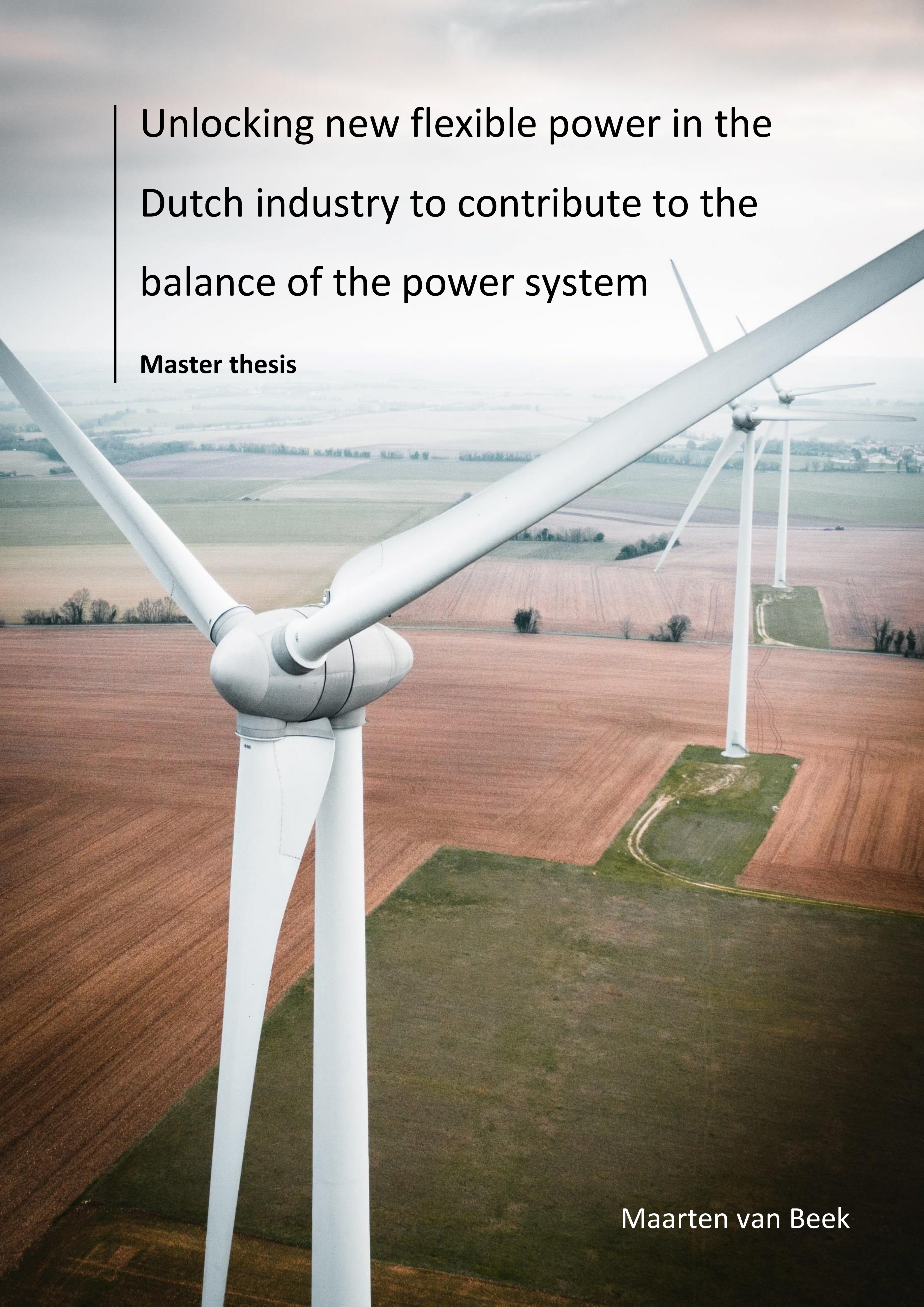
Unlocking new flexible power in the Dutch industry to contribute to the balance of the power system

Master thesis



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Executive summary

Fossil fuelled electricity production is making place for renewable energy sources. This comes with additional challenges. The decrease in baseload by conventional power production, and the rapid increase in variable renewable energy puts extra stress on the power system. This brings power production and consumption in disbalance, while at the same time electrical energy is difficult to store. In order to achieve balance in the power system, power consumption needs to be flexible in order to adjust to power production at all times. Aggregator companies have the capacity to bundle flexible power together in the power system.

This thesis investigates the possibilities of new flexible power in the Dutch industry, focusing on the potential of an aggregator company. By analysing data, reviewing literature, and interviewing 17 experts in the Dutch power system, in-depth knowledge is gained on industrial production processes and power load profiles. This allowed for a thorough examination of possible options for flexible demand side management. Some key findings from the overview of industrial processes and power load profiles include flexible use of compressed air and the implementation of electric boilers.

Furthermore, one industrial sector is analysed through the lens of a case study. A water board company located in the Netherlands was selected as suitable case study because the industry seemed very flexible. A model is constructed to estimate the financial and societal gain of utilising flexible power. A key finding of the investigation of this case was that the estimated financial gain turned out to be very beneficial. A key recommendation for water boards specifically is therefore to further research the applicability in practice. Utilising the flexibility opportunities in water pumping stations prove to be interesting to implement, and therefore should be executed in a later stage.

Furthermore, the paper and board industry, the animal feed industry, and the edible oils and fats industry also showed high potential in for utilising flexible power. But still more research needs to be done to determine what economic and societal gain this would have. Further research should be either in depth or width. More companies in other sectors should be investigated, but also the sectors included in this research should be further analysed.

Abstract

In order to combat the rise of greenhouse gas emissions in the atmosphere, countries worldwide are setting targets to transition from a fossil-fuel intensive to an energy system that is increasingly based on renewable energy sources. However, the increase in Variable Renewable Energy (VRE) sources causes disbalance in the power system, resulting in a key challenge: where initially power production needed to meet consumption, the energy transition implies that consumption now needs to meet production. Demand side management from flexible energy consumers is crucial in this arising challenge. Flexible potential can be unlocked by integrating flexible capacity in an aggregator pool. This thesis analyses Dutch industry sectors, where flexibility is already utilised in some industry sectors, while other sectors still show potential to unlock flexibility. Based on data analysis, a literature review and 17 semi-structured interviews with experts representing Dutch industry sectors, power load profiles and flexibility options of different sectors were determined. Furthermore, through the lens of a case study, the economic benefit of utilising flexibility within a water board company was analysed through a model in a model that systematically assesses the adjustments in power consumption as a reaction on electricity prices. This resulted in a list of suitable flexibility options within the sectors that are still to be unlocked. The results show that utilising flexibility was significantly economically viable, yet care should be taken in interpreting results as generalisation of industries is difficult in the water board sector. It is recommended that further research is done on improving the flexibility of the power system. The findings of this research suggest a great unused potential for the industry sector to contribute to the arising disbalance in the power system.

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Abbreviations

ACM	Authority consumer and markets
aFRR / FRR	Automated frequency restoration reserve
BRP	Balancing responsible party
BSP	Balancing service provider
CAES	Compressed air energy storage
CHP	Combined heat and power
DR	Demand response
DSO	Distribution system operator
DSR	Demand side response
EB	Energie Belasting
EE	Energy efficiency
EES	Electrical energy storage
ETPA	Energy trading platform Amsterdam
EU ETS	European Union emission trading system
EU-ETS	European Emissions trading system
FCR	Frequency containment reserves
LFC	Load frequency control
mFFRda	Manual frequency restoration reserve directly activated
OTC	Over the Counter
PCS	Power conversion system
PTU	Program time unit
RES	Renewable energy resources
Solar PV	Solar Photo-voltaic
TPES	Total primary energy supply
TSO	Transmission system operator
UPS	Uninterrupted power supply
VRE	Variable Renewable Energy
WWTP	Wastewater treatment plant

1. Introduction

1.1 Energy transition

In order to combat carbon emissions from fossil fuels, the Dutch government agreed to produce electricity with at least 70% renewable sources by 2030 (Dutch Government, 2019). This is also in line with the Paris Agreement (United Nations, 2015) and Sustainable Development Goals 7 (clean energy) and 13 (climate action). The main sources of renewable energy are solar PV and wind power, either on land or at sea. Renewable energy sources (RES) are heavily depending on weather conditions (Sioshansi, 2020). These weather conditions are fluctuating and hard to predict (Impram et al., 2020), which cause a major source of imbalance in the power system. When the amounts of produced and consumed power are equal, the power system is in balance. Power suppliers such as coal, gas or nuclear power plants provide a steady production of power. The disbalance in the power system is called the intermittency problem. The fundamental challenge of systems with high production of RES is their variability and intermittency (Sioshansi, 2020). *''In this context, interconnectors, demand response and energy storage can play an important role in increasing system flexibility and smoothing residual demand.''* (European Commission, 2016b). Energy storage could solve part of this problem by charging during a surplus and discharging during a shortage. However, energy storage is still bound by its limited capacity. Countries that experience large surpluses of variable renewable energy (VRE) sources, such as wind and solar power, over a long time could face insufficient storage capacity and therefore need to curtail their excess power. The curtailment of power leads to a loss of sustainable energy and is therefore undesirable. To avoid this curtailment, activities like demand side responses (DR) are a suitable solution (European Commission, 2016b). In times of a power surplus or shortage, flexible demand could avoid curtailment. The introduction of DR will increase the flexibility of the power system in times of irregular energy production. Therefore, it is important to explore possible ways to achieve a more efficient energy system.

1.2 Development in the energy transition

In 2019, 75.9% of the Dutch power was generated with fossil fuels, of which 58.2% by natural gas and 14.6% with coal. In total, 38.3% of the total electricity production is powered by decentralised power sources, such as combined heat and power (CHP) installations (Central Bureau of Statistics, 2020b). These include power production installations at companies that do not produce power as a core business activity. This also includes solar PV power and wind power, which was accountable for respectively 4.4% and 9.5% of the total electricity production in the Netherlands in 2019 (Central Bureau for Statistics, 2020b).

In 2015, three low-efficiency coal fired plants running on bituminous coal were closed. In 2017 two additional coal fired power plants closed. This was part of the Agreement on Energy for Sustainable Growth (IEA, 2020b). In 2019, the Netherlands introduced a ban on coal fired power plants (IEA, 2020a) *''The new energy law planned for 2022 aims to support demand-side response (DSR), energy services and aggregators, and other measures to create more flexible and efficient energy systems and markets.''*. In line with the Paris Agreement, the CO_2 reduction goals are 49% in 2030 and 95% in 2050 (Dutch Government, 2019; PBL, 2020). Further decrease in the number of coal fired power plants will lead to an increase in the demand for industrial flexible consumption (DNV GL, 2020).

Due to an increase in decentralised power production, the system must be as integrated as possible. Integration of multiple relatively small, decentralised power sources is done by an aggregator company. An aggregator company can combine the power production and load characteristics of multiple players in the electricity power system.

''An aggregator acts as a third-party intermediary between end consumers and power generators. As such, a demand response aggregator need not be the supplier as well, although there are obvious synergies between providing energy to an end consumer and managing their load for the sake of power system balancing.'' (Sioshansi, 2020, p.175).

Therefore, an aggregator company plays a key role in solving the intermittency problem in the energy transition. This thesis is commissioned by Enova, an aggregator company located in the Netherlands.

1.3 Research focus

Aggregator companies play a key role in the energy transition. The increasing intermittency problem can be solved by an increasingly integrated electricity power system. This research intends to further explore the possibilities of flexible power demand and generation through an aggregator company.

2 Theoretical framework

The next section contains the main theoretical concepts regarding the electricity power system considered in this research. First, the main concept of the electricity power system is explained. Then a deeper understanding of flexible power is provided. Furthermore, the author discusses basic concepts in the electricity market.

2.1 Theoretical concepts

Power production

The conventional way of producing electricity is with large power plants which are usually coal-, gas or nuclear powered. In the Netherlands, these centralised power plants range from 300MW to 1500MW installed capacity. The centralised power plants all are currently owned by one of the few power supply companies. Before the year 2000, centralised power production companies were fully owned by the government. After the year 2000, the so-called liberalisation of the power market occurred, and the production of power was privatized. Grid operating companies, however, are still regulated by the Dutch government and are falling under the jurisdiction of the ACM (Authority consumers and markets).

