthermore, the optimum amount of hours to charge and discharge increases slightly with the increase of efficiency. This means that there will be an optimum in capacity for the storage value of Arbitrage on the day-ahead market. This contradicts the discussed findings of Bolado et al. (2014) in which he concludes that there is an optimum of amount of hours not depending on the efficiency.

To understand the phenomenon of the efficiency that together with the amount of hours to charge and discharge influences the possible Arbitrage profit the graphs in Figure 18 are shown. The graphs show the same daily pattern with the same average price, however the red lines show the different differences between prices of the efficiencies needed to make profit, i.e. charging or discharging below or above the red lines, respectively, is likely to impact the profit negatively. It gives an insight into how the efficiency influences the amount of hours that the storage can be used on the day-ahead market to make a profit.

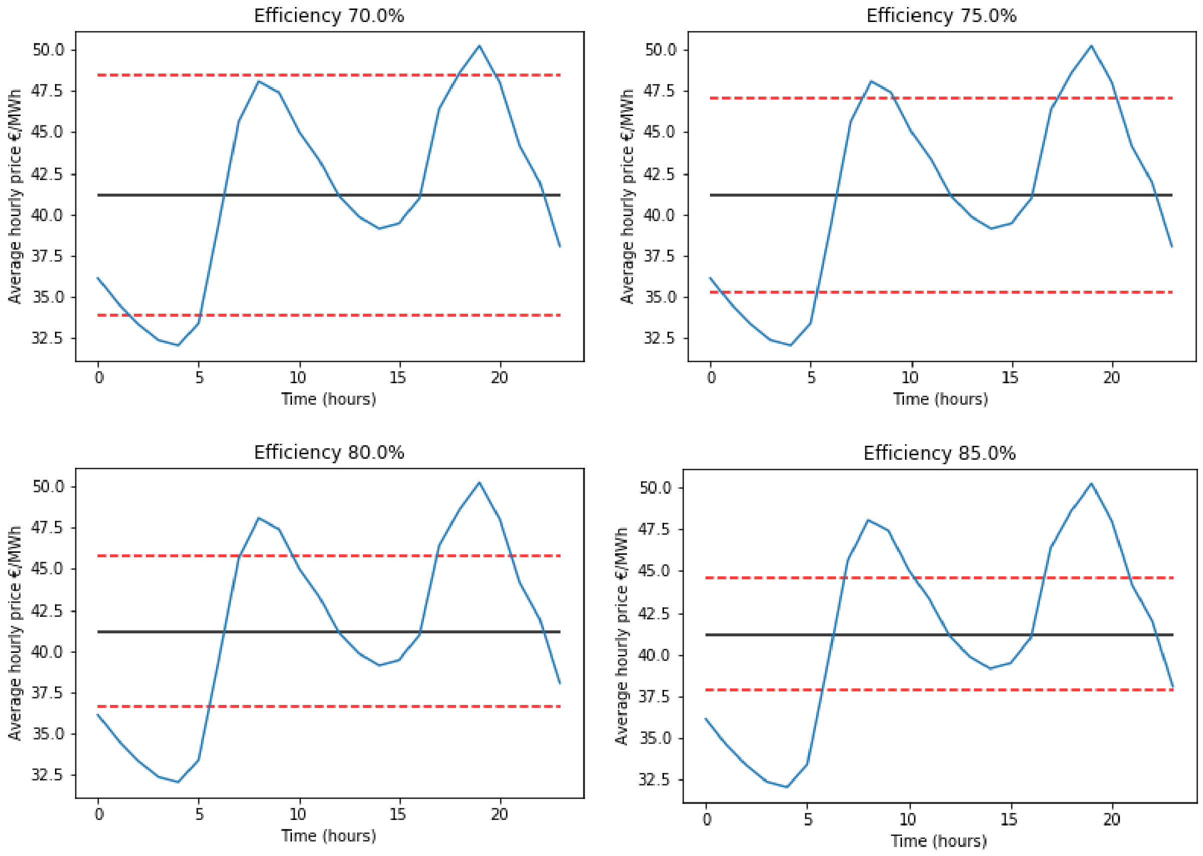

Figure 18 Efficiency and the amount of hours in the daily pattern of 2019

In Figure 18 it is illustrated how the efficiency has an influence on the amount of hours per day it is possible to use the storage without making losses. To trade daily on the day-ahead market a high efficiency is needed to have more hours to make profit. This means there is an optimum between capacity and efficiency when using and designing a storage facility that is used to buy and sell electricity on the day-ahead market.

4.1.4 Influence of price level and price difference on Arbitrage profit

The influence of price level and price difference on the Arbitrage profit is examined. The years 2015 to 2019 are displayed with the average price of that year and the maximum price difference of the days averaged over that year in Table 4. To calculate the average maximum price difference on a day is found by determining for each day in that year what the highest price and the lowest price is and calculating the difference for each day and averaging that over the year.

Table 4 Results of analysing price differences in the years 2015 to 2019

Year	**Average price [€/MWh]**	**Average maximum price difference on a day [€/MWh]**	**Arbitrage profit, 72,5%, 4h (dis)charge duration [€/MW]**
2015	40,05	32,19	11034,02
2016	32,25	25,26	8776,08
2017	39,31	29,82	7554,45
2018	52,53	37,12	8493,34
2019	41,20	26,59	2544,20

Table 4 shows that when the average price is comparable, for example between the years 2015, 2017 and 2019, but the price difference becomes smaller, the profit decreases. This confirms partly the findings of Bolado et al. (2014). Bolado et al. (2014) also found that the profit decreases when the price differences become smaller. However, in the table this finding is not true for all the years. The table shows that there are other variables influencing the profit as for not comparable average prices, like 2018 and 2015, the increase in price difference results in a lower Arbitrage profit.

Table 4 shows that when the price difference is similar (for example between 2016 and 2019) and the average price becomes higher, the profit decreases. This indicates that when the absolute price difference is the same, but the average price is higher, that the amount of possible profit is lower. This shows the signs of a connection between the average price and the profit of Arbitrage. So it seems that both the average price level and the absolute price difference influence the profit possibilities of a storage.

The connections between average price, the average price difference and Arbitrage can be explained by the following argumentation: when a storage has to overcome its efficiency losses it has to overcome a relative price difference between the price for buying electricity and the price for selling electricity to make a profit. When the average price is higher the relative price difference between the buying and selling price becomes bigger and so the absolute price difference needs to grow to make the same amount of profit.

4.1.5 Causal system diagram on the value of Arbitrage

Figure 19 shows a causal diagram with the influences of different discussed variables on the value of Arbitrage. The arrows show the direction of the causal link and the plus or minus shows the relation. A plus indicates that if the one variable increases it increases the other variable. A minus indicates that if the one variable decreases the other variable increases and vice versa. Some of the arrows don’t have a plus or minus, this is to indicate that there is a relation between the variables, but the relation is unclear or cannot be defined by a plus or minus. Furthermore, the variables with the striped blue background are external variables.

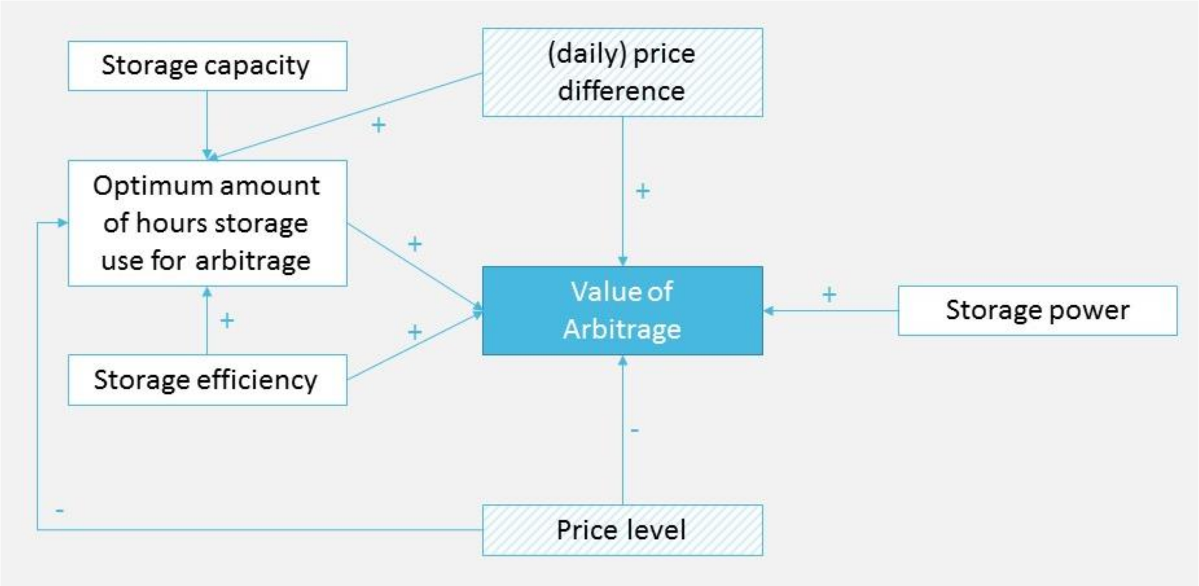

Figure 19 Causal diagram of the value of Arbitrage

Figure 19 shows that the amount of power and efficiency have a positive influence on the value of Arbitrage. These relations were already found in literature and are confirmed by the results of this research. A new found relation is that efficiency also influences the amount of hours that the storage can be used for the optimum amount of profit. If this optimum amount of hours is higher it also increases the value of Arbitrage. Efficiency influences the value of Arbitrage in two ways. Direct by reducing the amount of losses of profit by losing less energy and indirect by increasing the amount of hours that the storage can be used for profit.

Then the new external variable price level is added to the causal diagram. The identified relations found in subsection 4.1.4 are added to this causal diagram to show the new theoretical relations.

4.1.6 The value of Arbitrage by grid-scale storage in the future energy market

In the literature the effects from the increasing amount of renewable energy on the daily price pattern are hard to predict. Using the merit order effects from increasing renewable energy and decreasing fossil fuels like coal energy a few very general predictions will be discussed to put the results from before in perspective of the future.

Based on the projections from the PBL discussed in subsection 2.2.4, it can be expected that the coal price will disappear in the merit order and there will be a high increase of renewables. The merit order might produce more heavily fluctuating prices. However, the entrance of storage solutions could level the price fluctuations more. The value of Arbitrage heavily depends on the outcome of those processes on the market. Nevertheless, what can be expected is that the prices will be more influenced by weather patterns due to the increasing amount of wind and solar energy. How all those processes eventually work on the price pattern and price level and price difference of the market is hard to predict.

4.2 The value of Distribution Deferral

The value of Distribution Deferral is determined using interviews, documents and literature. First, the value of Distribution Deferral of Delta21 is analysed in Subsection 4.2.1. Then the recent development on the valuation of Distribution Deferral is discussed in Subsection 4.2.2. Finally, the interactions of different variables on the value of Distribution Deferral are presented in a causal system diagram in Subsection 4.2.3.

4.2.1 The value of Distribution Deferral of Delta21 in the current situation

In the current situation there is no valuation of grid deferral by grid-scale energy storage in place according to experts from TenneT and Uniper (Appendix B and C). It became clear that only when a storage is behind-the-meter or connection to the grid the storage can be valued. The amount of power needed on the connection can be reduced by using storage behind-the-meter. In this case the cost of the connection can be reduced. This system gives a value to the reduced need of the grid. However, for a storage directly connected to the grid there is no valuation in the current economic system.

This means that the value of Distribution Deferral by Delta21 cannot be valued in the current electricity system. This is due to the current market system, in which the location of the electricity production does not matter (Ina Schjelderup, Personal Communication, July 2020). This phenomenon is called the copper plate model (Ina Schjelderup, Personal Communication, July 2020). However, there is value in the placement of electricity production close to the use of the electricity due to transportation losses and grid investments needed to transport the electricity.