As shown in Figure 1, the energy mix in the Netherlands has fluctuated a lot in the between 1998 to 2019 (Central Bureau of Statistics, 2020c). Originally, coal fired power plants were used to supply a baseload supply of power, whereas gas fired power plants would supply a during peak demand. Figure 1 clearly shows that coal consumption for electricity production decreased in the last decade while the production from gas and VREs increased.

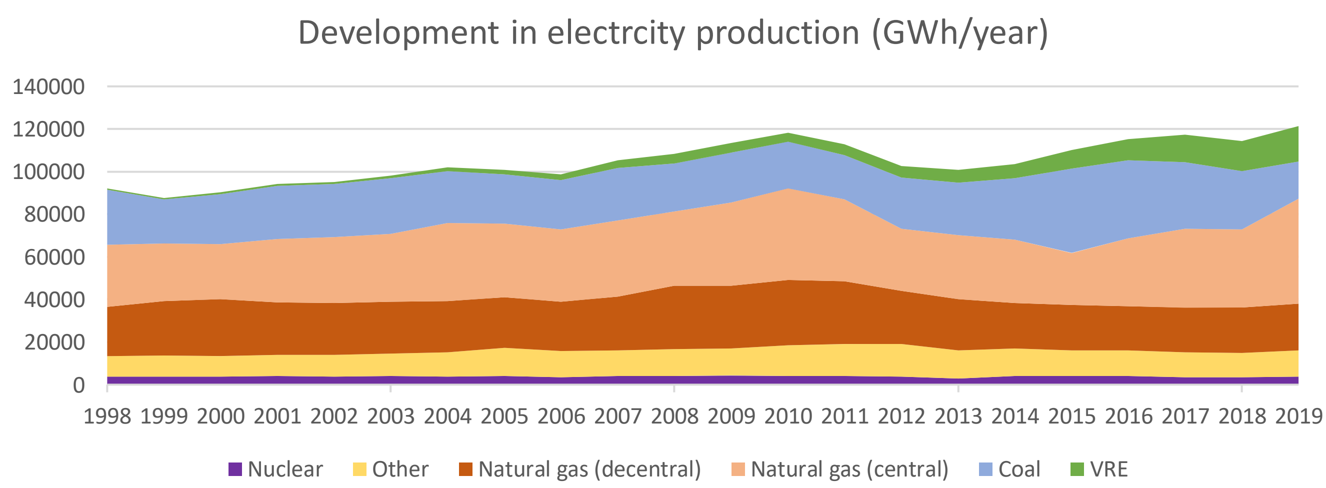

Figure 1 Development of electricity production (GWh/year) (Central Bureau for Statistics, 2019)

Decentralised power production

Next to conventional energy production by large scale power plants, decentralised power production is also a part of the energy production. This is done by different techniques such as small-scale CHP plants and small renewable energy production sites. Decentralised energy production is usually placed near sites of large energy use. As shown in Figure 1, the gas use for decentralised power production has been stable over the past two decades. The implementation of a CHP unit depends on the ratio between the electricity demand and the heat demand of that specific location. When put into correct use, a CHP plant is more efficient in converting fossil fuels into other energy carriers. Due to the fact that both heat and electricity is recovered, above 90% efficiency can be reached (Martens, 1998). CHP installed capacities range from several megawatts at large industrial installations to several hundreds of kilowatts at smaller specific locations.

Power consumption

In 2018 the total electricity demand was 114.0 TWh. The industry sector contributed by 31% to this electricity demand. The industry sector experienced a decrease from 42 TWh to 36 TWh in the period from 2014 to 2018 (IEA, 2020a).

Since RES are mainly focussed on producing electricity, and not on heat or gas, the Dutch government focussed mainly on electrification of energy consumption. Subsidies are given for electric vehicles as well as for big changes in the industrial sector. An example is moving from gas fired steam boilers to electric boilers.

Electrical energy storage (EES)

One way of resolving the intermittency problem is by storing energy. Electrical energy storage can be done in multiple different ways, where batteries are the most common. Another way of energy storage is pumping large amounts of compressed air into deep empty sub-surface gas cavity. When electricity is needed, the compressed air is converted back to electricity. Figure 2 shows a schematic overview of electricity storage. The two most important parts are the power system converter and the storage unit. Also, the most prominent location of energy losses is shown.

Next to EES also power to X is a prominent energy storage method. The X stands for a certain type of synthetic, thermal, or chemical energy carrier such as hydrogen, ammonia, or synthetic fossil fuels. This technology is still very much in the development stage but is expected to play an important role in a later stage of the energy transition. An example of power to X is power to heat where excess RES electrical power is converted into heat for industrial or residential use with the use of an e-boiler.

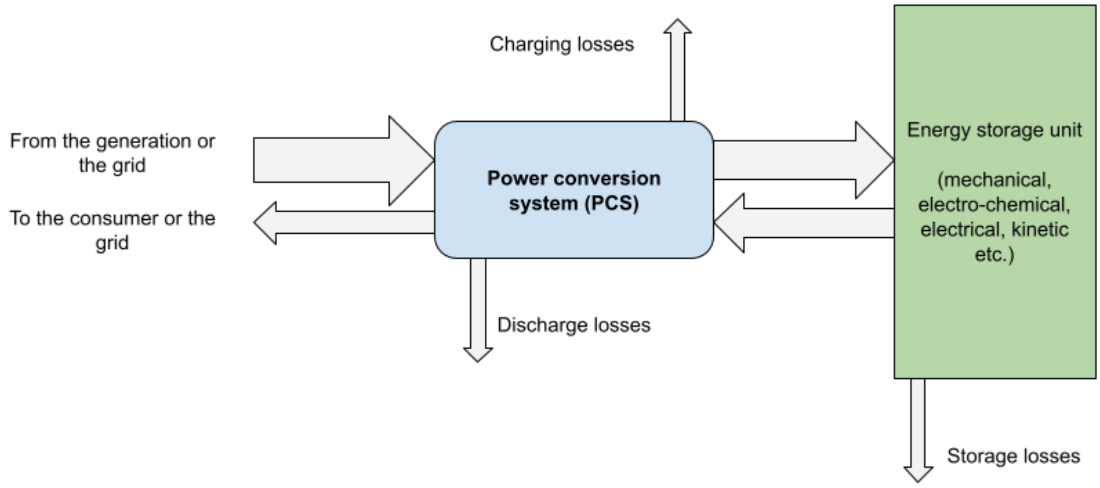

Figure 2 Schematic overview of electrical energy storage (EES) (Zakeri & Syri, 2015)

Thermal storage

Since large energy consumers also often need large amounts of heat, thermal storage in the form of buffers is used to store energy. This way, the timing of heat production and consumption can be decoupled (TenneT, 2019a). Thermal storage units are a common practice in the industry, for example with a steam accumulator and heat buffer. The presence of a buffer is key for flexibility as it increases the chance of load shifting and peak shaving.

Import/export

The Netherlands is well connected to neighbouring countries. The main countries where the Netherlands import electricity from are Germany, Norway, and Belgium. The main countries where the Netherlands export electricity to are the UK and Belgium. The import and export of electrical power also plays a role in the balancing of the electrical power system.

2.1.1 Electrical Power system

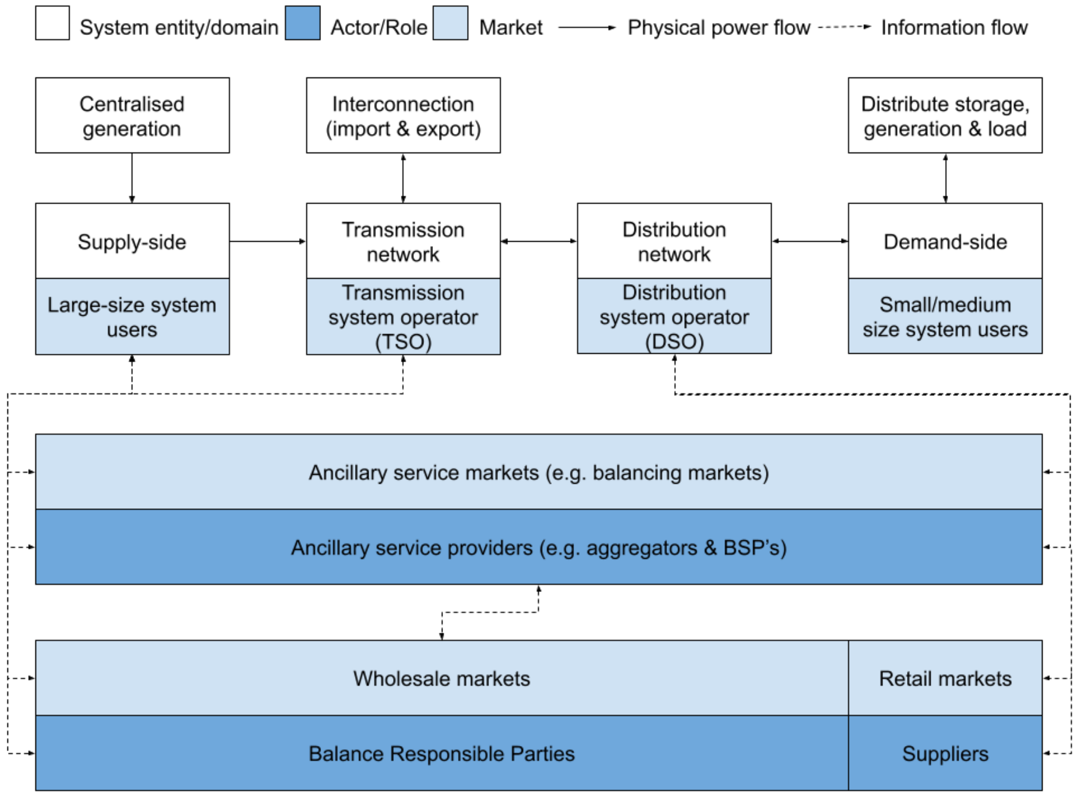

Figure 3 Conceptual architecture of the physical power system and the electricity sector organisation in the European context. Lampropoulos et al. (2015)

TSO (Transmission system operator)

Transmission system operators (TSO's) are companies that ensure the electricity connection on the high voltage level. The system operates on four high voltages levels, 380kv, 220kv, 150kv and 110kv as seen in **Error! Reference source not found.** (IEA, 2020a). TenneT is part of the International Power system Control Cooperation (IGCC) (TenneT TSO B.V., 2020). TenneT manages the different balancing reserves and their activation via the imbalance market to ensure the frequency is at a desired level.

DSO (Distribution system operator)

A distribution system operator is a company that manages the distribution of electricity on a regional level. The transmission of this electricity is on a lower level than a TSO, between 70kv and 400v. In the Netherlands 8 DSO's are operating, where the three largest (Liander, Enexis B.V. & Stedin B.V.) account for 95% of all market share.

Balancing service provider (BSP)

Balancing service providers are by TenneT acknowledged players in the electricity market that provide TenneT with balancing reserves (2.1.3). This is a list of 22 companies that are connected to TenneT, varying from electricity production companies to aggregator companies, or electricity storage companies. During the determined contract with a TSO, a BSP must provide the minimum price it wants when called upon to contribute to balancing reserve. A BSP provide balancing as a service to a TSO and receives compensation for that.

Balance responsible party (BRP)

A balance responsible party is always needed in case of large electricity users or consumers. Large electricity producers or consumers are responsible for their part of balancing the system. There are more than 50 BRPs in the Dutch electricity network. In the Dutch jargon this party is formerly known as a PV (''Programma verantwoordelijke'') party. A BRP is obligated to provide energy consumption and production schedule every day and is financially responsible if it deviates from this program.

Metering companies

An MRP (Electricity Metering Responsible Party) is acknowledged by TenneT to make sure metering is done independently and correctly. There are currently 13 metering parties active in the Dutch power system. The metering company nee to able to meter according to the ''MeetCode Electriciteit''. (Authority Consumer and markets, 2016)

Aggregator company

A specific type of BSP in the power market is an aggregator company. This is part of the ancillary service sector that combines the electricity consumption and production of multiple small companies to be large enough to operate on the wholesale electricity market. In Figure 4 the position of an aggregator company is visualised (Okur, 2021). As defined by Lampropoulos et al. (2018). *''Aggregator companies are organisations that can combine these distributed resources into a single system resource which can be utilised for the provision of flexibility services.''* An aggregator company can contribute to balancing reserves for load-frequency control (Lampropoulos et al., 2013) to ensure stability and reliability to the power system. As bidding and load shifting are complex actions and difficult for inexperienced agents, an aggregator can do this on the agent's behalf (Burger et al., 2017).