The location of Delta21 is close to the high-voltage network based on the information from TenneT, see Figure 20 (TenneT, 2019). This means that the cost of connection is lower, than if the storage would be in the North of the Netherlands. Furthermore, Figure 20 shows also that there are currently wind parks under development in the North Sea that still need to be connected (TenneT, 2019). At last, TenneT published on their website that there is a need for investments in the 380 kV grid of the Randstad and south-west of the Netherlands (TenneT, n.d.-a).

The connection of a wind park via storage can provide value due to the reduction of load peaks by a wind park. The storage and wind park can be placed together behind the connection to the grid. One of the things that makes the connection very expensive for the storage is that a production facility pays for the maximum amount of power it extracts from the grid.

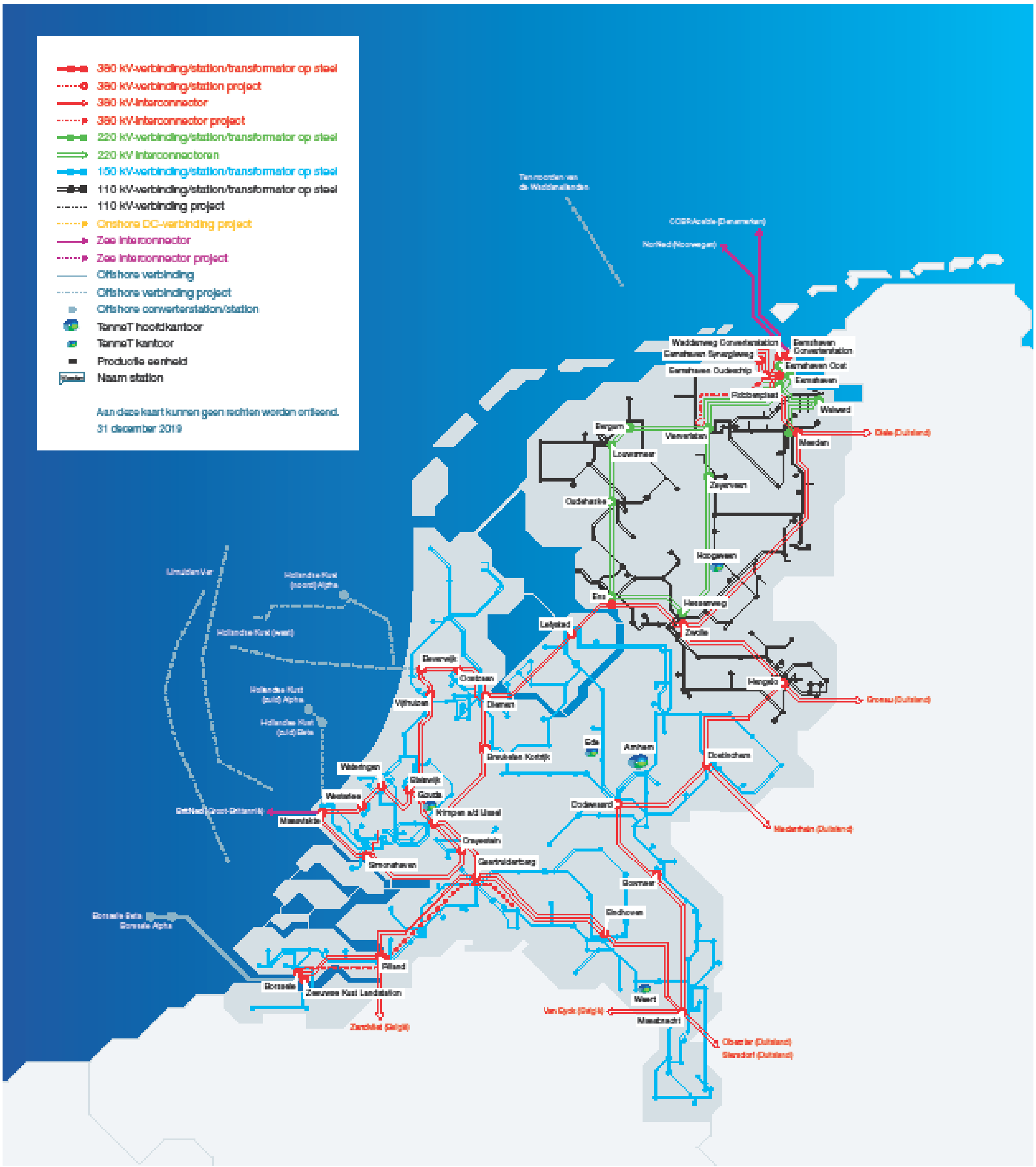

Figure 20 Netkaart Nederland. Retrieved from "Netkaart Nederland", TenneT, 2019

4.2.2 Recent developments on the valuation of Distribution Deferral

There are recent developments on the valuation of Distribution Deferral. TenneT, the TSO in the Netherlands, foresees grid capacity problems in the North of the Netherlands (TenneT, 2020c). Currently, TenneT has started consultation rounds to get more information on other solutions to solve the capacity problems (TenneT, 2020c). In their consultation rounds TenneT mentions storage behind and in front of the meter as possible solution to their capacity problem (TenneT, 2020c).

Also in Zeeland, TenneT has congestion problems. A congestion problem occurs when TenneT contracted more power than they can transport in their grid taking the failure reserve into account (TenneT, 2020b). These congestion problems mostly are caused by the growth of solar and wind energy.

4.2.3 Causal system diagram on the value of Distribution Deferral

In Figure 21 shows a causal system diagram with the influences of different discussed variables and storage properties on the value of Distribution Deferral. As the type of influence did not become clear from the analysis there are no plusses or minuses used. The diagram shows the found relations between the variables and storage properties. The variables with the striped orange background are external variables that is assumed to be not significantly influenced by other variables.

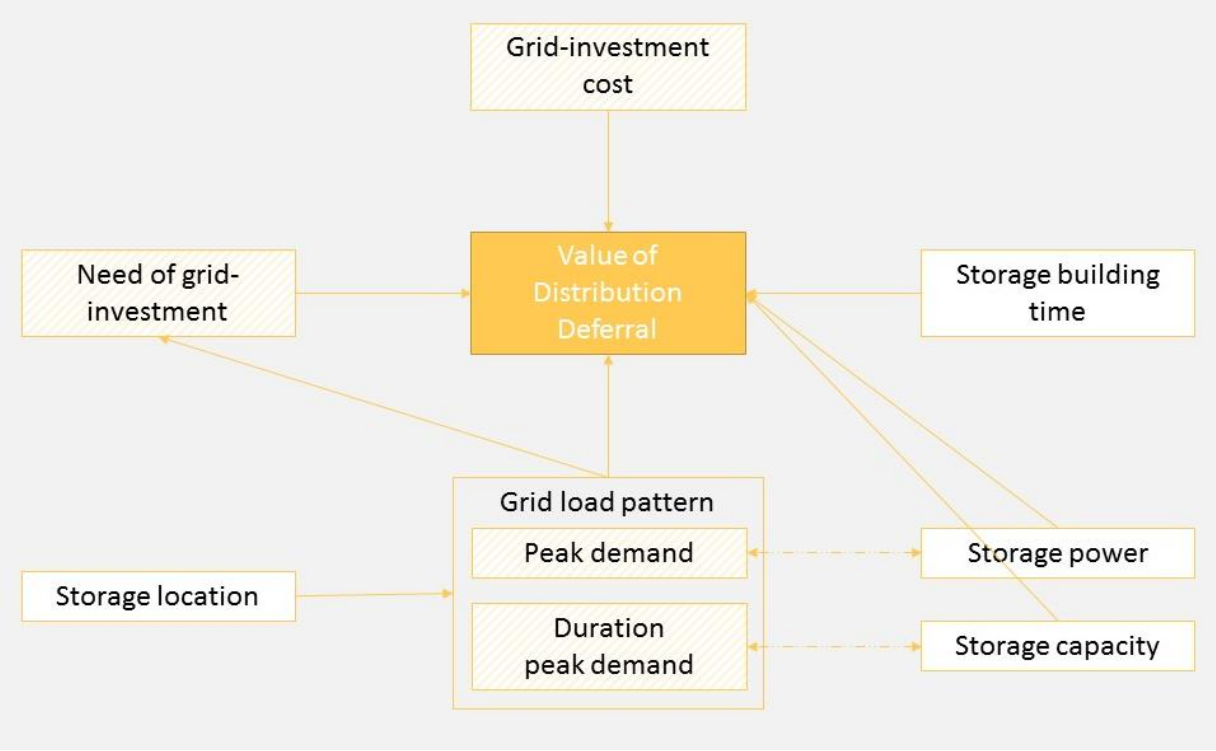

Figure 21 Causal diagram of the value of Distribution Deferral

4.3 The value of Carbon Abatement

The value of Carbon Abatement is determined using the average emissions of electricity production and the carbon price. In Subsection 4.3.1 the developments of the average emissions of electricity production and the carbon price are shown. Then, in Subsection 4.3.2 the value of the additional emissions by Delta21 are presented. After that, the value of carbon emissions by grid-scale energy storages are presented in Subsection 4.3.3. Finally, the causal system diagram of the results is shown in Subsection 4.3.4.

4.3.1 Emissions of electricity production and carbon price

The average emissions of electricity production and the carbon price are shown in Figure 22. The orange line shows on the left axis the carbon price. The blue line shows on the right axis the emissions of electricity production. This graph shows the different trends of the variables that influence the emission value per MWh extra emitted. In Figure 23 the emission value per MWh emitted is shown. This is based on the emissions of electricity production multiplied by the yearly average ETS carbon price.

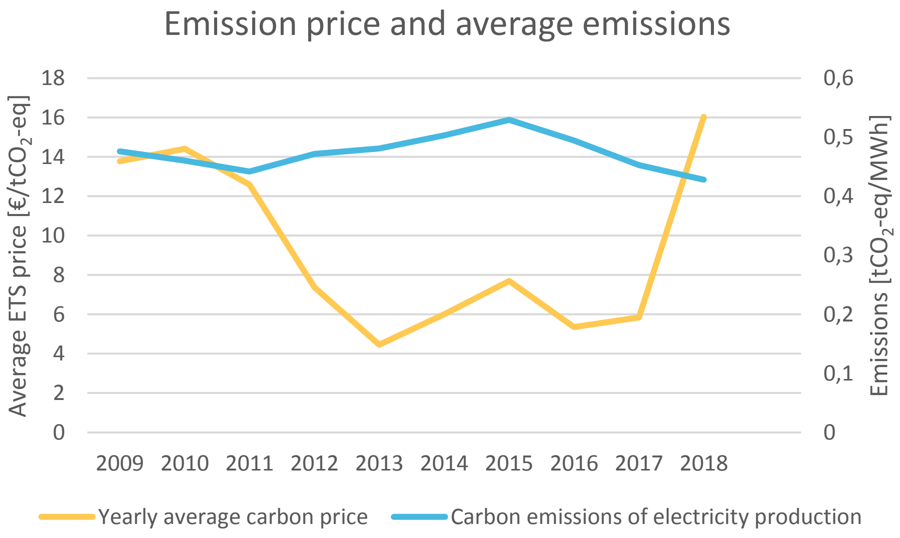

Figure 22 Emission price (ETS EU) and average emissions of electricity production in NL from 2009 to 2018

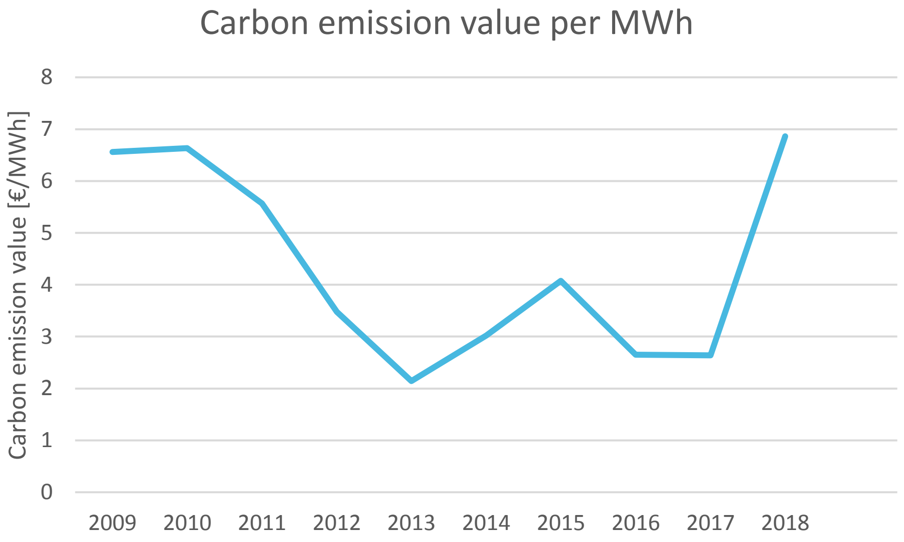

Figure 23 Carbon emission value per MWh of electricity produced in NL from 2009 to 2018

Figure 22 and 23 show that the carbon emission value mostly follows the ETS price. This is due to the higher relative changes in the ETS prices. The carbon emissions per MWh produced do not change that much. If the amount of emissions per MWh would reduce as quickly as the CO_2 price increases the value of the storage is kind of stable for the same amount of production.