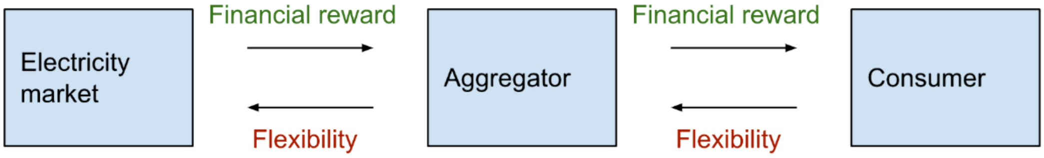

Figure 4 Aggregator's relation to consumer and flexibility (Okur, 2021)

Enova

An example of an aggregator company in the Netherlands is Enova. Enova offers services to control and adjust energy use for optimal economic use as well as consultancy on energy market strategies for her customers. Enova simultaneously offers balancing services for power system management to TenneT to keep de power system in balance. Enova mainly represents companies active in horticulture but is also active in the Dutch industry. This company combines the load and production capacity of multiple players in the electricity market to provide 500MW of production and 250 MW of consumption capacity to balance the power system (Enova.nl, 2021). A key part of its business is a smart switch, which can regulate individual power producing or consuming units. Due to constant monitoring of individual units, combined capacity is also constantly known. All these units are connected and operate in an *''aggregator pool''*, where flexibility is optimally benefitted.

Demand side response (DSR)

Demand Side Response can be defined as a system that reacts and operated based on demand and production of electricity in a system. It is expected that demand response will grow in a renewable dominated power systems (Richstein & Hosseinioun, 2020). As stated by the IEA (2020a) *''Digitalisation plays a key role in supporting energy transitions by allowing more efficient and flexible operation of the energy system.''* DSR can be based on different incentives, such as frequency-based, direct control over equipment, price-based, market-based and model-based (Lampropoulos et al., 2013).

Flexibility

In a future with deep RES penetration, control over power production decreases. In order to maintain the balance in the power system, demand needs to be responsive to the supply at that moment. This is known as flexible power. Until now, flexibility was mainly sourced from large generators at the supply-side. As stated by Lampropoulos et al. (2015) *''Currently, the focus of enabling flexibility is increasingly placed at the demand-side through flexible loads, distributed generation units and energy storage devices in the industry, commercial, and residential sectors. Unlocking the flexibility at the demand-side is considered a key factor for an effective energy transition which requires the active participation and empowerment of consumers.''* Peak shaving is sometimes used to cut out the highest peak demands for the system to be in balance. Where load shifting can be used to ensure the use of the total amount of needed energy, with peak shaving usually the total energy use is less.

2.1.2 Electricity markets

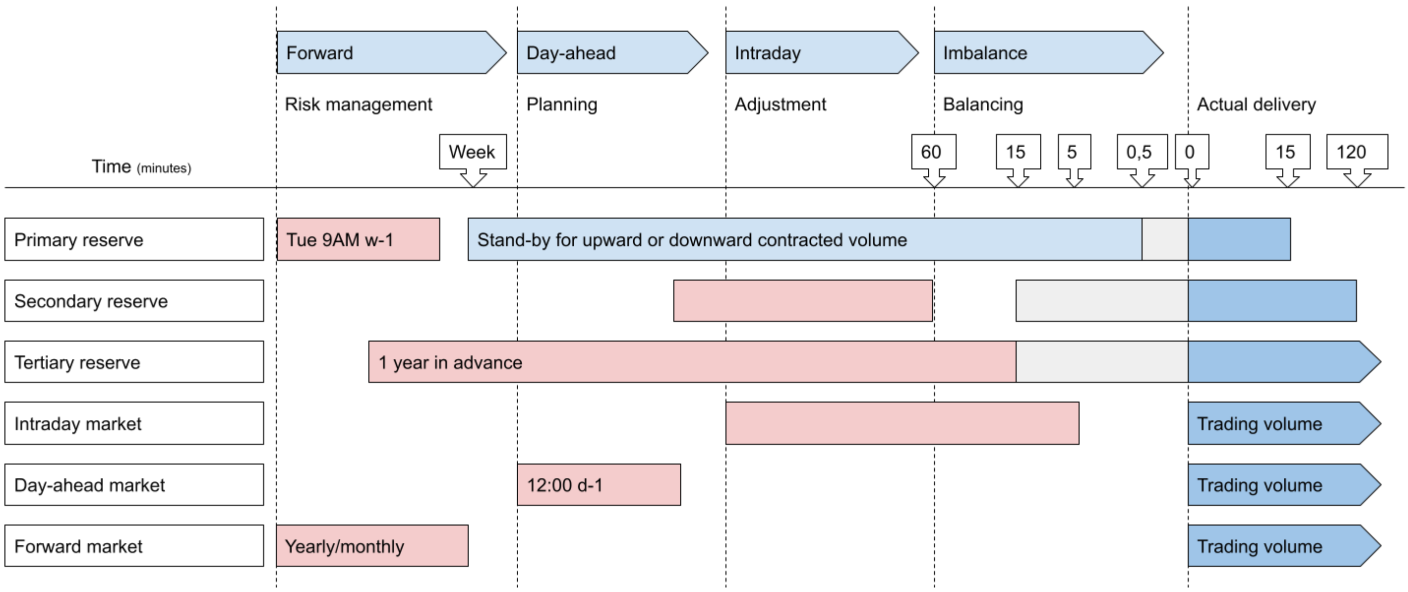

Figure 5 Electrical power market structure (Inspired by Movares, 2016)

Forward

The forward, or future market is a predetermined market price a consumer has agreed to pay for electricity for a certain period. This period can vary from weeks, months, or years, but will always be more than 24 hours. In the Dutch market this is known as the Over The Counter (OTC) bilateral trades (European Commission, 2016a). Consumers can choose to buy all their electricity, or a part of their electricity on the OTC. The OTC is a way of taking a financial position. With contracting a part of their electricity, the consumers eliminate the risk of paying too much for the electricity if the average price is higher than the OTC. But this also means that if the average electricity price is lower than the fixed predetermined price, the consumer pays more than it would have if it did not contract the OTC.

Day-ahead market (APX)

In the day-ahead electricity market, or APX (Amsterdam Power Exchange), consumers can take a financial position for the next day. Every day on 12:00 the prices for the next day are determined, based on the expected supply and demand. The APX is a daughter company of EPEX SPOT (European power exchange). The maximum levels of prices can range from -500 to +3000€/MW (European Commission, 2016a).

Intra-day

The intraday market acts in between the balancing and the day-ahead (APX) market. This a new market in the Netherlands. With the increase of decentralised electricity production, also an increase in need for intra-day marked occurred. Intra-day trading is done on the APX market as well as on the Energy trading platform Amsterdam (ETPA). The size of this market is still fairly small, in a month between 50-140GWh is traded, this is about the same as one day in the day-ahead market (van den Berg et al., 2017).

Imbalance

When the OTC, the day ahead, the intra-day and the imbalance markets are still not able to create balance to the power system, TenneT is responsible for the balance. Based on a fifteen-minute time frame called Program Time Unit (PTU) TenneT monitors the amount of imbalance in the power system. ''The imbalance of the control area is the difference between the measured cross border power exchanges and the scheduled exchanges before control power activation.'' (TenneT et al., 2011). The imbalance is based on the imbalance minus its activated control power per PTU. TenneT offers a certain price for delivering electricity to, or taking from the power system. If a BRP does not consume or produce the amount of power it promised to do in their e-program, it causes imbalance to the power market.

Taxes

The energy market is influenced by governmental interventions. This is in the form of taxes and subsidies, either on national level (Energy taxes and ODE) and on continental level (EU-ETS). Taxes are mainly used to demotivate users by penalizing them based on their emissions. the Netherlands two main taxes exist, the energy tax (EB) and the ODE (Opslag Duurzame Energie). The energy tax is implemented on the total use of energy a user has consumed in a certain amount of time. This tax is both on natural gas, and on electricity. Because the Dutch government want to stimulate consumers' electrification, the tax on gas has increased compared to the tax on electricity. Next to the normal energy tax, also the ODE tax is in use in the Netherlands since 2013. This tax has as a sole purpose to finance the expenses of the Dutch SDE++ subsidy. This tax is also based on the total energy use of a consumer, either on gas use, water use or electricity use. The ODE tax on electricity is based on the total amount of electricity that is used. The higher the energy use, the less taxes must be paid for both EB an ODE (Dutch tax authorities, 2021). For large energy consumers also, a European tax is in place, the EU-ETS (European Emissions trading system). This is a so called ''cap and trade'' system, this meant that there is a certain number of emissions are allowed in a certain amount of time. Companies buy or receive allowances to emit greenhouse gasses, which can then be traded.

Subsidies

Subsidies are used to motivate energy producers and consumer to be more sustainable. Many different types of subsidies are present in the energy market. In the Netherlands, the most important subsidy is the SDE++ (Stimulering Duurzame Energieproductie) (Rijksdienst Voor Ondernemend Nederland, 2021). This subsidy is now completely financed by the ODE tax. For a company to be able to get a subsidy on their projects for CO_2 emission reduction, an audit needs to be placed. This audit describes the amount €/tonne CO_2 reduction the company expects to reach. If this amount is low enough the company will get this audit, and a subsidy contract of 15 year will be issued for this company. In the audit system a merit order system is used.

2.1.3 Balancing reserves

The AC frequency of the power system needs to be 50hz, leaving some space to move between 50.2Hz and 49.8Hz. It is very important that this frequency is maintained. If not maintained well, damage to electrical units in the power system occurs. Or in an extreme event, power outages occur. The frequency is regulated on European scale between TSOs and by Balancing Responsible Parties. In this case the Dutch TSO TenneT is responsible for the Dutch balance; this is done with balancing reserves.

The balancing reserves are divided into three products and used in the same respective order: the FCR, the aFRR and the mFFR, also called the primary, secondary and tertiary balancing reserves. When the FCR is not sufficient, the aFRR is activated. When de FRR is not sufficient, the mFRR is activated.

Primary balancing reserve - Frequency containment reserves (FCR)

Frequency containment reserves, or FCR, are the primary reserves which can adjust quickly. FCR is an energy reserve that is used to contain the frequency of the power system. This reserve is used to flatten small peaks and drops for a short amount of time (CEDEC et al., 2018). In the Netherlands, the total capacity of FCR is around 100MW (Personal communication, TenneT, 2020a) The ''Nominal Frequency'' is 50 Hz, this means that the power system operates at an alternating current the switches between positive and negative voltage 50 times per second. It is very important to maintain this frequency for the power system to be in balance.

Secondary balancing reserve - Automated Frequency restoration reserves (aFRR)

Frequency restoration reserves, also called secondary reserves, can be operated either automatically (aFRR) or manually (mFRR) (CEDEC et al., 2018). This is the main reserve used to regulate power by TenneT and is offered to TenneT-NL market players (TenneT TSO B.V., 2018). The total capacity of this balancing reserve is around 300MW in the Netherlands (van den Berg et al., 2017). The aFRR is activated when the FCR is not sufficient to contain the balance of the power system. In practice, when this product is activated, the FCR is deactivated for that reserve to be able to charge back to its normal capacity. The requirements for a BSP to apply for this secondary reserve is a capacity of minimum of 4MW. This market structure operates as a bid price ladder merit order (van den Berg et al., 2017). This means that TenneT will first determine how much capacity it needs and will then look at the offers. TenneT will use a merit order to buy the offers, starting from the cheapest, until it reaches the desired capacity. In the bidding, a distinction is made between upward and downward bids. Figure 6 shows the price setting that resulted from the upward and downward bids. If a bid gets accepted by the TSO, and the BSP provide their service, the price of that bid will be paid completely.