4.3.2 The value of carbon emitted by Delta21

In Table 5 the years 2015 to 2018 are represented with the amount of hours that the storage would be used based on the analysis of Arbitrage. Then the total amount of MWh energy storage is shown with the assumption of full power usage. This leads to the additional energy in MWh needed due to the storage efficiency losses. Together with the amount of CO_2 emissions per MWh of electricity produced, based on the numbers from CBS. It leads to an approximation of the CO_2 emissions induced by the storage. The CO_2 emissions combined with the CO_2 price give the economic value of the carbon emissions emitted extra by the energy system due to the losses of the storage.

Table 5 Results of theoretical carbon emission value Delta21 in 2015 to 2018

Year	**Amount of hours per day**	**Total MWh**	**Additional MWh**	**Emissions of electricity production [tonne CO_2/MWh]**	**Tonne CO_2**	**CO_2 price [€/tCO_2]**	**Carbon emission value €**
2015	5	3.285.000	903.375	0,53	478.789	7,69	**3.683.566**
2016	6	3.942.000	1.084.050	0,49	531.185	5,35	**2.843.814**
2017	5	3.285.000	903.375	0,45	406.519	5,84	**2.372.948**
2018	5	3.285.000	903.375	0,43	388.451	16,03	**6.227.727**

Table 5 shows that the amount of CO_2 per MWh of electricity produced was reduced during the last four years. In 2016, however, the amount of CO_2 that would be emitted by Delta21 is higher due to the higher amount of hours that the storage is used. The carbon emission values seem to be mostly influenced by the CO_2 price.

In Figure 24 the amount of emissions of Delta21 in the years 2015 to 2018 are shown, as if it were active in that year. Figure 25 shows the value of the total emissions of that year by Delta21 in the years 2015 to 2018. These numbers correspond with the values of the sixth and eighth column of Table 5 respectively.

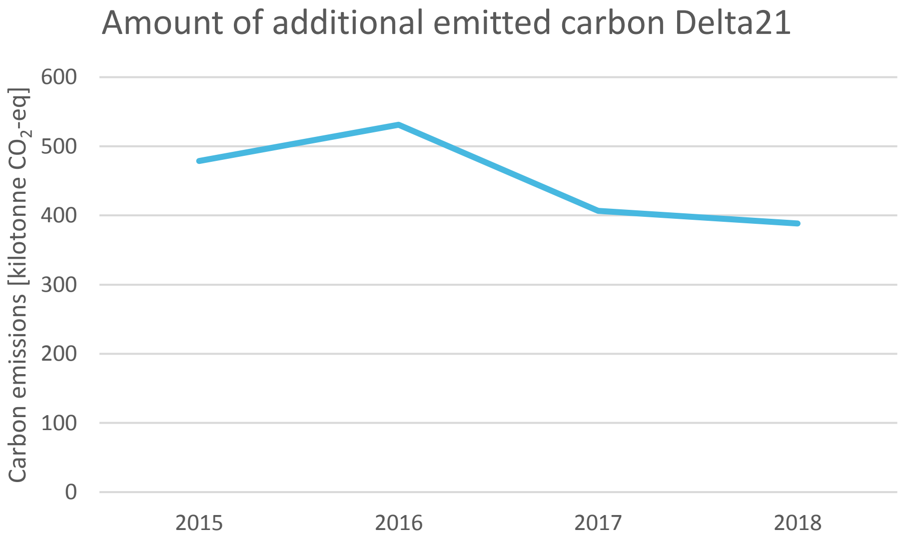

Figure 24 Amount of theoretical additional emitted carbon by Delta21 in the years 2015 to 2018

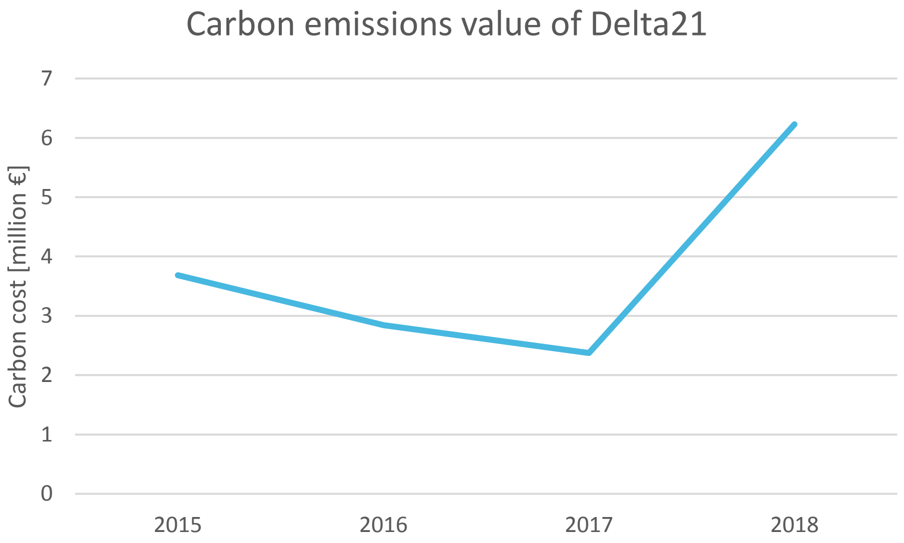

Figure 25 The value of theoretical carbon emissions of Delta21 in the years 2015 to 2018

Figure 24 and 25 show that although the amount of emissions of Delta21 could decrease, the value can still increase. This is related to the increase in the CO_2 price in 2018. This also shows that if the amount of emissions of electricity production does not decrease, the negative carbon abatement value will increase.

4.3.3 The value of carbon emissions of grid-scale energy storage

The method that was applied to Delta21 is also applied to the different efficiency levels that a Pumped Hydro Storage can have. In Figure 26 the amount of additional emitted carbon is shown over the years 2015 to 2018. The lines represent the different efficiency levels. In Figure 27 the value of the carbon emissions is shown over the years 2015 to 2018.

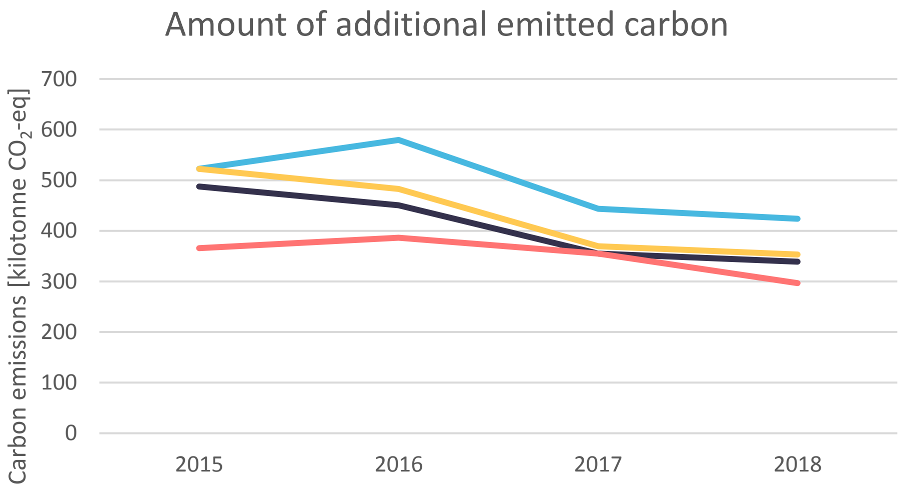

Figure 26 Amount of additional emitted carbon in the years 2015 to 2018 for different efficiency levels

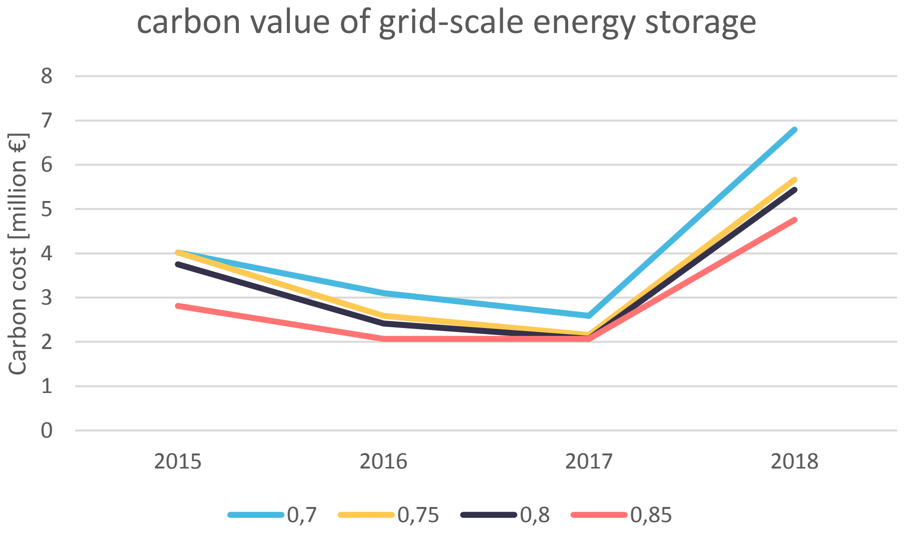

Figure 27 Value of carbon emissions by grid-scale energy storage in the years 2015 to 2018 for different efficiency levels

The graphs in Figure 26 and Figure 27 show that the higher the efficiency the lower the additional emitted carbon due to the storage losses. It also shows that with a higher efficiency the carbon emissions value can be slightly reduced.

4.3.4 Causal system diagram on the value of Carbon Abatement

Figure 28 shows a causal diagram with the influences of different discussed variables on the value of Carbon Abatement. The arrows show the direction of the causal link and the plus or minus shows the relation. A plus indicates that if the one variable increases it increases the other variable. A minus indicates that if the one variable decreases the other variable increases and vice versa. Some of the arrows do not have a plus or minus, this is to indicate that there is a relation between the variables, but the relation is unclear or cannot be defined by a plus or minus. Furthermore, the variable with the striped blue background is an external variable that is assumed to be not significantly influenced by other variables. At last, there is one blue arrow that is a relation discussed in the results of Arbitrage.

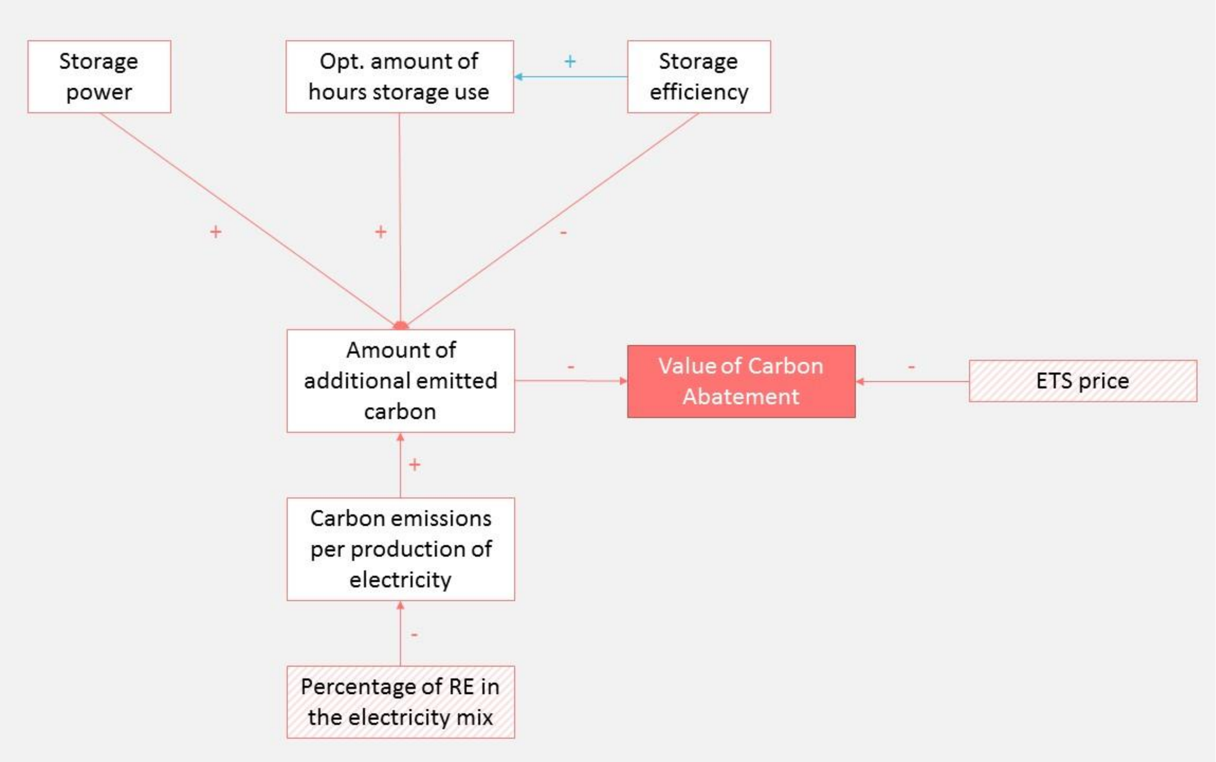

Figure 28 Causal diagram of the value of Carbon Abatement

What becomes clear in this overview is that the storage efficiency has both a negative as well as a positive influence on the value of Carbon Abatement. However, as was shown in the results in the sections before the negative relation between the storage efficiency and the amount of additional emitted carbon is stronger than the indirect positive relation between storage efficiency and amount of additional emitted carbon via the optimal amount of hours storage use for Arbitrage.

As the percentage of RE in the electricity mix is expected to grow in the coming years it will increase the value of Carbon Abatement of a storage. However, as the ETS price is likely to increase due to the reduced amount of available emission certificates this can decrease the value of Carbon Abatement of a storage.

4.4 The relations between the values of the services

To understand the relations between the values of the different services a causal diagram is used to visualise the relations. In the diagram, in Figure 29, the different services are presented in different colours. The coloured relations are the relations discussed in the different result sections of the services. The lightly striped variables are the external variables and the full coloured are the value of the services. The diagram shows the overlapping variables that are in all the previous causal diagrams in the black outlined boxes.

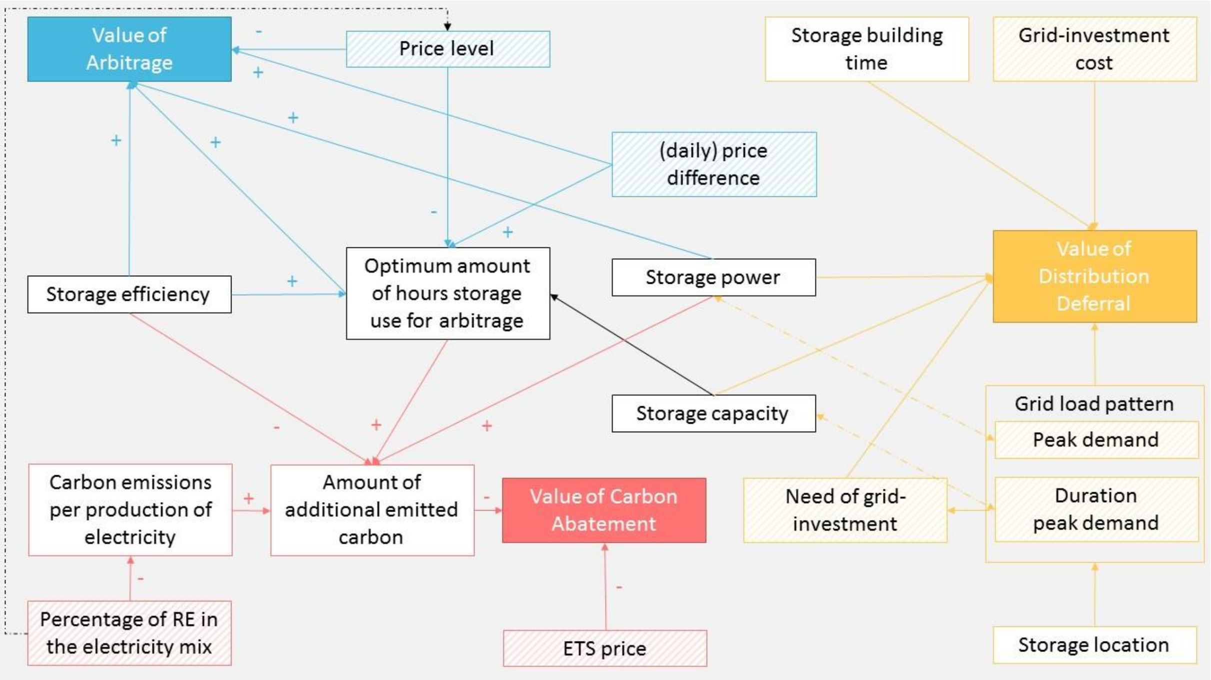

Figure 29 Causal diagram of the values of the different services

The diagram shows that the overlapping variables are the variables that are properties of the storage or influenced by the properties of the storage. The important overlaps will be discussed per storage property below.

Storage efficiency has a positive influence on both the value of Arbitrage and the value of Carbon Abatement. As was shown in section 4.1 and section 4.3 it has a high influence on the value of Arbitrage and Carbon Abatement. However, in the analysis of the valuation of Distribution Deferral the direct influence of storage efficiency is not found.

Optimum amount of hours storage use for Arbitrage has a positive influence on Arbitrage. This means that the higher the optimum amount of hours is the more Arbitrage value there is. However, the amount of hours that the storage is used has a negative influence on the value of Carbon Abatement. This is due to that the more hours the storage is used to store energy the more efficiency losses occur and the more carbon is emitted in the current market.

The optimum amount of hours storage use is limited by the storage capacity. The storage capacity is then linked to the value of Distribution Deferral. The storage capacity determines the duration of the peak demand reduction the storage can generate.

The power of the storage also has a positive influence on the value of Arbitrage, but a negative influence on the value of Carbon Abatement. Furthermore, the power of the storage is connected to the peak demand the storage can reduce on the grid for Distribution Deferral.

Then there is also the influence of the percentage of Renewable Energy (RE) in the electricity mix which influences the amount of carbon emissions per production unit of electricity. It also influences the price level of the electricity market, as the short run marginal cost of Renewable Energy is close to zero. The price level of the electricity market reduces due to the merit order effect, as discussed in Section 2.2.2.

5. Discussion and recommendations

This chapter discusses in Section 5.1. how the results are in relation to the discussed literature. In Section 5.2 there is reflection on the important assumptions. Then in Section 5.3 recommendations to both Delta21 as RWE are given. Concluding with further research recommendations in Section 5.4.

5.1 Discussion

In Section 4.4 the most important results are summarized and linked to each other in Figure 29. In this section, the discussion, the results are placed in context of the theory and previous research and the implications are discussed.

The results show that both storage properties and the daily price pattern influence the Arbitrage profit. In line with the literature discussed in Section 2.1.1 the properties efficiency, amount of hours to charge and discharge and power have a positive influence on the amount of Arbitrage profit. However, different from the literature is that in this research it was found that the amount of hours to use the storage on a day to charge and discharge has a certain optimum and that that optimum is dependent on the efficiency. Bolado et al. (2014) found that increasing the amount of (dis)charge hours would increase the amount of profit, but the growth rate of this increase stabilizes. This could be due to the fact that Bolado et al. (2014) do not use an optimization over 24 hours. It is however, not really clear from their paper how the (dis)charge duration is used in the model to understand the full implications.

The influence of the price pattern on the Arbitrage profit was in the literature only discussed as the absolute price difference that has a positive influence on the profit. This influence was discussed in the research of Bolado et al. (2014) and used in the research of Sidhu et al. (2018). However, in this research it became clear that next to the absolute price difference the average price level has an influence on the Arbitrage profit. This result is in line with the calculations that Connolly et al. (2011) used to determine when to buy and sell based on price predictions.

The results of the analysis in the value of Distribution Deferral show that there is value in the location of energy production. However, this is not valued at the moment. Due to not valuing the location of energy production and storage a suboptimal system can emerge, when looking at the whole of the electricity system. There are limited incentives to have demand and supply of electricity close to each other. Generally, production of electricity is placed on ground that is cheap and - depending on the technology - where there is sufficient solar or wind. This induces problems for TenneT for the connections in the North and South of the Netherlands. Investments in expansion of the grid or in storage are needed to solve the congestion problems in the regions.

The results of the analysis in the value of Carbon Abatement show that on the short term the carbon emissions increase. This is in contradiction with the research of Sidhu et al. (2018) in which a carbon reduction is used. However, the source from which the reduction is derived cannot be accessed anymore. Furthermore, this research used a simple calculation method for which the information was available and so no reduction could be calculated with this calculation method.

5.2 Limitations

For Arbitrage the storage is analysed as a price taker. This is an assumption that is likely to hold for the analysis of one storage. However, when more storages enter the market one could expect cannibalisation. This cannibalization is due to the fact that the price pattern, like the one in Figure 18, will change. The price peaks and valleys will reduce and increase, i.e. flatten, and eventually will no longer cross the red lines of Figure 18. This will influence the business case of the storages.

For Distribution Deferral the calculation methods found where not applicable to this case. There was no data available on the load profiles of the high voltage grid. The analysis is purely done on the interviews and literature found and interpretation of this literature.

For Carbon Abatement a calculation method was used that can only calculate the short term increased energy and uses the average emissions of the energy to calculate the emissions. There was no information found on the marginal emissions of certain times of charging and discharging. This would provide a better estimate on the amount of emissions that the storage would emit.

The approach of assessing the total value of a storage based on the values of different services has a downside. It is not always true that the value of a good or object is the summation of all the services or parts. There could be services not covered or the totality of the parts can provide more than all the parts apart from each other. However, it is an approach that does not involve analysing the system as a whole, but rather one storage facility.

5.2 Recommendations

In Subsection 5.2.1 the practical recommendations for the case of Delta21 will be given and applied to the SWOT analysis. In Subsection 5.2.2 the recommendations for RWE Generation – Innovation and Technology are presented.

5.2.1 Recommendations Delta21

In order to advise Delta21 on the steps they can take, a SWOT analysis is done on the electricity storage part of their project. Based on the SWOT some recommendations follow. The complete SWOT can be found in Table 6. The different recommendations will be explained below the table.

Table 6 SWOT analysis Delta21

SWOT analysis		**Recommendations**
Internal	**Strengths:** - High Technology Readiness Level - High power and capacity - Beneficial to multiple stakeholders by combination of purposes	
	Weaknesses: - Low efficiency (for PHS) - Short term CO_2 increase	R1: Investigate higher efficiency PHES R2: Research if capacity lowering could provide lower investment cost
External	**Opportunities:** - Wind park connections - Developments in the north of NL on valuation of grid investment deferral - Expected growth of Renewable Energy	R3: Wind park connections with storage can provide lower grid connections. See if valuation is possible. R4: Get involved in the developments of grid investment deferral.
	Threats: - Other storage projects that enter the market - Connection cost – no grid deferral valuation	

R1: Investigate higher efficiency PHES

The currently planned storage has a round trip efficiency of 72,5%. This is not that high for a pumped hydro plant. The latest pumped hydro plants have efficiencies of around 85%. Investigating the possibilities of a higher efficiency and associated costs could provide a lot of benefits. A higher efficiency would increase the Arbitrage profits and lower the additional carbon emissions in the system due to storage losses. Both are significantly valuable.