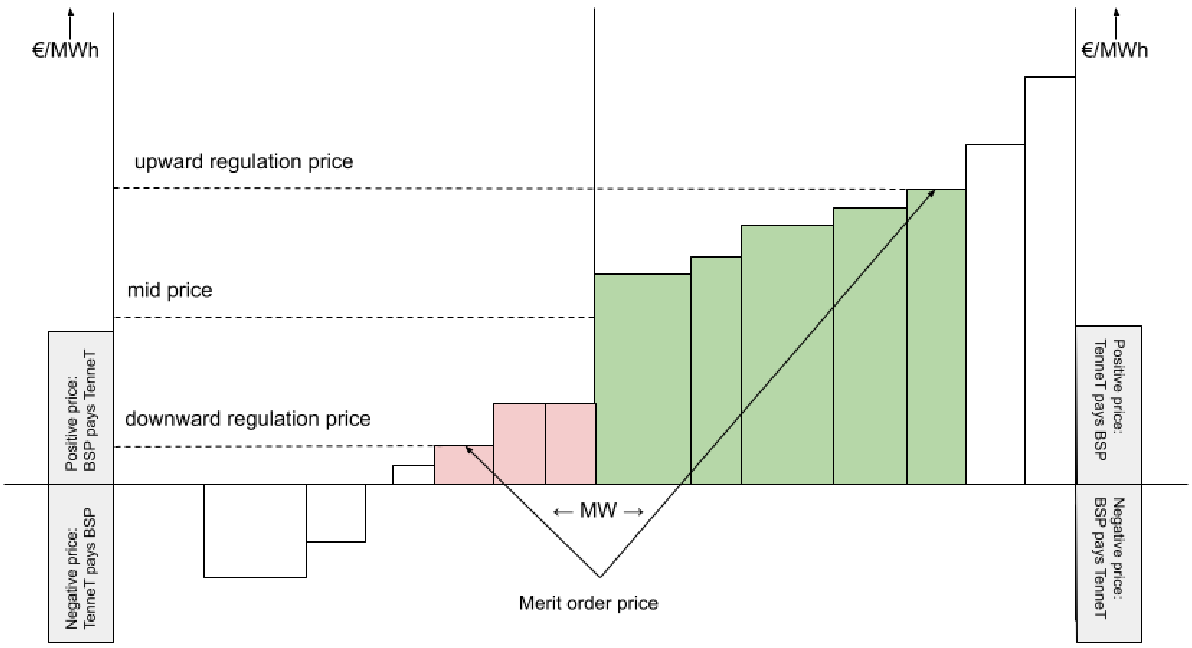

Figure 6 Marginal price setting based on merit order of upward and downward regulation (TenneT, 2020b)

Tertiary balancing reserve - Manual Frequency Restoration Reserve (directly activated) (mFRR(da))

Manual frequency restoration reserve is the tertiary balancing reserve. This reserve is manually activated in times of incident reserve need (TenneT TSO B.V., 2019). This reserve is only activated when aFRR is not sufficient to restore the balance to the power system. For a BSP to provide this service to TenneT it needs to fulfil the following requirements. The service provider must have at least 20MW of capacity, and this needs to be available for at least 97% of all the PTU's of the year. The reserve must be available within 15 minutes after call, and for at least one hour. It is allowed for the reserve to consist of multiple smaller installations (van den Berg et al., 2017). Therefore, if an aggregator is large enough it can connect to this reserve. The total installed capacity of mFRRda in the Netherlands is around 1000MW. This is based on the biggest single power plant in the Netherlands. BSPs or BRPs that provide this balancing reserve to a TSO do this based on contractual availability. In this balancing reserve, no bidding is done.

GOPACS

In 2019 the Power system Operator Platform for Congestion Solutions (GOPACS) program was introduced (IEA, 2020a). This program is mainly focused on solving the congestion problem, which occurs when the capacity of a cable is exceeded and there is no possibility for the cable to transport more energy. This problem can occur when large concentrations of PV or wind power are located at a location without electricity demand. The GOPACS operates to find solutions for this geographical problem. When a congestion problem occurs in a certain area, GOPACS tries to find a similar amount of power demand in an area outside the congestion area and matches these two. Therefore, no cables are required to transport the electricity. The GOPACS project is still in the development stage.

2.2 Previous research

Previous research on industrial demand side response is still limited. Wohlfarth (2019) conducted a PhD-thesis on the energy efficiency and the demand flexibility of companies in Germany. This thesis explains the definition of demand flexibility very well. However, the industry is not very well represented in this thesis. A report from DNV GL (2020) stated that there is still a limited sense of urgency to increase the flexible power supply. TenneT published the Flexibility Monitor in 2019, recommending to *''Initiate sector-specific studies into demand response, through stakeholder interaction and detailed sector studies, either with a selected set of representative individual parties, or through a sector approach with relevant sector associations.''* (TenneT, 2019a) According to the report *''Monitoring Leveringszekerheid''* (TenneT, 2019b) the Netherlands has a base capacity of 700MW installed, and a peak capacity of 2000MW of market response capacity. Lampropoulos et al. (2020;2019;2013) and Okur (2021) did extensive research on the role of aggregator companies and the role of demand side management. The IPPC published reports on the best available techniques for many different industrial and energy intensive sectors (Sontanja, 2019, Surh, 2015 & Brinkmann 2016). Helin et al. (2017) did research in demand side response in the paper industry and found that demand side response has a cost potential but is limited by risk considerations. Paulus & Borggrefe (2011) mainly researched chemical processes, and the steel making industry. Concerning wastewater treatment plants beneficial potentials have been found, but certain challenges have to be overcome to facilitate the participation wastewater treatments plants in DSR programmes (Kirchem et al. 2019).

2.3 Relevance

2.3.1 Scientific relevance

According to the Flexibility Monitor (TenneT, 2019a) the focus for the sector studies need to be on horticulture, chemical industry, and industries with high temperature heats based processes. There is limited knowledge on industrial parties for required investments to reach the full potential of flexibility according to DNV GL (2020). According to ECN (2020), at peak capacity, the fast-growing electricity demand, and the lack of investments in an integrated flexible production capacity are the main drivers for improvements in demand side response. Insights in industrial processes and the level of flexibility are still largely unknown in many sectors. In depth knowledge on specific industrial processes provides both useful insights in energy efficiency and cost effectiveness. The overview in this thesis is useful for the direction of further research.

2.3.2 Societal relevance

This research is relevant for three of the 17 Sustainable Development Goals: 7, Affordable and clean energy, 9; Industry, Innovation, and Infrastructure and 13; Climate action. In the end, the electricity consumer will always pay the price if the intermittency problem is not solved. When high levels of flexibility are reached, also high levels of RES penetration can be reached. This can contribute to lower electricity prices for consumers and the Netherlands will be closer to reaching the SDGs.

3 Research design

3.1 Problem definition

The increasing amount of production from renewable energy sources also increases the level of intermittency on the power system. Flexible load shifting and decentralised power production could solve this problem. Therefore, the demand for flexible energy users increases. The solution could be provided by the increase of integration of flexible energy users in the power system. However, there is a limited understanding of the potential of flexible power from large energy users. This research aims to unlock the flexibility for the industrial demand response in the wholesale electricity sector in the Netherlands. This leads to the following formulation of a research aim, a main research question and sub-questions.

3.2 Research aim

The aim of this research is to provide an overview of large players in the energy market that can contribute to the flexible power system through an aggregator company, in order to eventually contribute to solving the increasing intermittency problem caused by the penetration of VREs. On the one hand, this is useful for companies in the industrial sector to explore their flexibility. On the other hand, the insights are useful for companies responsible for the stability of the power system like transmission and distribution operators. This research will eventually contribute to reach the goal of 70% electricity production of RES by 2030. (United Nations, 2015)

3.3 Research question and sub research questions

Main research question

How can flexible demand response from large energy consumers contribute to solving the rising intermittency problem from RES penetration in the Dutch power system, by connecting to an aggregator company?

Sub-question 1

What are large energy consumers and producers in the Netherlands, and what type of energy do they consume or produce?

Sub-question 2

How can the term ''flexible power'' be defined, and what are the different types of flexible power?

Sub-question 3

What is the energy load profile of processes in the Dutch industry?

Sub-question 4

How flexible are the industrial process based on the energy load profile?

Sub-question 5

What are the opportunities or barriers for the industry to contribute to the stability of the power system?

Sub-question 6

What recommendations can be formulated following from the results of sub-question 1 to 5?

3.4 Research framework

A schematic overview of the research framework is provided in Figure 7. The research is done in three phases. The **first phase** has more of an explorative nature, where sub-questions one, two and three are answered. In the **second phase** the results are synthesised, where the load profile of energy consumers is rated based on their flexibility. After the results from this step the decision is made on what industry a case study will be performed. The possibilities of flexibility are described, and in the case study the theoretical economic gain is calculated through a model. In **phase three** recommendations are formulated for the case study, as well as for the other sectors in this thesis.

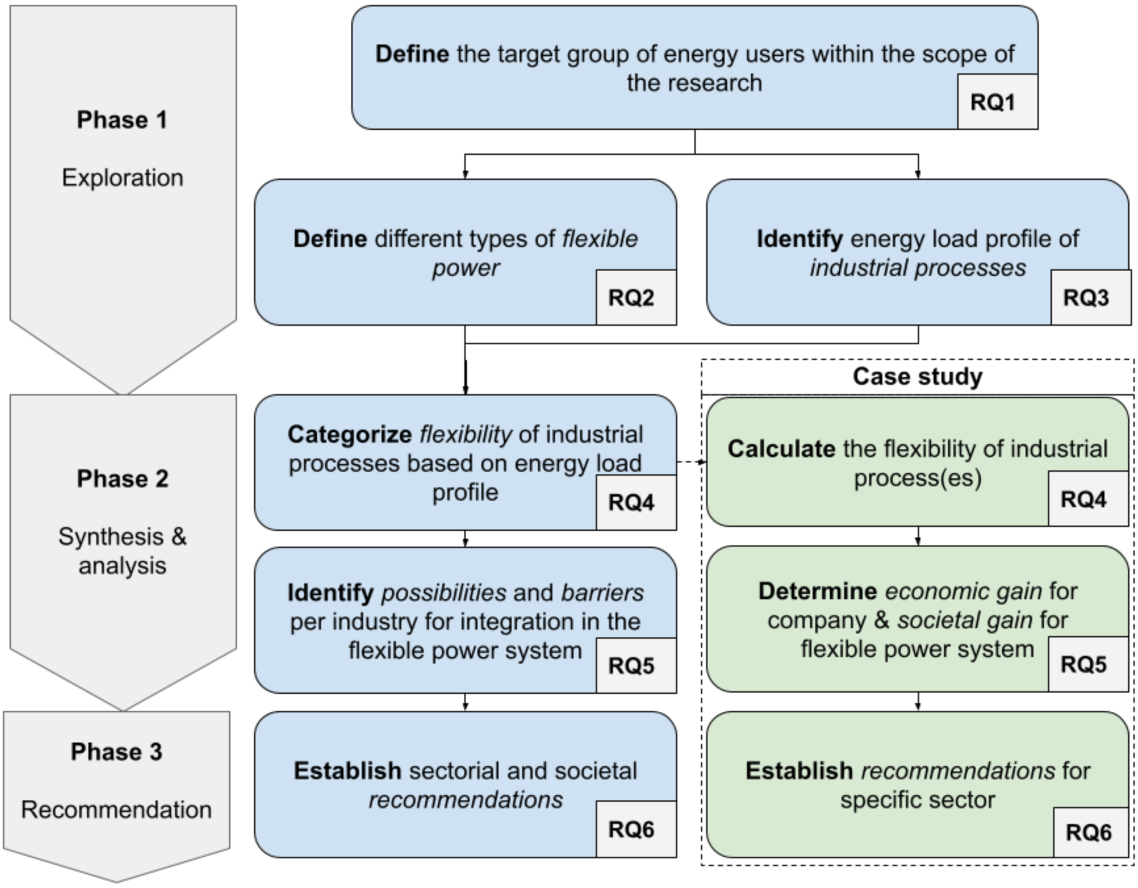

Figure 7 Schematic overview of research framework

4 Methods

This research is conducted from February 2021 until July 2021 and is divided into three phases, this is visualised in Figure 7. The combination of a detailed literature analysis, expert interviews, and systematic data processing and a case study aims to provide a strong base for a thorough research, which may lead to new and useful insights in the energy transition. This chapter explains the steps taken in the research, and the methods that are used.

Table 1 Research phases and methods

Phase	Questions	Methods
Exploration: Target Group, flexible power & energy load profile	*Sub-question 1:* What are large energy consumers and producers in the Netherlands, and what type of energy do they consume or produce? *Sub-question 2:* How can the term ''flexible power'' be defined, and what are the different types of flexible power? & *Sub-question 3:* What is the energy load profile of processes in the Dutch industry?	*Literature review & expert conversations* to determine criteria for suitability of industrial sectors. *Preliminary data analysis* to identify large energy consumers or producers that are within the scope of this research with a multi criteria analysis. *Literature research* to identify the definition of flexible power, and to categorize different types and criteria. *Expert interviews* with Enova to determine the definition of flexible power, and to categorize different types and criteria. *Literature research on* processes and power load profile. *Expert interviews* with companies on mainly used processes and equipment per industry/sector or company.

Synthesis & analysis	*Sub-question 4:* How flexible are the industrial process based on the energy load profile? *Sub-question 5* What are the possibilities or barriers for the industry to contribute to the stability of the power system?	*Data analysis* and *literature* research to define the flexibility of industrial processes. *Perform a case study* for one sector to determine the economic
Recommendation	*Sub-question 6* What sectorial and societal recommendations can be formulated?	

4.1 Target group

To determine what sectors are relevant to this research, a preliminary analysis is carried out. In this analysis literature sources, data sources and expert sources are utilized. First, the criteria are formulated which a sector needs to fulfil, which is mostly done with expert sources, and then backed-up with literature. Furthermore, a quantitative multi criteria analysis is carried out to determine most suitable industries.

4.1.1 Literature review

Literature sources have been used to determine what criteria are important for choosing the target group of industries. Together with conversations with experts a set of criteria are built. This is then used in the MCA.

4.1.2 Data analysis (multi criteria)

Preliminary multi criteria analysis is conducted to identify large energy consumers or producers that are within the scope of this research. This is done by consulting the database from the Central Bureau for Statistics (CBS) of the Netherlands. In the first phase of the research, certain sectors of energy consumers are eliminated based on specific characteristics gathered from semi-structured expert interviews with Enova and expert interviews accompanied by literature sources. The energy use of a specific sector is expressed in Energiebalans; aanbod & verbruik, sector (Central Bureau for Statistics, 2021a) and the number of companies is retrieved from the dataset Bedrijven; bedrijfstak (Central Bureau for Statistics, 2021b).

Step 1: Syntheses of Energiebalans; Aanbod & Verbruik **AND** Bedrijven; bedrijfstak.

Step 2: Calculate the average amount of energy consumed and produced per company.

Step 3: Determine energy use criteria that makes a company relevant.

Step 4: Create a suitability matrix based on the predetermined criteria for the first selection.

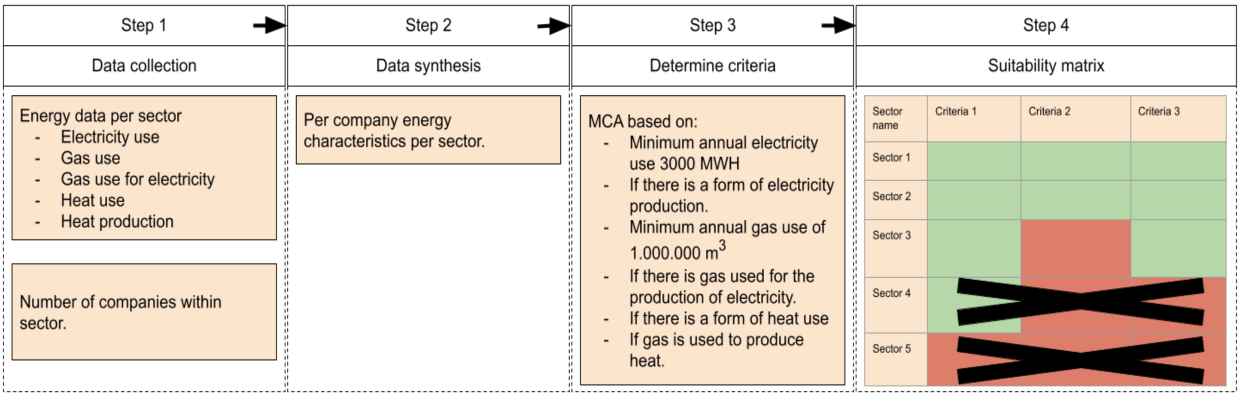

Figure 8 Steps in MCA

Step 1: Collection of both datasets

In the first phase of the thesis, a broad selection is done. Raw data from Central Bureau for Statistics is combined to categorize the sectors. The following two databases are combined: ''Energy balance; aanbod en verbruik'' (Energy balance; supply and demand) **and** ''Bedrijven; bedrijfstak'' (Companies: Company sector). This resulted in a combination of the total energy use per (sub)sector, and the total amount of companies. With this data an estimation is be made on the energy use per single company.

Bedrijven; bedrijfstak

Data used from this database is: Total number of companies that are present in the Netherlands within a certain industrial sector.

Energiebalans; Aanbod en verbruik

This database explains all characteristics of energy use and production per sector and energy carrier. The main energy carriers that are relevant to this research are electricity use, gas use and electricity production. The most recent data that could be extracted from the open-source database of CBS is from 2019, therefore the data concerning companies is also from the last quarter of 2019.

This dataset includes the following characteristics:

- Total electricity use per industrial sector (MWh/year)
- Total electricity production per industrial sector (MWh/year)
- Total gas use per industrial sector (m^3/year)
- Total gas use for electricity production (m^3/year)
- Total heat use (MWh)

- Total gas use for heat production (m^3/year)

Step 2: Calculate the average energy characteristics per company within sectors.

In this step of the analysis, the values from step 2 are calculated per company per year. This is done by dividing the total amount in that sector by the number of companies in that sector. The raw CBS data is given in Peta Joule, this is converted to MWh by multiplying it with 277.777,78. This calculation is shown in the formula below. This is done for all values that are included in the dataset.

$$Energy\ characteristics\ \ per\ company\ per\ year\ within\ sector =$$

$$\frac{Total\ amount\ of\ energy\ in\ whole\ sector\ per\ year}{Total\ number\ of\ companies\ in\ sector}$$

Step 3: Determine energy use criteria that makes a company interesting.

Electricity use

This criterion is based on the total electricity use per company per year within a sector. This includes the use of electricity from the power system, and the use of self-produced electricity. This gives an image of the total electricity demand companies within this sector. According to Enova (J. Kruijt, 04-04-2021) the minimum amount of electricity use needed for a company to be relevant for flexible power is 3.000 MWh per year, therefore the selection can be made based on the scale of the companies. An average household uses 2.050 kWh per year (Central bureau for Statistics, 2020), so this threshold is almost 1.500 times higher.

Electricity production

Next to electricity use, production (MWh/company/year) is also an important factor that makes a company relevant for flexible power. Decentralised electricity is usually produced by small CHP plants, which also produces heat in the form of hot water or steam. The possibility for a company to produce its own electricity is important for the flexible power network. The minimal threshold for this factor is set at zero because electricity production makes the sector relevant for flexible power.

Gas use (total)

Expressed in m^3/company/year the total gas uses in this case includes gas use for electricity (and heat) production, and for other purposes. The minimal threshold of the total gas use per company is set on 1.000.000 m^3 gas per year. With this amount of gas use the companies are large enough to be economically viable. The average natural gas use of a household per year is 800 m3 (Central Bureau for Statistics, 2020a). This means that the threshold for one million m^3/year is about 1.250 times higher than an average household.

Gas use for electricity production

This number represents the amount of gas that a company used for the decentralised production of electricity (and heat). Sectors that can produce their own electricity with gas are interesting for flexible purposes (TenneT, 2019a). The minimal threshold for this factor is set at zero because the fact that a company uses gas for electricity or heat production already makes it relevant for flexible power. This is around the amount a thousand households per year.

Heat use (total)

This number expresses the total heat used per company in this sector per year (including own produced heat). For some sectors, heat is important for their activities. This number expresses the amount of heat that a company uses within this sector over a year. The consumption of heat is an important factor for flexible power use (TenneT, 2019a) The minimal threshold for this factor is zero, because a sector consuming heat already makes it relevant for flexible power.

Heat production

This number expresses the amount of heat produced per company per year. Heat can be produced with a boiler or a CHP plant as secondary energy next to electricity production. Heat is an important factor in the flexible power as it can be stored and transported. The minimal threshold for this factor is zero, because a sector producing heat already makes it relevant for flexible power. According to the Flexibility monitor from TenneT (2019a), heat production can be done in multiple different ways such as power to heat. Here, a conventional gas boiler will be replaced by an electric boiler.

Step 4: Create a suitability matrix based on the data from step 2 and the criteria from step 3.

In this step, a suitability matrix is created based on the calculation from the previous steps. This matrix includes all predetermined criteria. With the use of the IF function in Excel, data is converted to usable values. If the minimal threshold of a certain factor is reached, that cell becomes a 1, if the threshold is not reached the cell becomes a zero. This way, multiple criteria are combined and analysed. In the end all values (1 or 0) are summed up, which gives the total score of that sector. This way, the suitability of that sector is graded based on scale and energy use characteristics. This MCA is then used to determine which sectors are relevant to consider for this research, and what sectors are not relevant

4.1.3 Expert interviews

Semi-structured expert interviews are either conducted with Enova, or with other companies. These interviews are supplemented by literature reviews. In the first phase of the research this is mainly done to determine the target group of this research.

4.2 Define flexible power and identify criteria

In this part of the research, the term flexibility will be described. The outcome of this parted is aimed at determining whether a certain industrial process is flexible, and on what level. This is done with literature sources, data sources and expert interviews in the energy market.

4.2.1 Literature review

The main sources to determine flexibility criteria are both the balancing reserves TenneT provides, and the flexibility monitor from TenneT (2019a). Also, an extensive report from DNV-GL is used to determine different types of flexibility. The dissertation from Özge Okur (2021) also provides valuable information on this topic.

Literature research, including grey and academic literature*,* is conducted to further develop the theoretical framework and understand technical concepts that complement this research. *Literature research* is also conducted to identify the definition of flexible power in phase two, and to categorize different types and criteria of flexibility. Some examples of criteria are ramp-up/down time, run-time, and scalability. These types and criteria are then used to determine the flexibility of a sector.

4.2.2 Expert interviews

Semi-structured expert interviews are conducted with Enova to determine the definition of flexible power and to identify what is required to be suitable for integration in the flexible power system. These conversations are also used to determine the definition of flexibility.

4.3 Energy load profile

To state that a process is suitable for any kind of flexibility, the energy load profile needs to be created. The goal is to create a clear image of how the specific process is done, what steps are taken, what and how much energy is used per step, how long this takes and if there are possibilities for buffering or load shifting. This is based on the literature research, data analysis, but mostly on extensive semi-structured expert interviews with people working in the sector.

An example of a flow diagram is shown in Figure 9. Green boxes describe the type of material that flows from one process to another. This step also includes possibilities for storage or buffer. Blue boxes describe a process step where energy is used to alter the material in any form. This box includes the type of step what type of energy that is used and what share of amount of energy is used compared to the total amount of energy in the whole process. This way, the scale of the facility does not matter in the results. Finally, the red box describes the final product in that process line.

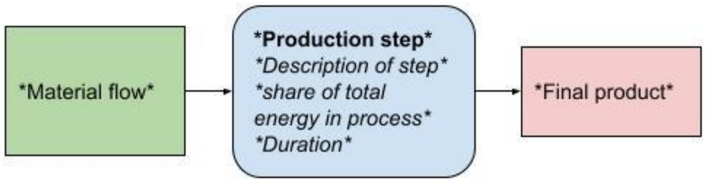

Figure 9 Example of diagram process steps

4.3.1 Literature research

Literature research is conducted in the second phase to identify processes and/or equipment used in specific industries or sectors, which are then rated on the flexibility. Examples of processes in an industry are: Must-run processes, Batch-processes, chemical processes, heat based, electrolysis, cutting, metal working, pressing, moulding, melting etc. These processes are analysed based on the flexibility characteristics that are determined before. These processes are then categorized. Where literature lacks data, *expert interviews* can complement this. The same is done for industrial equipment and their energy load profile. Equipment serves a certain purpose, but there are alternatives in the choice for the type of equipment. Examples for equipment that are suitable for flexible demand are: Electrode boilers, electrical resistance heating, heat pumps, steam recompression, electric arc furnaces (de Bruyn et al., 2020) CHP installations and the availability of a buffer (TenneT, 2019a).

The main source of literature are the Best Available Technique (BAT) reports from the Intergovernmental Panel of Climate Change (IPCC). In these reports the main activities of certain sectors are extensively described. Also, literature from the MIDDEN project in the Netherlands is used. This project was carried out by two Dutch institutions, Planbureau voor de Leefomgeving (PBL) and TNO, describing decarbonisation techniques for the Dutch manufacturing industry.