R2: Research if capacity lowering could provide lower investment cost

At this moment the capacity of the pumped hydro storage is 12 hours of storage on full power. However, for Arbitrage on a daily basis this is too much. Research if a smaller lake would decrease investment cost and try to optimize between Arbitrage profits and investment cost. However, it is strongly advised in this particular case to first focus on the water safety requirements first and then optimize on the energy storage trade-offs.

R3: Wind park connections with storage can have smaller grid connections. See if valuation is possible

A large amount of connections of wind parks at sea need to be made. A wind park in combination with storage can have a lower connection power due to the peak shaving character of the storage. The connection of the wind park and storage could even be combined. This could provide lower grid-connection cost. In this case (part of) the grid deferral is valued.

R4: Get involved in the developments of grid investment deferral

Currently, there is a vast amount of developments in the area of grid investment deferral. TenneT foresees problems in the North and the South of the Netherlands. At this moment there is a market consultation ongoing on how to approach the problems with congestion management in the North of the Netherlands. It is believed to be wise to get involved and follow the updates on how this market problem will be solved.

5.2.2 Recommendations RWE Generation Technology and Innovation

A recommendation is to decide on a strategic level on what kind of role storage will play in the energy market (in the future) and if they want to partake in that role. If they would want to partake in that role, it is important to understand how a storage can create value in their portfolio of energy production. In this thesis the value of Arbitrage is researched. However, as discussed in Section 2.2.1 there are other markets and Ancillary services which a storage can provide. Furthermore, in a portfolio of an energy producer a storage could also handle the insecurities of wind and solar energy production. Which are becoming a more important part of the portfolio.

Furthermore, when RWE wants to invest in storage a few more practical recommendations can be made. When designing a storage or choosing a storage type for on the energy market investigate the ratio between the efficiency and the capacity of the storage and how this influences the profit on that market. When designing a storage or choosing a storage for behind-the-meter explore the load peak and peak duration that could be reduced and the corresponding power and capacity to match this function.

At last, there is a risk of cannibalization of the business cases of storage on the energy trading markets, like the day-ahead. I would propose to research the best business cases of different storage mediums and its sensitivity to changes in the energy markets.

5.3 Further Research

There are many opportunities for further research on this topic. A few that are identified based on this research and will be shortly explained.

First, as it was pursued to find future scenarios on the price development of electricity none were found that could be applied to this research. As the value of Arbitrage from a storage for the owner is actually the expected profit, it is important to put the results into future perspective. Furthermore, scenarios on how the price patterns and electricity markets will behave would provide insight in the value of storage. This can be done by analysis on the price patterns of other countries that have similar markets but already have higher renewable energy. It could also be done by using an Agent Based Model for the energy system. This would also provide the possibilities to test different scenarios or maybe subsidy types.

Second, in this research it was found that there are almost no methods on how to determine the Distribution Deferral. As it is currently not marketable thus not often discussed. More research into the value of Distribution Deferral and how to determine this value would improve science, but could also be of use in practical ways. Currently, it is not valued in the system, but there is significant and evident value. The advice would be to start collecting more data about the load and more specifically load peaks of the system, especially in the area's with a lot of congestion.

Third, in the research on Carbon Abatement it was found that on the short term carbon emissions increase. It would be interesting to analyse when there is enough Renewable Energy in the system that a storage can provide abatement of the emissions.

6. Conclusions

The main research question is:

"How can the (economic) value of services provided by grid-scale energy storage in the Dutch electricity systems be determined?"

This thesis used an approach to assess the value of a grid-scale storage by determining the value of the different services that the storage can provide. The services that a grid-scale energy storage can provide are mainly Arbitrage, Distribution Deferral and Carbon Abatement. This leads to a sub-question on each of the services and a sub-question about the link between the services.

1. *How can the economic value of Arbitrage provided by grid-scale energy storage in the Dutch electricity system be determined?*

Arbitrage creates economic value by shifting load from peak load to low load by buying during low prices and selling during high electricity prices. A strategy of buying and selling can be tested on former years and predictions of Arbitrage profit can be made to determine the value. In this thesis a strategy is developed that uses previous years to determine on which hour of a specific day and month the storage owner should buy or sell energy. Right now, this approach can be taken due to the fact that the electricity price mostly fluctuates over the day and the season. In the future it can be expected that the electricity price will more and more depend on weather patterns.

This research and analysis show that efficiency and the amount of hours per day that a storage is used to charge and discharge have a strong influence on the amount of profit that can be made with Arbitrage on the Dutch day-ahead market. Furthermore, this research shows that there is an optimum in the amount of storage capacity dependent on the efficiency of the storage . The lower the efficiency the less hours the storage can be used in the market to make profit from Arbitrage.

Efficiency influences the amount of Arbitrage profit via two ways. Thus efficiency is an important variable of the storage for the amount of value that can be achieved via Arbitrage.

2. *How can the economic value of Distribution Deferral provided by grid-scale energy storage in the Dutch electricity system be determined?*

At this moment Distribution Deferral is not valued in the economic system. The economic system only charges for the needed infrastructure to connect the storage and the delivery on the grid. However, a storage can provide investment deferral in the grid due to load shifting of peaks to valleys. There is almost no research into the Distribution Deferral by grid-scale storage on the high voltage network.

To value Distribution Deferral only two different methods are found. One is based on the value of the grid investment that otherwise should be done and can only be used when the storage project is an alternative for grid investments. The second one is a project with multiple batteries on the low voltage network. Both are not relevant for a stand-alone project that should be connected to the high voltage network.

However, based on the found literature and conversations with experts the following conclusions can be made. First, there is a value in the location of storage. However, this is currently not valued in the economic system. TenneT currently experiences congestion problems in the North due to the high increase in solar energy production. Storage can provide congestion management by reducing load peaks and so reducing the need for grid investment. Second, there is value in the building time of a storage. This is due to the obligation of TenneT to make sure there is a connection within four years after application, without compromising the stability of the grid. If a storage can be built within four years and is more economically interesting than investments in the grid this could be an added value.

Concluding, this research question cannot be answered. However, the research shows there is economic value that should be considered by the energy sector and there is a need for a way to value this in the current electricity market.

3. *How can the economic value of Carbon Abatement provided by grid-scale energy storage in the Dutch electricity system be determined?*

There are many different ways to determine Carbon Abatement or enlargement. It depends mainly on the scope and scale and the approach that is taken.

In short term one could argue that storage adds carbon due to efficiency losses and the increase of electricity demand during low price hours. One could use the merit order or a model to calculate this addition precisely. In the long term the energy system has an increase in curtailment, if an increase in renewable energy is expected. The storage would decrease carbon emissions when a storage facility transports energy over time that would otherwise be wasted.

The value of Carbon Abatement is negative in the short term due to the added electricity demand, caused by the efficiency losses of the storage. To reduce the short term additional carbon emissions a higher efficiency is important. The higher efficiency even compensates for the extra hours that the storage is used for Arbitrage. So, a higher efficiency leads to lower amounts of short term carbon emissions, while using the storage more hours per day.

4. *How do the values of the services (abovementioned) relate to each other?*

The values of services relate in different ways. First there are multiple storage properties that influence multiple service values. Mostly Arbitrage and Carbon Abatement relate greatly to each other in this way. The amount of power and the amount of hours use per day increase the value of Arbitrage to a certain optimum. However, those decrease the value of Carbon Abatement due to the short term emissions by the losses of the energy stored. Increasing efficiency, however, has a positive influence on both of the values, as it decreases carbon emissions and decreases energy losses for selling and buying.

Second, the service of Arbitrage and Distribution Deferral are closely related. The service of Arbitrage has a load levelling outcome. This load levelling can reduce the need for grid investments. It is complicated to determine whether the valuation of Arbitrage already values this load levelling or that it is a positive externality.

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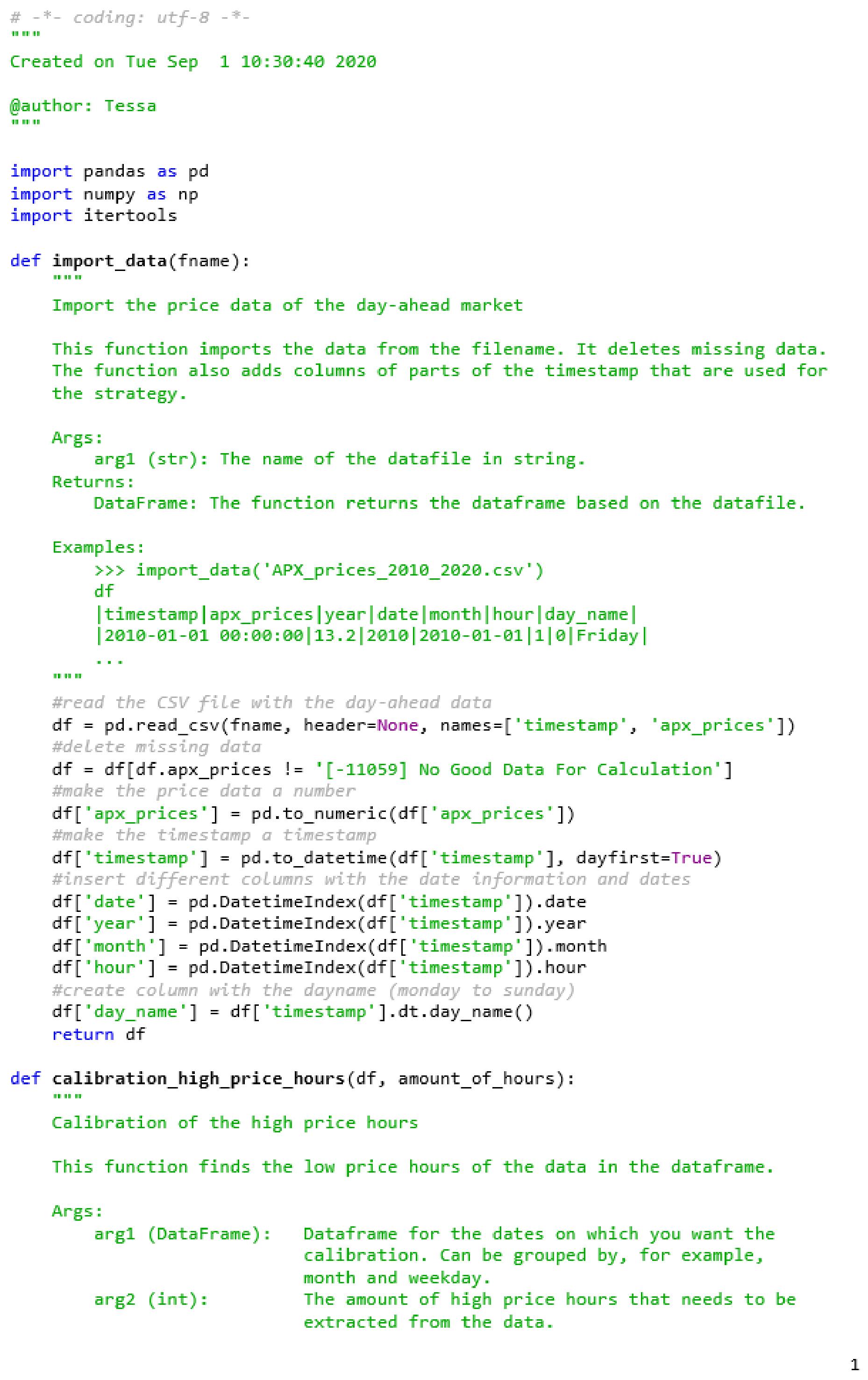
Appendices