4.3.2 Expert interviews

In phase three, also *expert interviews* are conducted to determine energy load profile as well as identify barriers and solutions for the integration of certain industries, sectors, or companies in the flexible power system. These interviews are then complemented with literature to create an energy load profile of the process. Also, the level of flexibility is determined based on the expert knowledge of the interviewees.

In total 17 people have been interviewed in this research, ranging from 7 different sectors as seen in **Error! Reference source not found.** in Appendix A.1. The interviews are semi-structured and are divided into two parts. The first part of the interviews is of an explorative nature, to answer sub question 3. The second part of the interview must answer sub question 4 and 5 and is focussed on the barriers for the adjustments that are necessary for that specific industry, sector, or company. In this thesis interviewees are approached via LinkedIn or via email. Here, the focus has been on the type of function of the approached person. Since the number of people from a certain sector that would be willing to conduct an interview was unknown beforehand, the method has amore a stochastic nature. The questions of the interviews are listed in 0. Chemical industries have been excluded from this research due to the high complexity of the processes.

5 Results

5.1 Target group

The result from the MCA is shown in Figure 19 in Appendix A.2. Here the sectors are listed from top to bottom based on suitability for flexible power. This is a list of 17 industries in the Netherlands. In phase 2 of the research these industries have been approached to conduct interviews with.

The list is ranked from top to bottom, from most interesting industries to fewer interesting industries based on the MCA. Here we see that the manufacturing and processing industries score positive on many criteria. According to this list many companies have been approached to conduct interviews. This resulted in the list of interviewees in **Error! Reference source not found.** and Table 3.

5.2 Define flexibility & Identify criteria

General information

To determine on what level a process or process step is flexible, both flexibility categories and criteria must be defined. This is mainly done based on literature and expert interviews. According to Okur (2021) and DNV-GL (2020), flexibility can be obtained using *dispatchable power plants*, *energy storage*, *interconnections,* and *demand response.* This report is only focussed on demand response.

Demand response can be defined as *'' the changes in electric usage by end-use consumers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when systems reliability is jeopardized''.* (US Department of Energy, 2006; Aghaei and Elizadeh, 2013;Okur, 2021). For a consumer to benefit from their flexibility, an aggregator company is essential. An aggregator is placed in between the consumer and the electricity market. Due to the large number of connected consumers, and aggregator makes sure that the consumers only provide flexibility to the power system whenever they can. This means that the process will be less effected. This is also shown in Figure 4 (Okur, 2021).

Categories

As explained in the theoretical framework in chapter two, especially **Error! Reference source not found.**, the electricity market is a complex and ever-changing system. Here we see four different flexibility markets in place. First, the *market structure (Imbalance)* is in place which is chronological and based on financial positions agents take. Secondly, the three balancing reserves of a TSO need flexibility. The second balancing reserve is split into two types, either on call basis or contracted volume. Therefore, the categories in this thesis will be five in total, namely: *Imbalance, Primary balancing reserve (FCR), Secondary balancing reserve on call basis (aFFR), secondary balancing reserve contract basis, and tertiary balancing reserve.*

Criteria

Within these categories multiple different criteria were formulated. As already shown in **Error! Reference source not found.**, the most important criteria are *ramp-up/down time* and *duration* of the flexible power. It is also important to know on what *frequency* this flexibility is needed in the market i.e., how many times per week the flexibility is requested. And on what basis the flexibility needs to be present.

Some balancing reserves are only needed once a year, while others are needed every day. These categories and criteria are combined into a matrix as shown in Table 2. It is then possible to integrate industrial processes or steps into this matrix. A process can be inserted into the matrix, based on how it scores on the three criteria.

	Imbalance	**FCR**	**aFFR**	**aFFR (contract)**	**mFFRda**
Ramp up time	4 sec* / 15min	4 sec	5 min	5 min	15 min
Duration	15 min*	80 sec	30 min	30 min	120 min
Frequency	0%*	100%	8%	Once per three months	Once per three months

*Table 2 Flexibility criteria matrix (J. Kruijt, Personal communication, May 5, 2021, & TenneT, 2019a) *imbalance criteria are only based on the market incentive for the flexibility to be requested.*

This matrix is used to determine if a process is flexible, and on what level this process is flexible. For example, if a process step can ramp up or ramp down within 4 seconds, and stay like that for both 80 seconds, and 15 minutes. This process step is suitable for both *Imbalance* and *FCR.*

5.3 Energy load profile

In this section the energy load profile of every industry is presented, this is a combination of expert interviews and literature research. The results are presented for every sector specifically, where first an overview of the processes is explained, then the specific energy demand per step is given, this is explained in 4.3.

The industries that will be handled in this thesis are show in Table 3.

Chapter	Sector	Number of interviews
5.3.1	Animal feed industry	2
5.3.2	Edible oil and fat industry	1
5.3.3	Water board & WWTP	7
5.3.4	Paper and board industry	4
5.3.5	Beer industry	1
5.3.5	Potato processing industry	1

Table 3 List of industries in this thesis

In the documentation of the industries the following order is used. First, general information of the industry is described, with the number of companies and the size of these companies. Then the process steps of this industry are shown with a figure. This figure is then explained, with a focus on the steps that use energy (Electricity or heat). Finally, the flexibility options of this industry are discussed.

5.3.1 Compound animal feed production industry

General information

In total, representatives of two companies in this sector have been interviewed. The animal feed industry is the industry that produces food for domestic animals. The representatives of the two companies (Appendix B.16 & B.17) that are interviewed produce compound food specifically for livestock such as cattle, chicken, sheep, or pig. This is one of three subsectors of the animal feed industry: Compound animal feed industry, Dry pet food and wet pet food. In the Netherlands, around 150 companies exist within this industry, of which 20 are large companies (CBS, 2021). The production process is not complex but uses large amounts of energy (Table 4). The process is mainly batch based, because the customers of these companies mostly require a specific mix of ingredients which are weighted and mixed before the start of the process. The complete process is dry, this means that no water is added to the materials during the process. Only at the end, steam is used to be able to compress the pellets into bite size parts. The size of these parts depends on the animal that the feed is produced for. The average energy use of compound animal feed production per tonne is the lowest in the pet food industry, with an average of 0,05MWh/tonne (Santonja et al. 2019) or 0,032 MWh/tonne (Appendix A, conducted on 04-05-2021). Where dry pet food and wet per food consume 0,49 MWh/tonne and 0,75 MWh/tonne respectively (Santonja et al., 2019). Common materials in compound animal feeds sector are: storage silos, grinders, conveyer systems, mixers, conditioning units, press lines, coolers, boilers and dust abatement systems (Santonja et al. 2019).

	Company 1	**Company 2**
Average annual electricity consumption per factory	8.500 MWh	12.000 MWh
Average annual natural gas consumption per factory	7.680.000 m^3	1.080.000 m^3
Number of factories	9	6
Number or mills	10	-
Installed capacity of mill	135-400 kW	135-400 kW
Number of pellet mills	10	-
Installed capacity of pellet mills	110-710 kW	110-710 kW

Table 4 Company data from interviews animal feed industry

Process steps

In Figure 10 the process steps of the animal feed industry are shown. The process consists of 5 steps. After weighing and selecting the right ingredients for a specific batch, the raw materials enter a hammer **mill grinder (1).** This machine reduces large fragments to required size. A hammer mill can process multiple tonnes of raw material per hour and is able to turn on or off when needed. Usually, the usually installed power capacity is between 130 – 400 kW per mill., depending on the size of a hammer mill. Usually, multiple mills are installed parallel next to each other. After this step the ground material is transported to a **mixing (2)** machine. This machine mixes the ground material to a homogeneous blend. The electricity use of this machine is low and installed capacity is usually between 15 and 45 kW. Very large mixers use up to 132 kW. After this step the material is separated into two streams. About 20% of the material is directly ready for sale. The other 80% still needs to be pelleted. This makes the material easier to handle and increases the nutritional concentration. In this step the material is also heated, water is added to be able to be presses through a die. In this step 100% of the factories gas is used, and 40% of the total electricity is used. A typical **pellet press (3)** has an installed capacity between 110 and 710 kW. Usually, multiple of these machines are present in parallel in the factory. When the homogenous blend does not need to be pressed into bite size bits, the meal is only **heat treated (4)** to kill any harmful bacteria such as salmonella. The product is cooled with **air coolers (5)**, and the **packaged and transported (6)** to a truck.

The total time that a factory usually needs to handle one batch of material is 2.5 hours. Between all steps in the process, batches can be stored to be handled later. Also, at the end of the production line, product can be stored without any problem. This makes such a factory very suitable for demand side process management.

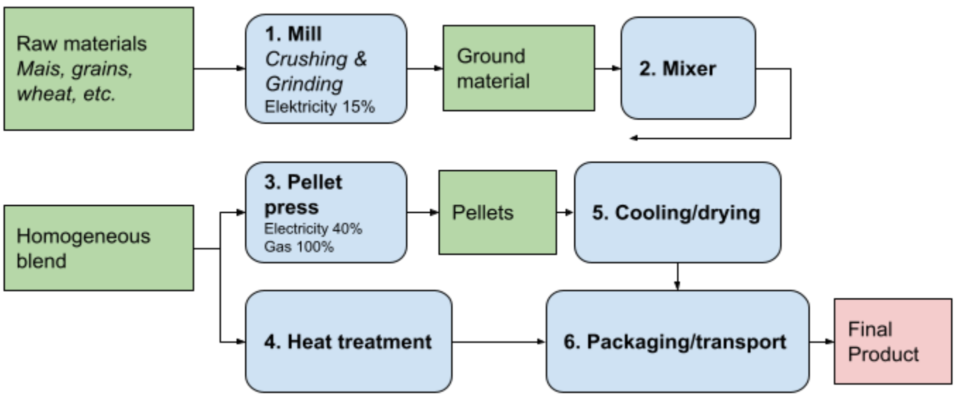

Figure 10 Process steps animal feed industry

Flexibility options - Without adjustments

Because of this, industry consist entirely of batch-processes. The whole process is dry; therefore, storage is no problem. After every step, a form of product storage is present, this makes the whole process flexible. Also, a prepared mixture could be made in advance, and when the energy prices are low, this next energy intensive step can be activated.

Flexibility options - With adjustments

Electric boiler

In industries where heat is an important factor in the process, an electric boiler can be a perfect option. This boiler will work together with the gas fired boiler of the location, and based on price signals, the boiler can be used to act most cost effective on the imbalance market. Also, due to the size of the boiler, it can contribute to the ancillary services to help balance the power system.

5.3.2 Edible oil and fat industry

General information

In the Edible oil and fat industry, seeds like rape, soya or sunflower containing oil are processed to make oilseed. In this research, a representative of one company has been extensively interviewed (Appendix B.1). The main applications for soybean oil are for cooking, as vegetable oil or used for oil paints or printing inks. The second product in this industry is the protein-rich meals, this is used for the animal feed industry. The EU a total of 50 oil mills are present. Oil mills are either integrated, where the produces oil is also refined, or stand-alone oil mills, where no refining takes place (Santonja et al., 2019). The company that is interviewed runs an integrated rape and soy oil mill. The main process of this industry is to crush the raw material and extract the oil. Factories process large quantities at the same time, and large amounts of power and heat is used (Table 5). Because the high heat and power demand, this factory has installed a CHP power plant. All the produced power is used in the factory, and some is sold back to the power system. When extra steam is needed in the process, a boiler is present that increases the heat to steam when needed. Furthermore, two bean dryer production lines consume gas for drying the beans. Finally, the crude oil refineries also consumer natural gas.

	Company
Average annual electricity consumption per factory	-
Average annual natural gas consumption per factory	33.650.000 m^3
Gas use CHP	15.000.000 m^3
Boiler	17.000.000 m^3
Bean dryer B	450.000 m^3
Bean dryer C	200.000 m^3
Refinery kettle 1	800.000 m^3
Refinery kettle 2	200.000 m^3
Daily amount of oil product	700 tonnes

Table 5 Company data from interview edible oil and fat industry

Process steps

In the production process of edible vegetable oils (see Figure 11) multiple steps are needed, which use large amounts of energy. The soybeans or rapeseed are usually transported by ships, and arrive at the factory, usually places at a harbour. First the material enters a **cracking system (1),** that crushes the seeds for the shell breaks, then the beans are **dehulled (2)**, in this step the skin or the bean is peeled off. In step 3 the beans are **conditioned (3)**, with the use of steam the beans are heated up and dried. Then the beans are pressed into **flakes (4)** and moved to the expander. The expander forms the flakes into highly dense and porous material, this ensures the high oil extraction. The collet flakes are transported to the extraction line, here the oil will be **extracted (6)** by a hexane extractor with Solid Liquid Extraction (SLE). The mix of hexane and wet meal or oil are then processed through a **desolventiser toaster (DT) (7 & 8),** with indirect heat and steam the hexane removed and no solvent is present anymore in the mix. The meal passes through a **toaster (9)** and then a **cooler (10).** In this factory also a CPH engine is present that creates the desired heat and electricity. This CHP is backed-up by a gas boiler to make sure the heat demand is met.