Appendix A. Code of the time based strategy for Arbitrage

The code of the strategy is presented in this appendix. First, the function file is shown in which all the functions are described. Then, the execution file with the different analysis is shown in which the functions from the function file are used.



```python
# -*- coding: utf-8 -*-
"""
Created on Tue Sep  1 10:30:40 2020

@author: Tessa
"""

import pandas as pd
import numpy as np
import itertools

def import_data(fname):
    """
    Import the price data of the day-ahead market

    This function imports the data from the filename. It deletes missing data.
    The function also adds columns of parts of the timestamp that are used for
    the strategy.

    Args:
        arg1 (str): The name of the datafile in string.
    Returns:
        DataFrame: The function returns the dataframe based on the datafile.

    Examples:
        >>> import_data('APX_prices_2010_2020.csv')
        df
        |timestamp|apx_prices|year|date|month|hour|day_name|
        |2010-01-01 00:00:00|13.2|2010|2010-01-01|1|0|Friday|
        ...
    """
    #read the CSV file with the day-ahead data
    df = pd.read_csv(fname, header=None, names=['timestamp', 'apx_prices'])
    #delete missing data
    df = df[df.apx_prices != '[-11059] No Good Data For Calculation']
    #make the price data a number
    df['apx_prices'] = pd.to_numeric(df['apx_prices'])
    #make the timestamp a timestamp
    df['timestamp'] = pd.to_datetime(df['timestamp'], dayfirst=True)
    #insert different columns with the date information and dates
    df['date'] = pd.DatetimeIndex(df['timestamp']).date
    df['year'] = pd.DatetimeIndex(df['timestamp']).year
    df['month'] = pd.DatetimeIndex(df['timestamp']).month
    df['hour'] = pd.DatetimeIndex(df['timestamp']).hour
    #create column with the dayname (monday to sunday)
    df['day_name'] = df['timestamp'].dt.day_name()
    return df

def calibration_high_price_hours(df, amount_of_hours):
    """
    Calibration of the high price hours

    This function finds the low price hours of the data in the dataframe.

    Args:
        arg1 (DataFrame):   Dataframe for the dates on which you want the
                            calibration. Can be grouped by, for example,
                            month and weekday.
        arg2 (int):         The amount of high price hours that needs to be
                            extracted from the data.
```

```
    Returns:
        list:   The function returns a list with the high price hours for each
                group.

    Examples:
        >>> calibration_high_price_hours(df, 8)
        [8, 9, 10, 11, 12, 17, 18, 19]
    """
    #Each unique date is used, these are groups with 24 numbers of price data
    df = df.groupby('date')
    #For each date find the n hours with the largest price, where n is defined
    #by amount_of_hours
    high_price_hours = df.apply(
            lambda grp: grp.nlargest(amount_of_hours, 'apx_prices'))
    #Count for each hour how often it is in the data set. Select the n hours
    #that are the most often in highest_price_hours.
    #Return those n hours in a list
    high_price_hours = (
            high_price_hours['hour'].value_counts().nlargest(amount_of_hours)
            .sort_index().index.tolist()
            )
    return high_price_hours

def calibration_low_price_hours(df, amount_of_hours):
    """
    Calibration of the low price hours

    This function finds the low price hours of the data in the dataframe.

    Args:
        arg1 (DataFrame):   Dataframe for the dates on which you want the
                            calibration.
        arg2 (int):         The amount of low price hours that needs to be
                            extracted from the data.
    Returns:
        list:   The function returns a list with the low price hours for each
                group.

    Examples:
        >>> calibration_low_price_hours(df, 8)
        [0, 1, 2, 3, 4, 5, 6, 23]
    """
    #Each unique date is used, these are groups with 24 numbers of price data
    df = df.groupby('date')
    #For each date find the n hours with the smallest price, where n is defined
    #by amount_of_hours
    low_price_hours = df.apply(
            lambda grp: grp.nsmallest(amount_of_hours, 'apx_prices'))
    #Count for each hour how often it is in the data set. Select the n hours
    #that are the most often in highest_price_hours.
    #Return those n hours in a list
    low_price_hours = (
            low_price_hours['hour'].value_counts().nlargest(amount_of_hours)
            .sort_index().index.tolist()
            )
    return low_price_hours

def execution_selling_and_buying(df, high_price_hours, low_price_hours):
    """
    Execution of the buying and selling on the execution year
```

```
    This function finds the prices for which electricity is sold and bought in
    the high and low price hours.

    Args:
        arg1 (DataFrame):   Dataframe for the dates on which you want to
                            execute the buying and selling in the given hours.
        arg2 (list):        The list with the high_price_hours
        arg3 (list):        The list with the low_price_hours
    Returns:
        list:   The function returns a list with the sum of selling and the sum
                of buying prices

    Examples:
        >>> execution_selling_and_buying(df, [8, 9, 10, 11, 12, 17, 18, 19],
                                         [0, 1, 2, 3, 4, 5, 6, 23])
        [610.05, 396.11]
    """
    #The sum of the apx_prices of the dataframe \
    #for the hours in high price hours
    total_selling = df[(df.hour.isin(high_price_hours))]['apx_prices'].sum()
    #The sum of the apx_prices of the dataframe
    #for the hours in low price hours
    total_buying = df[(df.hour.isin(low_price_hours))]['apx_prices'].sum()
    return total_selling, total_buying

def strategy(df, calibration_years, execution_year,
             strategy_hours, efficiency):
    """
    Strategy of buying and selling of a storage on the day-ahead market

    This function is the strategy of buying and selling electricity based on
    the dataframe with electricity prices. It uses the functions
    calibration_high_price_hours and calibration_low_price_hours to determine
    when to buy and sell. Then it uses the function
    execution_selling_and_buying to used the hours of high and low prices
    to buy and sell and find the corresponding prices in the execution year.


    Args:
        arg1 (DataFrame):   Dataframe for the dates on which you want the
                            calibration. Can be grouped by, for example,
                            month and weekday.
        arg2 (list):        The amount of high price hours that needs to be
                            extracted from the data.
        arg3 (int):         The year on which the strategy is applicated.
        arg4 (int):         The amount of hours to buy and sell per day.
        arg5 (float):       The efficiency of the storage.
    Returns:
        float:  The function returns a list with the high price hours for each
                group.

    Examples:
        >>> strategy(df, [2010, 2011, 2012, 2013, 2014], 2019, 3, 0.7)
        1218,8019
    """
    #df_calibration is the df with the years in the calibration_years and
    #grouped by the month and day_name
    df_calibration = df[(df.year.isin(calibration_years))].groupby(['month',
                        'day_name'])
```

```
    #apply to each group, so each weekday and month combination,
    #the function calibration_high_price_hours
    high_price_hours = df_calibration.apply(calibration_high_price_hours,
                                            amount_of_hours=strategy_hours)
    #apply to each group, so each weekday and month combination,
    #the function calibration_low_price_hours
    low_price_hours = df_calibration.apply(calibration_low_price_hours,
                                           amount_of_hours=strategy_hours)
    #create a list of all the weekday and month combinations
    iteratelist = itertools.product(df['month'].unique(),
                                    df['day_name'].unique())
    #df_execution is the df with only the year of execution
    df_execution = df[(df.year == execution_year)]
    #applying the function execution_selling_and_buying
    #for each month and day combination
    #on the df_execution with the high_price_hours and low_price_hours
    buying_selling_list = [execution_selling_and_buying(
            df_execution[(df.month == month) & (df.day_name == day)],
            high_price_hours.loc[month, day],
            low_price_hours.loc[month, day]) for month, day in iteratelist]
    #splitting the results in the buying and selling_list into two list
    total_selling, total_buying = np.hsplit(np.array(buying_selling_list), 2)
    #calculating the profit for each day by multiplying the efficiency
    #to the total selling
    profit_list = efficiency * total_selling - total_buying
    #returning the sum of the profit list,
    #which is the arbitrage profit for the execution year
    return profit_list.sum()

def create_results(df, hour_list, efficiency_list, calibration_years,
                   application_year, csv_name):
    """
    Creating the results of the analysis

    This functions creates the results of a calibration combination on a
    application year for all the different combinations of efficiency levels
    and hours that are entered.

    Args:
        arg1 (DataFrame):   Dataframe with the price data,
                            imported with the function import_data .
        arg2 (list):        The list with the amount of hours that
                            the electricity storage is used.
        arg3 (list):        The different efficiency levels the storage can
                            have in a list.
        arg4 (list):        The calibration years that are used to calibrate
                            the strategy on.
        arg5 (int):         The year on which the strategy is applicated.
        arg6 (str):         The name of the csv in which the results will be
                            stored.
    Returns:
        csv-file:   The function returns a csv with the results
                    from the analysis.

    Examples:
        >>> create_results(df, range(1,13), [0.7, 0.75, 0.8, 0.85],
                           [2010, 2011, 2012, 2013, 2014], 2019,
                           'results2019.csv')
        results2019.csv
        |index|charge_duration|efficiency|profit|year|
```

```
    |0|1|0.7|820.851|2019|
    ...
"""
#Create a list of combinations of hours and efficiency
test_loop = list(itertools.product(hour_list, efficiency_list))
#Use the list to execute the strategy function on and create a list
#with results for every hour and efficiency combination
temp_result = [strategy(df, calibration_years, application_year, hour,
                        efficiency) for hour, efficiency in test_loop]
#Create dataframe with the loop in the colums
df_all_result = pd.DataFrame(test_loop,
                             columns = ['Charge_Discharge_Hours',
                                        'Efficiency'])
#Add the different profit results to the dataframe
df_all_result['Profit'] = temp_result
#Add the application year to the dataframe
df_all_result['Year'] = application_year
#Export the results to a csv
df_all_result.to_csv(csv_name)
```

```python
# -*- coding: utf-8 -*-
"""
Created on Tue Sep  1 10:29:51 2020

@author: Tessa
"""

import pandas as pd
import itertools
import random
import functions_final

fname = 'APX_prices_2010_2020.csv' #name of the file with the data
df = functions_final.import_data(fname) #import and prepare data

#%% Create random calibration year combinations
#the calibration is executed on the year 2019
application_year = 2019
#set the random seed for repeating the same process
random.seed(100)
#get the years that can be used, that is all the years in the dataframe
#without the application year
years = df[df.year != application_year].year.unique()
#make a list of all the combinations with 5 different years
calibration_option = list(itertools.combinations(years, 5))
#select 4 random calibration years combinations
calibration_option = random.sample(calibration_option, 4)

#%% Calibration execution
#Variable inputs
hour_list = range(1,13)
efficiency_list = [0.70, 0.75, 0.80, 0.85]
application_year = 2019
#Create the results of the analysis in 5 different CSV.
#This is done considering memory and speed limits.
#Tip: do the analysis one by one rule
functions_final.create_results(df, hour_list, efficiency_list,
                               [2014, 2015, 2016, 2017, 2018],
                               application_year, 'results_2019a.csv')
functions_final.create_results(df, hour_list, efficiency_list,
                               calibration_option[0],
                               application_year, 'results_2019b.csv')
functions_final.create_results(df, hour_list, efficiency_list,
                               calibration_option[1],
                               application_year, 'results_2019c.csv')
functions_final.create_results(df, hour_list, efficiency_list,
                               calibration_option[2],
                               application_year, 'results_2019d.csv')
functions_final.create_results(df, hour_list, efficiency_list,
                               calibration_option[3],
                               application_year, 'results_2019e.csv')

#%% Analysis grid-scale energy storage
#Variable inputs
hour_list = range(1,13)
efficiency_list = [0.70, 0.75, 0.80, 0.85]
calibration = [2010, 2011, 2012, 2013, 2014]
#Create the results of the analysis in 5 different CSV.
#This is done considering memory and speed limits.
#Tip: do the analysis one by one rule
```

```
functions_final.create_results(df, hour_list, efficiency_list, calibration,
                               2015, 'results_2015_test.csv')
functions_final.create_results(df, hour_list, efficiency_list, calibration,
                               2016, 'results_2016.csv')
functions_final.create_results(df, hour_list, efficiency_list, calibration,
                               2017, 'results_2017.csv')
functions_final.create_results(df, hour_list, efficiency_list, calibration,
                               2018, 'results_2018.csv')
functions_final.create_results(df, hour_list, efficiency_list, calibration,
                               2019, 'results_2019.csv')

#%% Analysis Delta21
#Variable inputs
hour_list = range(1,13)
efficiency = 0.725
calibration = [2010, 2011, 2012, 2013, 2014]
application_years = [2015, 2016, 2017, 2018, 2019]
#Create results, with one level of efficiency
test_loop = list(itertools.product(hour_list, application_years))
temp_result = [functions_final.strategy(
        df, calibration, application_year, hour, efficiency
        ) for hour, application_year in test_loop]
df_all_result = pd.DataFrame(test_loop,
                             columns = ['Charge_Discharge_Hours', 'Year'])
df_all_result['Profit'] = temp_result
df_all_result['Efficiency'] = efficiency
df_all_result.to_csv('results_2015_2019_Delta21.csv')
```

Appendix B. Interview with TenneT

In this appendix the report of the interview with TenneT is shown. As the interview was in Dutch, the report is also in the Dutch language.