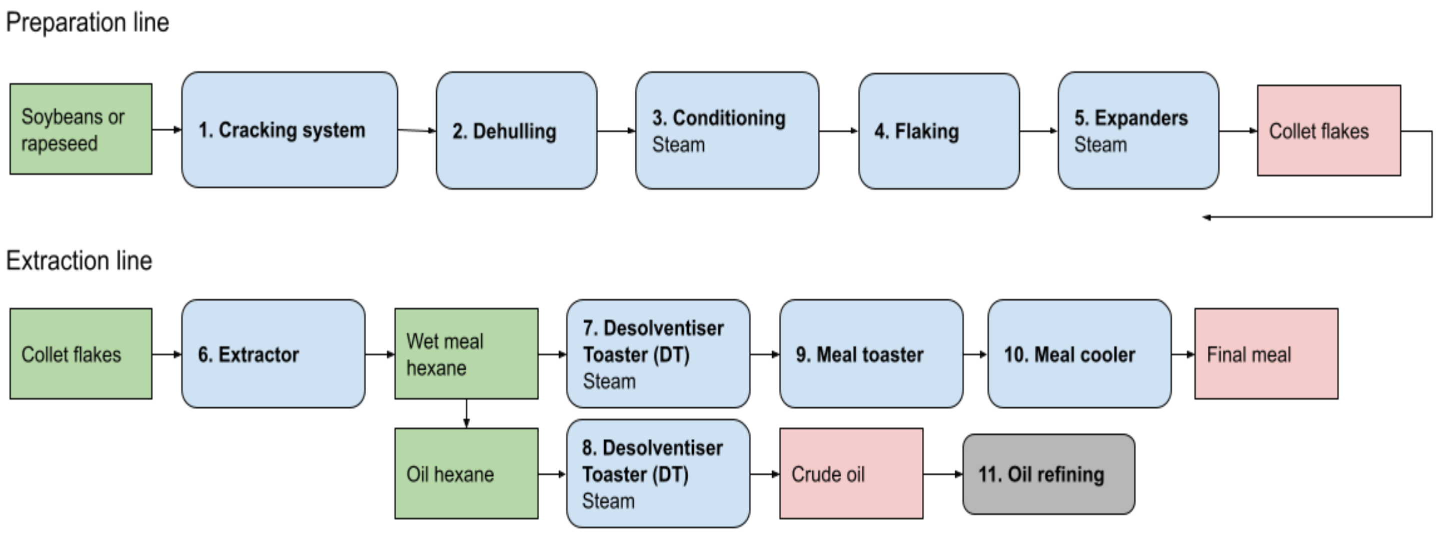

Figure 11 Process steps edible oil and fat production

Flexibility options – With adjustments

E-boiler

Due to the high heat demand in this sector the implementation of an e-boiler can create financial benefits. Together with the Gas boiler and CHP the e-boiler will provide the factory with a choice based on price signals.

5.3.3 Water management and wastewater treatment

General information

During data gathering seven expert interviews were conducted within this sector (Appendix B.7 to B.14). Water management and sewage treatment companies are owned by the Dutch government. The two main activities of these companies are treating sewage water and maintaining correct surface water levels in their service area with pumping stations, locks and. There are currently 22 water management companies in the Netherlands. Because these companies have two independent activities, these will be handled in separate parts: 5.3.3.1 Wastewater treatment plants, and 5.3.3.2

Flexibility options – Without adjustments

Dewatering of sludge

One of the last steps of the process is the dewatering of the sludge before it is transported to a sludge incineration plant. This process only requires electricity and uses around 5% of the total electricity use of a WWTP. This step is flexible because there is a storage tank before, and after the dewatering unit. Depending on the size of the

Table 6 Flexibility of dewatering of wastewater sludge

Criteria of flexibility	Value
Duration	-
Ramp-up/down	4 sec
Frequency	100%

Flexibility options – With adjustments

Aeration step

The aeration process step in WWTP consumes around 80% of all electricity. The total electricity use depends on the size of the WWTP. This process air is blown into the sludge to activate the bacteria that process the sludge. Until now the blowers of the aeration are activated based on the amount and dirtiness of inflow of sewage water. This is a biological process, and therefore not flexible by itself. However, if a compressed air storage tank is introduced into the system. This creates the possibility for the compressor pumps to operate only if prices are beneficial. This could mean that the process of WWTP could be added to the flexibility market with 80% of their electricity use.

Water pumping stations.

In the Netherlands around municipal 400 WWTP are present, which are mostly operated by water board institutions. The process of the treating wastewater is similar in all facilities, and the share of energy consumption per process step is also the same for all facilities. The total amount of energy used per plant differs per size. Some plants do not process their own sludge, this is transported to a near sludge processing facility, or to another WWTP.

Because of the number of water authority organisations that have be interviewed, and many were willing to share metering data. This sector is also worked out in further detail in a case study in Chapter 6 of the thesis. The possibilities of both WWTP and water pumping is assessed.

Process steps

5.3.3.1 Wastewater treatment plants (WWTP)

One of the main activities of Water boards in the Netherlands is the treatment of municipal sewage water. This process requires heat and electricity, as shown in Figure 12. The main goal of these activities is to clean the sewage water from organic and hazardous materials. First the water is passed through a **grit removal (1)** station to remove large items in the water, this is to prevent damage to facility equipment. The next step in this process is the **pumping (2)** of sewage water out of a storage area to the beginning of the treatment process. These pumps require around 15% electricity of the total electricity use of the treatment plant. Then the sewage water enters a **primary settling (3)** tank. In this tank organic material sinks to the bottom and is pumped away, this is called primary sludge. The cleaner surface water flows to the **aeration tank (4).** In this tank active bacteria are present that in combination with added oxygen activates the aerobic reaction of the sludge. This process step uses 80% of all electricity use of the WWTP facility, where compressors are used. In the **second settling (5)** tank the activated sludge can sink to the bottom and is again pumped away as secondary sludge.

Both primary and secondary sludge is then pumped into a **sludge fermentation (6)** unit. The sludge will remain for around 30 days in these tanks. It is heated up to 36 degrees Celsius and anaerobic fermentations occurs. Among other gasses, biogas is produced and used either in a **biogas CHP** unit, or upgraded to natural gas to be pumped into the national gas power system. The biogas CHP is used to produce electricity and heat. The heat is used in the sludge fermentation process, and the electricity is either sold back to the power system or used in the different steps in the process. After this step the sludge goes to the **centrifugal dehydrator (7)** unit, which uses 5% of the total electricity of the facility. This removes the high-water content from the sludge. After the dewatering the sludge is then transported to a sludge treatment plant to be incinerated.

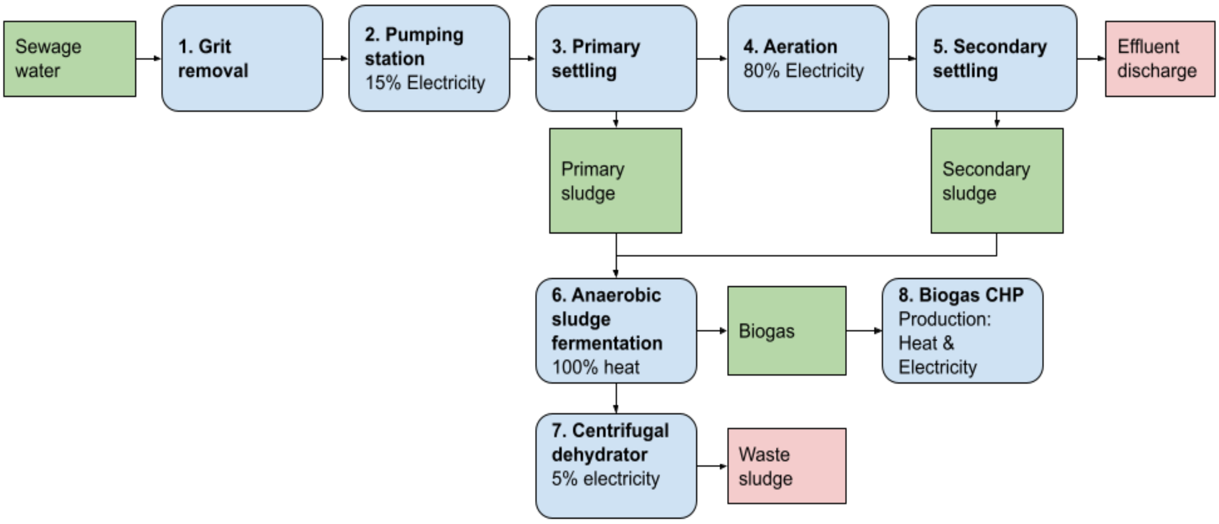

Figure 12 Process steps Wastewater treatment plants

Flexibility options – Without adjustments

Dewatering of sludge

One of the last steps of the process is the dewatering of the sludge before it is transported to a sludge incineration plant. This process only requires electricity and uses around 5% of the total electricity use of a WWTP. This step is flexible because there is a storage tank before, and after the dewatering unit. Depending on the size of the

Table 6 Flexibility of dewatering of wastewater sludge

Criteria of flexibility	Value
Duration	-
Ramp-up/down	4 sec
Frequency	100%

Flexibility options – With adjustments

Aeration step

The aeration process step in WWTP consumes around 80% of all electricity. The total electricity use depends on the size of the WWTP. This process air is blown into the sludge to activate the bacteria that process the sludge. Until now the blowers of the aeration are activated based on the amount and dirtiness of inflow of sewage water. This is a biological process, and therefore not flexible by itself. However, if a compressed air storage tank is introduced into the system. This creates the possibility for the compressor pumps to operate only if prices are beneficial. This could mean that the process of WWTP could be added to the flexibility market with 80% of their electricity use.

5.3.3.2 Water pumping stations

The main activities of water pumping stations are keeping the groundwater at the right level. Within the water board companies in the Netherlands the activities in water pumping vary more than in sewage treatment plants. Water is elevated from lower ground to higher waterways, or into the sea, in order for the ground water level is at the right hight. Especially for regions where the seawater level is higher than the ground level, a lot of electrical power is spent on the pumping of water. This is mainly needed where drainage with gravity is not possible. Water pumps require electricity to operate and are remotely controlled. Figure 13 shows a schematic overview of how water pumping stations work.

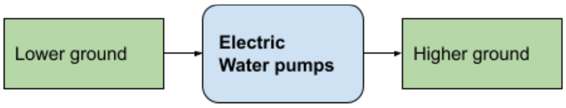

Figure 13 Schematic overview of a water pumping station

Flexibility options

Water pumping stations

Another activity that is already flexible are the pumping stations of water board companies. The main activity of these stations is to maintain the water level of a certain area. When it rains or due to seepage through dikes the pumps need pump this water away. This pumping activity uses electrical energy. The pumping activities are flexible in the sense it is possible to adjust the electricity consumption.

Table 7 Flexibility of water pumping stations

Criteria of flexibility	Value
Duration	Several Hours
Ramp-up/down	3 – 30 minutes
Frequency	100%

5.3.4 Pulp, paper, and board industry

General information

In this report four companies have been interviewed, of which two paper manufacturing companies (Appendix B.4 & B.5) and one board manufacturing company (Appendix B.3) and one interview has been deducted with the Dutch paper and board sector organisation (Appendix B.6). *''Paper is essentially a sheet of cellulose fibres with a number off added constituents, when necessary, to affect the quality of the sheet and its fitness for the intended end use.''* (Suhr et al., 2015). In this process both heat and electricity are consumed in large amounts. The paper making process consists of three parts, the pulp production, the stock preparation, and the paper making process (Suhr et al. 2015, Rademaker & Marsidi, 2019). In the paper mill and board industry either virgin fibre or recovered fibres are used as main raw material. In the Netherlands only one paper factory exist that produces pulp from virgin fibres (Rademaker & Marsidi, 2019). Virgin fibres come directly from trees, while recovered fibres come from recycled paper and board. The average energy demand in terms of electricity is between 1 and 4 GJ/tonne product, while in terms of steam demand this is between 4 and 6.3 GJ/tonne product.