Interviewverslag TenneT

Onderdeel van de Master Thesis van Tessa Rombouts

Auteur: Tessa Rombouts

Geïnterviewde: Alan Croes, Sr. Manager Corporate Asset Owner, Tennet

Andere aanwezigen: Huub Lavooij & Leen Berke, Delta21

Datum interview: 06-04-2020

Medium van interview: Videoconference, WebEx van TenneT

Gespreksverslag:

Hoe ziet de TenneT de rol van energieopslag in de periode 2030-2050?

Energieopslag is een cruciaal onderdeel van het hele energiesysteem. TenneT verwacht een veel grotere rol voor energieopslag dan de rol die het in het huidige net speelt. TenneT is niet de enige afnemer van energieopslagservices. De markt heeft, in de toekomst, klanten die gedurende de periode van minder productie door wind- en zonne-energie vraag hebben naar elektriciteit. Deze klanten zullen zorgen voor vraag naar opslag. Het uitgangspunt is dat het grootste deel van de opslag buiten TenneT om zal lopen. Een elektriciteits- of energieleverancier heeft afspraken met hun afnemer(s) voor energielevering deze zullen ze ook moeten voldoen gedurende de periodes van minder productie door hernieuwbare energie. TenneT speelt alleen een rol in de fouten in productie en vraag afstemming. Het grootste onderdeel, zo'n 80 a 90 procent van de energieopslag zal dan buiten TenneT omgaan.

Hoeveel grootschalige opslag verwacht de TenneT de komende aantal jaren (2030 en 2050)?

Het is een kip-en-ei-verhaal. Wat moet er eerst komen? Opslag of meer zon- en windenergie. Hoe kunnen we ervoor zorgen dat er meer gebeurt bij opslag en dat het niet alleen maar op locatie plaatsvindt. Flexibiliteitsopties worden op een open acces manier ontsloten en partijen moeten elkaar kunnen vinden.

Er is nog wel een discussie met EZK (Ministerie van Economische Zaken) over wat te doen met situaties die maar eens in de 5 of 10 jaar voorkomen. Op dit moment is er ook strategische opslag van olie. In de toekomst zijn we waarschijnlijk afhankelijk van het weer en minder van olie en gas toevoer. Het zou kunnen dat TenneT een opslag nodig heeft die eens in de 5 of 10 jaar gebruikt zou moeten worden gedurende bijvoorbeeld een Dunkelflaute.

Opslag zou kunnen helpen voor het optimaliseren van het energiesysteem. Hoe kun je de waarde bepalen van dit optimaliseren?

Wat we nu zien is dat er veel zon productie verwacht wordt in gebieden met weinig activiteiit, dus weinig infrastructuur. Door opslag systemen, bv batterijen, kun je dan de productie in 8uur met een lagere piek verdelen over 24uur. Daarmeekun je de noodzaak voor infrastructuur ontlasten. Ook door direct naar een andere energie drager te gaan (warmte / bv waterstof) kun je de elektrische infrastructuur ontlasten. Vermeden kosten voor TenneT kunnen op dit moment niet worden toegekend aan projecten.

Op dit moment zijn we bezig met een marktconsultatie om een manier te vinden om zonne-energie met opslag te kunnen faciliteren. Deze pilot kijkt naar 2 mogelijkheden, of een opslag systeem achter de meter, of bij TenneT in de infrastructuur. Beide opties worden ook bekeken in relatie tot de mogelijke vergoedingen voor de investeringen.

Er is voor TenneT dus geen manier om grootschalige batterijprojecten een voordeel te geven wanneer er uitgestelde investeringen zijn? Bij afnemers kan dit wel, heb ik begrepen?

Producenten betalen een tarief van 0 euro voor hun aansluiting. Afnemers/Industrieparken kunnen wel een voordeel krijgen omdat ze een minder grote aansluiting nodig hebben en dus minder aansluitingskosten betalen. Op dit moment is het overigens over het algemeen goedkoper om netwerk aan te leggen en ergens anders te produceren dan energie op te slaan. Dit heeft te maken met de omzetting naar de andere energie dragen. Daarbij komen veel efficiëntie verliezen en kosten kijken. Het begint pas echt iets op te leveren als er een hoge belasting van het netwerk is en er meer flexibiliteit nodig is. In de periode van 2030 tot 2035 is er waarschijnlijk veel meer flexibiliteit nodig. Dat lijkt zoveel te zijn dat er nu al dingen moeten gebeuren om genoeg opslag te realiseren voor die periode.

Wat is de waarde van bijvoorbeeld een NorNed kabel, waar eigenlijk ook opslagmeren achter zitten?

Waarde van NorNed tot op heden zit in het verlagen van de Wholesale prijs op de Nederlandse net. De waarde van NorNed zit niet in flexibiliteit. Het geeft de mogelijkheid om goedkoop stroom inkopen en het heeft z'n investering in 8 à 9 jaar terugbetaalt. Het heeft dus vooral invloed op de elektriciteitsmarkt. Verder kopen de Noren soms in van het Nederlandse net, wanneer er krapte is op hun waterbekkens. Dit is vaak voor hun goedkoper dan het opstarten van energiecentrales. Het is dus een Wholesalemarktinstrument. Het zorgt voor een verdeling van elektriciteit van lage prijszone naar hoge prijszone. Op de intraday market wordt ook gehandeld met de mogelijkheden van NorNed, dit zou je wel onder de flexibiliteitsproducten kunnen scharen.

Hoe waardeert de TenneT het uitstellen (of vermindering) van investeringen in het net? (Investment Deferral)

Er wordt gezocht naar mogelijkheden. De vraag is hoe kun je nu een investering in infrastructuur koppelen aan een ander project dat er 40 jaar moet zijn. De functie van TenneT is altijd geweest om de dienst van transport voor elektriciteit te verzorgen. Als je een opslag in beheer zou hebben dan koop je elektriciteit in en dat mag TenneT niet doen. Het is misschien vergelijkbaar met de spanning op het net. Dit werd een product. Als energieproducenten niet draaien moeten ze de volle prijs betalen. TenneT kan alleen in eigen infrastructuur investeren en niet betalen voor vermeden transmissiecapaciteit. De rechten en plichten van TenneT staan hier soms in de weg om de juiste oplossing of de goedkoopste oplossing te vinden. Het framework van de energiemarkt moet op de schop waarschijnlijk als TenneT zelf in opslag moet gaan investeren. Als TenneT het als een dienst gaat inkopen hoeft het minder op de schop.

Hoe zou de waarde kunnen liggen als bijvoorbeeld een project als Delta21 gekoppeld is aan een windpark?

Windparken draaien soms wel 2 à 3 weken achter elkaar aan één stuk. Dit zou betekenen dat je opslag waarschijnlijk al snel vol zit en er nog steeds een even grote aansluiting moet liggen als het mogelijke piekvermogen. De infrastructuur is dus nodig om dat te kunnen faciliteren. De waarde van het opslagmeer zou voor TenneT meer in de mogelijke flexibiliteitsproducten en blackstart producten zitten. Dat zijn specifieke producten waar TenneT waarde aan toekent en de rol voor TenneT ligt. Verder zou het valmeer gekoppeld met een zonnepark wel waarde kunnen opleveren qua aansluiting. Zon heeft een dagritme en de piek kan goed verdeeld worden in een opslagmeer.

Een aanrader is om naar de TSO2020 cost benefit analyse te kijken. Daar staat meer achtergrond in over hoe de elektriciteitsmarkt werkt. Als er iets gebouwd moet worden omdat het noodzakelijk is voor de maatschappij dan kan het zijn dat er een vergoeding gegeven kan worden. TenneT beoogt ook een maatschappelijk belang waarbij de kosten van elektriciteit voor de maatschappij zo laag mogelijk gehouden moeten worden.

Hoe zit het met de waarde van flexibiliteit?

Iedereen is moeite aan het doen om flexibiliteit te ontsluiten. Waarde van de flexibiliteit daalt dan want bij meer flexibiliteit op de markt gaat de vraag weer omlaag. In Zeeland loopt er nu een project met een batterijsysteem. Ook zijn we als TenneT bezig met een pilot met electrolysers. Marktpartijen zien dat flexibiliteit na 2035 nodig gaat zijn. De flexibiliteitsmarkt neemt qua omvang toe. Hij is commercieel nog niet erg aantrekkelijk op dit moment. Investeren in innovatie is duur dus bijvoorbeeld bij een zonnepark is het goedkoper om extra panelen aan te leggen dan een batterij of opslag te plaatsen. Daar wordt meer geld mee verdiend. Ondanks dat ze op de piekproductie waarschijnlijk elektriciteit moeten weggooien. Soms gooien ze meer dan 50% van de elektriciteit weg gedurende piekproductie.

Er is dus veel sprake van curtailment en de verwachting is dat dit in 2030 tot hele hoge percentages kan oplopen? Wie is daar verantwoordelijk voor?

TenneT verwacht dat er richting 2050 een factor 6 meer productie kan zijn dan de belasting van het net. Daar lijkt het naar toe te groeien. Dat is nodig om, gedurende de tijd dat er geen productie is maar wel afname, genoeg energie te hebben. Bij zon is het op dit moment goedkoper om een deel van de piek weg te gooien. Bij wind is het echter zo dat ze nu subsidie krijgen voor hoeveel kWh er geproduceerd wordt. TenneT moet soms de hoeveelheid wind terugdraaien om niet te veel productie te hebben. Voor offshore wind is de subsidie al naar nul en daar zul je dus ander gedrag gaan zien als die eenmaal aangesloten zijn.

Klopt het dat de waarde van opslag dan net zo groot wordt als de kosten van nieuwe productie?

Daar gaat het wel op lijken. De vraag is of we veel gaan importeren vanuit het buitenland. Groene waterstof zouden we kunnen importeren. Dan vind er elektrolyse plaats in het buitenland en staan er centrales in Nederland. Dan is het net als dat we nu gas importeren. Geopolitiek gezien zou je misschien ook een groot deel zelf willen kunnen produceren. Echter, we zijn nu ook al jaren afhankelijk van olie en kolen uit het buitenland.

Het is waarschijnlijk dat opslag na 2030/2035 een concurrent wordt van de huidige gascentrales in Nederland. Die krijgen ook weinig draaiuren. Het is maar de vraag of opslag een concurrent wordt van de infrastructuur. Dat hangt erg af van de acceptatie. In Duitsland was TenneT bezig met een project voor het aanleggen van een bovengrondse kabel. Er kwam veel verzet tegen dit project en deze kabel moet nu ondergronds worden aangelegd. Ondergronds aanleggen van een kabel is vier keer zo duur en zodoende heeft de acceptatie van infrastructuur veel invloed op de kosten hiervan.

Appendix C. Interview with Uniper

In this appendix the report of the interview with Uniper is shown. As the interview was in Dutch, the report is also in the Dutch language.

Interviewverslag Uniper

Onderdeel van de Master Thesis van Tessa Rombouts

Auteur: Tessa Rombouts

Geïnterviewde: Hans Peters, Business Development Manager Energy Services, Uniper

Andere aanwezigen: Huub Lavooij & Leen Berke, Delta21

Datum interview: 06-04-2020

Medium van interview: Videoconference, Zoom

Gespreksverslag:

Hoe ziet Uniper de rol van energieopslag in te toekomst?

Ik heb geen idee hoe die prijzen zich gaan ontwikkelen. Het is zeker dat we in 2035 met Uniper CO_2 neutraal willen produceren. Dit moet direct of indirect gebeuren. Door groene opwekking en anders met compensatie van de uitgestoten gassen.

Wij denken dat in de energietransitie de duurzame gassen een grote rol gaan spelen. We zien een rol voor ons in die ontwikkeling. In Duitsland heeft Uniper al een electrolysers. Daar wordt van duurzame elektriciteit hydrogen gemaakt. Er is dan ook nog een installatie van Uniper die van hydrogen methaan maakt. Wel denken we dat in de transitie er niet één oplossing is, maar meerdere oplossingen parallel aan elkaar. Het zal een combinatie worden met ook wind, zon, opslag en misschien wel nucleaire energie.

Ook hebben we met Uniper al een Pumped Hydro storage. Deze handelt voornamelijk op de Wholesale markt. Ook heeft Uniper de grootste CAES (Compressed Air Energy Storage)van Europa. Hierbij wordt er lucht in een zoutcaverne op druk gebracht en kan een gasturbine zonder compressor draaien. Als de stroom goedkoop is dan drijft de generator tevens elektromotor de compressor aan en wordt er lucht in de zoutcaverne op druk gezet. Vervolgens wordt deze comprimeerde lucht gebruikt tijdens de ontbranding op momenten dat de stroom duur is. Hierdoor gaat er niet twee derde van de energie verloren aan de compressor. Deze gascentrale was gebouwd als Blackstart eenheid in de jaren 70 en is vervolgens omgebouwd in 2004. Deze CAES heeft een vermogen van 320 MW en houdt het ongeveer 2 uur vol. De eerder besproken electrolyser is ongeveer 2 MW.

Hoeveel grootschalige opslag verwacht Uniper de komende aantal jaren (2030 en 2050)?

Er zijn veel verschillende opties waar we als Uniper naar kijken. Om te investeren maken we berekeningen om te zien hoeveel de investeringen opbrengen. We kijken dan naar de Return on Investment en het project met de hoogste verwachte IRR worden vaak beloond. Afhankelijk natuurlijk van de investeringen die ook nodig zijn. De horizon die bekeken wordt voor de terugverdientijd is ongeveer 4 jaar.

Naar welke markten kijken jullie voor de opbrengsten van de investering?

Alle markten worden meegenomen. De strategie van Uniper is op dit moment om industriele stoom op te wekken direct bij de klant. Dit zijn vaak bedrijven en fabrieken zoals LyondellBasell en Neste. Wij investeren en bouwen dan de faciliteit voor de klant op hun grond voor industriele stoom opwekking. Het probleem bij energietransitie is dat naar industriele stoomopwekking een groot aandeel van het totale landelijke energie verbruik zit. Op dit moment zou biomassa een goede optie kunnen zijn, maar daar is de publieke opinie over verdeeld. Verder is duurzame waterstof een goede optie, maar dat is te duur op dit moment. Eigenlijk is de goede oplossing er op dit moment nog niet.

Warmteopslag doen jullie (Uniper) daar aan?

We hebben stadsverwarming in Rotterdam, Den Haag en Leiden. Rotterdam is grotendeels restwarmte van de vuilverbranding van AVR. Wij zorgen in deze projecten voor de dispatch en het op druk houden van het systeem. Ook hebben we installaties voor peak en backup vermogen bij deze systemen. Op dit moment zijn we in Den Haag aan het kijken of we er een eBoiler zouden kunnen bouwen. Met een eBoiler kan je warmte bufferen. In Duitsland heeft Uniper al centrales met een aantal E-boilers om dat te doen

Wat is de visie van Uniper op de verdeling tussen elektriciteit en waterstof in de periode 2030-2050?

Daar is geen duidelijke visie op. Het bedrijf (Uniper) is afgesplitst van E.ON. Het oude Ruhrgas(eigenlijk een soort Gasunie in Duitsland) is nu onderdeel van het huidige Uniper. Daarnaast heeft Uniper ook elektriciteitsproductie voor bedrijven gedreven door kolen. Alle kolencentrales moeten uiteindelijk dicht. Het hele portfolio van Uniper gaat derhalve veranderen. We hebben ook een paar gascentrales in eigendom Ik denk echter niet dat er nog een nieuwe CCGT gaat komen. Misschien gaan we een beetje richting windenergie maar niet veel. Mijn persoonlijke mening is dat we waarschijnlijk langzaam richting duurzame gasinvesteringen gaan. Uniper heeft ervaring met gas. De duurzame elektriciteitsopwekking zat bij E.ON en ligt nu bij RWE. Ik denk niet dat we nog in windparken gaan investeren, maar meer richting de electrolyser gaan. Het past beter bij het bedrijf om naar het duurzame gas, zoals waterstof en biomethaan te gaan. Daarnaast is Uniper actief in hydro energieopwekking.

Wat is de visie van Uniper op het waarderen van ondersteunende functies die opslag kan bieden op het elektriciteitsnet ?

Verschillende opslagmedia hebben verschillende functies. Batterijen worden nu kleinschalig gebouwd maar ik denk niet dat die technologie veel te bieden heeft in de hoeveelheid opslag die we nodig hebben. Met windenergie en piekvragen redt je het denk ik niet alleen met batterijen. Opslag in water (pumped hydro) zou wat meer kunnen voor seizoensopslag. Ik denk alleen niet dat je er onderuit komt om in te zetten op duurzaam gas. In de winter is het koud en wordt er weinig/minder energie duurzaam opgewekt, maar er is wel meer energie nodig. Men is bereidt om meer te betalen voor een piekvraag.. Vooroplopen met het bouwen van een goede opslagfaciliteit kan betekenen dat je meer verdient in de eerste jaren dan later wanneer er meer opslag beschikbaar is. Vooroplopen kan dus zin hebben.

Welk percentage van "curtailment" van door zon en wind opgewekte energie verwacht de Uniper in 2030-2050?

In de toekomst moet je niet al de offshore windparken willen aansluiten met het land. Verder op zee zouden windparken ook gekoppeld kunnen worden aan een electrolyser voor waterstof opwekking. Transporteren van gassen in plaats van elektronen kan veel goedkoper zijn verder op zee. Er zijn in de Noordzee nog lege olie en gasvelden aanwezig inclusief leidingwerk en platformen. Het lijkt mij handig om ter plekke waterstof te maken. Samen met electrolysers op land kan dan overtollige stroom worden omgezet in waterstof. Dan zou je dus ook geen last van curtailment of extreme lage prijzen voor electriciteit meer hebben.

Zijn de Nederlandse gasnetten geschikt voor waterstof?

De netten in de steden zijn van kunststof en die lijken geschikt. Bij de voornamelijk stalen transportleidingen is dat ingewikkelder. De druk gaat waarschijnlijk het materiaal over tijd verbrossen. Er zijn veel bedrijven waar we mee samenwerken die ook interesse hebben in het gebruik van waterstof. De conclusie is vaak dat waterstof nog veel te duur is. Groene waterstof is ongeveer vier keer zo duur dan grijze waterstof. Blauwe waterstof zit daar qua prijs tussen in. Blauwe waterstof is met de afvang en opslag dan wel hergebruik van CO2.

Er ligt dus al wel veel leidingwerk in de Noordzee dat gebruikt zou kunnen worden. Daarbij komt kijken dat als je iets uit bedrijf neemt je het ook moet weghalen. Dat zou veel geld kosten om al die infrastructuur weg te halen. Hergebruiken van die infrastructuur zou dus ook veel geld schelen aan vermeden kosten.

Wie heeft er een grotere interesse in opslag in water (pumped hydro storage)?

Leveringsbedrijven zoals bijvoorbeeld E.ON doen voornamelijk het commerciele klanten gedeelte. Ze proberen goedkoop in te kopen en vervolgens te verkopen aan klanten. Opslag zou zo bij hun interessant kunnen zijn.

Produktiebedrijven zoals bijvoorbeeld Uniper of RWE hebben verplichtingen en hebben stroom verkocht aan afnemers en moeten dat kunnen leveren. Als ze niet leveren kost dat veel geld. De interesse in de opslag zou dus ook bij produktiebedrijven kunnen liggen.

Het stuk opslag is afgestoten van E.ON naar Uniper en er zit dus wel wat ervaring bij Uniper met opslag. Er zou dus bij Uniper ook interesse kunnen zijn.

Zou Uniper waarde zien in het aansluiten van wind- en zonneparken op een opslagfaciliteit, zoals Delta21, om de aansluiting op het net minder piekbelasting te geven? Hoe zou de Uniper deze waarde bepalen of inschatten?

Op dit moment wordt het uit elkaar getrokken. Offshore windparken krijgen losse subsidie en worden los aangelegd. Het zou meer integraal bekeken moeten worden. Het zou interessant zijn als er zowel naar opslag en productie tegelijk gekeken kan worden. De subsidieverstrekking is verzuild en daardoor ontstaan er dus geen integrale oplossingen.

Hoe bepalen jullie op dit moment de waarde van een grootschalige opslag/ hoe zouden jullie de waarde van een project als Delta21 bepalen?

Leveringszekerheid is een belangrijk deel van de strategie. Als het voldoet aan de investeringsoverwegingen en eisen zouden we kunnen investeren. Dit hangt samen met de IRR.

Hoe kijk je naar de werking van de markt? Je zei al dat nu de subsidies zijn verzuild? Zie je andere mechanismen voor je om opslag en/of hydrogen te faciliteren?

Dat is moeilijk, want er is gekozen voor geliberaliseerde energiemarkt. Als overheid kun je dan ingrijpen met subsidies. Dit kan door een heel nieuw systeem of uitbreiding van SDE++. Nieuwe technologieën zijn heel erg duur. Daar moet veel gesubsidieerd voor worden, dit zie je ook bij zonneparken. De eerste projecten hebben een zo genaamde onrendabele top en daarna is worden projecten steeds goedkoper en daardoor rendabeler. Je ziet dit ook bij de batterijen gebeuren. Op dit moment is het nog niet rendabel om ergens een electrolyser ter plekke te exploiteren. De overheid zou dit moeten subsidiëren totdat de kosten op een redelijk niveau zijn beland. Dat zou bij grote megaprojecten ook kunnen met openboek. Openboek betekent dat de partij die het uitvoert eerlijk moet vertellen wat alles kost en wat het oplevert. Dan kan de overheid het verlies dekken. Op een gegeven moment kunnen de projecten zonder subsidies gebouwd worden.

Wat vind je vanuit de elektriciteitssector wat TenneT zou moeten doen? En wat is de rol van de Gasunie?

In feite faciliteren zijn een open markt. Ik denk niet dat het de taak van TenneT is om opslag te faciliteren.

De Gasunie heeft veel kennis en zijn op kleine schaal met projecten bezig. Gasopslag wordt ook niet gebouwd door Gasunie. Uniper heeft een aantal gas storages in Duitsland en UK voor aardgas. Ik denk dat gasstorages voornamelijk eigendom zijn van commerciële bedrijven.

Voor grote projecten zijn samenwerking tussen meerdere partijen/bedrijven niet ongebruikelijk. Demcolec, het vergassen van kolen, daar is als sector in geïnvesteerd. In Duitsland zijn de meeste nucleaire centrales gebouwd in consortia tussen 2 of meer bedrijven.

Naschrift op 09-04-2020.

Uniper en Siemens hebben vandaag aangekondigd nauw te gaan samenwerken op het gebied van verduurzamen van de energie en transport sector door waterstof verder te gaan ontwikkelen op industriele schaal.

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