Process steps

Mills usually receive fibres with around 10% moisture content. With a **pulper (1)** the fibres are suspended in substance that can be pumped. Pulping can be done either done chemically of machinal. In chemical pulping Kraft pulping is the most prominent with 75% of use in the paper industry (Bajpai, 2015). After the pulper a storage tank is available, but this is not very large, therefore this step does not contain much flexibility (Appendix B.4). The slurry needs to be **screened and cleaned (2)** from unwanted impurities. The **refining (3)** step is carried out to improve the bonding. In the refining step a set of two discs move relative to each other, the material flows between the two discs. The distance between the two discs can be adjusted based on the quality of the desired end-product. The refining process uses between 10 to 500 kWh/tonne but can be up to 3000 kWh/tonne. Therefore, the refining process usually consume the most electricity in a paper mill (Suhr et al. 2015) After the stock preparation is done, the material is pumped into storage or mixing tanks. This acts as a buffer for the continuity of the whole process (Suhr et al. 2015 & Appendix B.4 &B.5) The next part of the process is the paper machine. Here the material is **dewatered (4), pressed (5), dried (6),** and **put** on to large **rolls (7).** This is an energy intensive process because the solid content of the material needs to be brought to at least 95% (Bajpai, 2015).

The final finishing steps include **coating (8)**, **cutting (9)**, and **finishing (10)**. The final product is either finished rolls, or pellets of cut stacked paper sheets. (Appendix. B.4 & B.5)

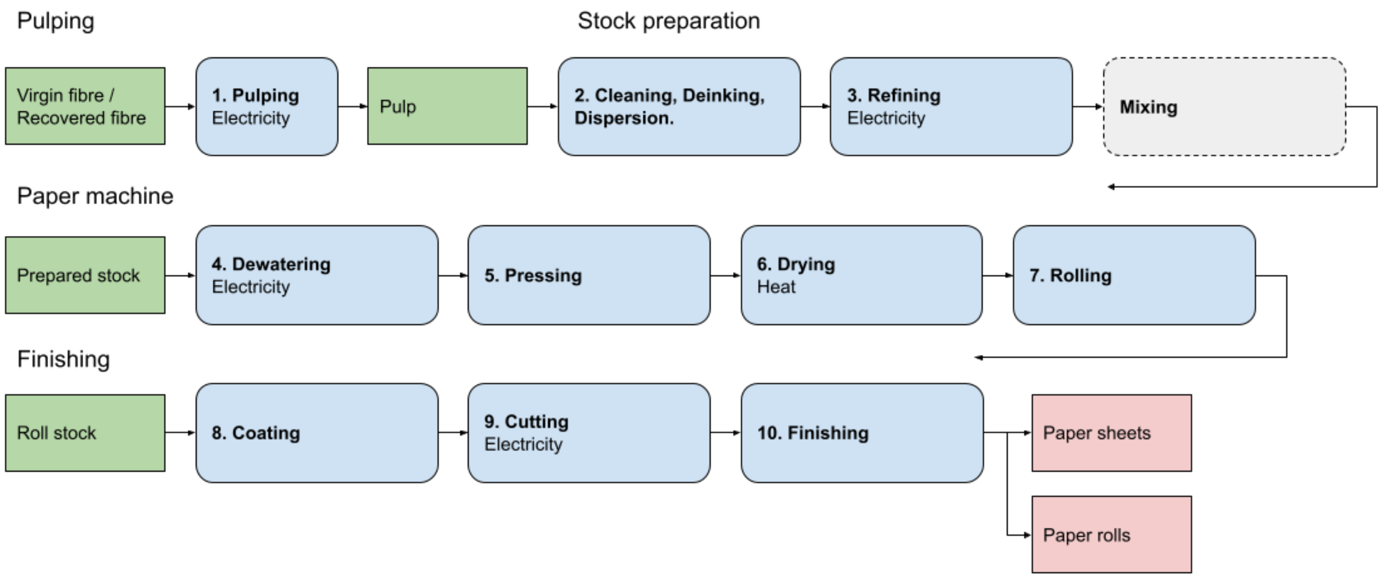

Figure 14 Process steps paper and pulp industry

Flexibility options – without adjustments

Compressed air

The paper and board industry used compressed air for the pneumatical machines to work. And to blow away dust and excess paper in the milling machines. Compressed air is needed when the machines operate. But not always on the same level, introducing a form of compressed air storage, the compressed can be operated based on price signals. The duration depends on the size of the storage tank. Without any changes, this is at least three minutes.

Table 8 Flexibility of compressed air in paper and board industry

Criteria of flexibility	Value
Duration	3 minutes
Ramp-up/down	4 seconds
Frequency	100%
Installed capacity	1 MW

Steam accumulator

In paper factories steam accumulators are present. These devices can store steam to be used for a later moment. In one of the factories this steam accumulator a storage capacity is present for 15 minutes of steam use.

Table 9 Flexibility of a steam accumulator in paper and board industry

Criteria of flexibility	Value
Duration	15 minutes
Ramp-up/down	-
Frequency	100%

Pulping machine

In the beginning of the process of paper making, recycled paper enters the factory and is transported through a pulping machine. These machines have a storage possibility before, and after this process step. Therefore, the step itself is flexible, and can be managed based on external incentive such as price signals. At a large factory this is a process that can turned higher or lower. The maximum amount of time the crushed paper can stand still is a couple of hours.

Table 10 Flexibility of a pulping machine in the paper and board industry

Criteria of flexibility	Value
Duration	>1 hour
Ramp-up/down	-
Frequency	100%
Installed capacity	1 MW

Pulp refiner

This process comes after the pulping machines. In between a storage tank is present that can store the processed material. A refiner processes the pulp fibres together with water into a mixture of a certain consistency. After this step also a storage tank is present. The stand time in this tank can be a couple of hours. The refiners usually operate around 50% capacity factor.

Table 11 Flexibility of a pulp refiner in the paper and board industry

Criteria of flexibility	Value
Duration	3-4 hours
Ramp-up/down	-
Frequency	100%
Installed capacity	4 MW

Flexibility options – with adjustments

E-boiler

Also, in this industry an e-boiler can be used to produce steam with electricity for the heat demand. Also, in this industry it is a very suitable option to increase the flexibility. According to Rademaker & Marsidi (2019) e-boilers are very suitable for the paper and board industry and will increase their flexibility.

5.3.5 Other sectors

Potato processing industry

General information

In this research only one company had been interviewed (Appendix B.21) therefore this sector is only explained in general. The potato processing industry in is part of the fruit and vegetable processing industry. In this process raw materials in the form of potato's are processed into different types of end products such as potato chips of fries. This process consumers both heat and electricity, and is therefore approached in this research. The product is either boiled in water, fried in oil, or grinded into flakes and granulates. In order to store the product it is usually thermal treated, dried and frozen or cooled (Santonja et al., 2019).

Process steps

Process steps include: Washing → grading → peeling → cutting → blanching/boiling/frying → cooling → packaging → storage (cooling/freezing).

The most energy intense steps based on electricity are peeling, cutting and cooling or freezing. Where the most heat intense steps are blanching, boiling and frying.Multiple peeling methods are available such as mechanical peeling, steam peeling and caustic peeling.

Potato fries are often blanched with steam or water generally around 60 to 85 °C (Santonja et al., 2019 & Appendix B.21). after blanching the potatoes are dried and fried. Frying usually is done between 160 and 175 ° (Santonja et al., 2019). Freezing of the product is done either with a fluidised bed freezing installation or with belt freezing (Santonja et al., 2019).

Flexibility options

Beer industry

General information

In this industry only one company has been interviewed (Appendix B.18). The Beer industry consists of two main parts, the malting factories, and the brewing factories. Sometimes these factories are integrated, where both activities take place. But mostly the two are separated, which was also the case for the company that has been interviewed. In this process both heat and electricity are used. The whole process takes between two and five hours.

Process steps

The process begins with imported and prepared malt. This is mixed → Mashed → boiled → separated → Cooled → Fermented → Matured → Filtered → Packaged.

The most energy is in the boiling and cooling step, where mostly steam and electricity are used.

Flexibility options

In the process not many flexibility options are available. There is a possibility of adding steam accumulator, or an e-boiler. But the scale of this factory is not sufficient to make this work.

5.4 Summary results

In this paragraph a summary of alle results is presented. Here, all flexibility options are listed, together with the type of flexibility.

Table 12 Summary of flexibility options

	Duration	Ramp up/down	Frequency	Type of flexibility
Dewatering of the sludge	-	4 sec	100%	FCR
Water pumping stations	Several hours	3-30 minutes	100%	FFR/mFFRda
Compressed air	3 minutes	4 seconds	100%	FCR
Steam accumulator	15 minutes	-	100%	-
Pulping machine	>1 hour		100%	FFR
Pulp refiner	3-4 hours		100%	FFR
e-boiler	Minutes to hours	-	-	FFR/mFFRda

6 Case study

6.1 Introduction

After the preliminary analysis and the interviews with different experts in the Dutch industry, a case study is performed. In the previous chapters of this research the flexibility of different sectors is analysed based on expert interviews and literature research. In this case study one sector is analysed in more detail. A model is written to show to what extent this sector could contribute to the balance of the power system, and what economic benefit it could have been for this water board company. The sector that is analysed in more detail are the water board authorities. To execute this case study bot Enova and Daltares were interviewed to provide knowledge. In this analysis the total amount of energy that will be contributing to imbalance market will be calculated, as well as the theoretical economic benefit. Because the analysis is complicated with many factors influencing the outcome, some assumptions have been made (6.2.2).

6.2 Method

6.2.1 Objective

The objective of the case study in this research is two ways, on the one hand the analysis can determine on what level the water management sector can contribute to the balancing of imbalance market. On the other hand, the analysis is used to determine what the financial gain would be for the company itself. Therefore, the objective is: Determine to what extent DSR by water board authorities can contribute to balancing the power system and estimate the economic gain for that company.

6.2.2 Assumptions

- The water level of the streams is not considered.

The electricity use of water pumps is based on the difference in height it must overcome to pump the water. In this analysis this height difference is not taken into account due to the complexity.

- Electric water pumps operate stepless.

Electricity consuming units often operate based on different steps in consumption. In this analysis it is assumed that the consumption of unit is stepless, between the full range between zero and the maximum capacity.

- Ramp-up and ramp-down is not considered.

The ramp-up/down time is not considered due to complexity of modelling. Therefore, in some extreme cases the pumps consume maximum power in one PTU and are zero at the following PTU.

- During an imbalance settlement period, the consumer does not know what the definite price will be for that PTU. In this model the imbalance price is used as if the imbalance price is already known in the beginning of that PTU.
- It is also assumed that the deficit or surplus must not be higher than a certain share of to the rolling forecast. This creates a virtual ''buffer'', and therefore the model will not get extreme values. Even when the imbalance prices are extreme for a longer period. The level of this buffer can be adjusted in the model.

6.2.3 Data collection

Energy use data for this analysis is provided by water board company Scheldestromen. The market price data is made publicly available by TenneT, and Entsoe. The time series are the same for all data and range from 01-01-2020 00:15:00 to 31-12-2020 23:59:59 and include all 15-minute time stamps of that year.

Table 13 Variables and unit case study

Data type	Unit
Electricity use	MWh/PTU
Maximum Installed capacity of power consuming unit	MW
Capacity of buffer	%
APX price	€/MWh
Imbalance price upward	€/MWh
Imbalance price downward	€/MWh

Table 14 Summarizing statistics case study

	Value	Unit
Annual electricity use	6.910	MWh
Average daily us	18,8	MWh
Installed capacity	8,73	MW
Average APX price	32,24	€/MWh

6.2.4 Analysis

In the analysis the theoretical revenue will be estimated from a pump system, if it were acting on the imbalance electricity market that time. In this analysis three possibilities are present:

Possible situations

The first situation is when the imbalance price is the same as the APX price, now the company does not need to change anything in their actions. The second situation is when the imbalance price is lower than the APX price on that moment. This means that the company must increase their energy use to take advantage of the surplus renewable energy. The third situation occurs when the imbalance price is higher than the APX price on that moment. This gives an opportunity to sell the electricity that was bought in the day-ahead for a higher price. The company will then use less electricity at that moment so the difference can be sold.

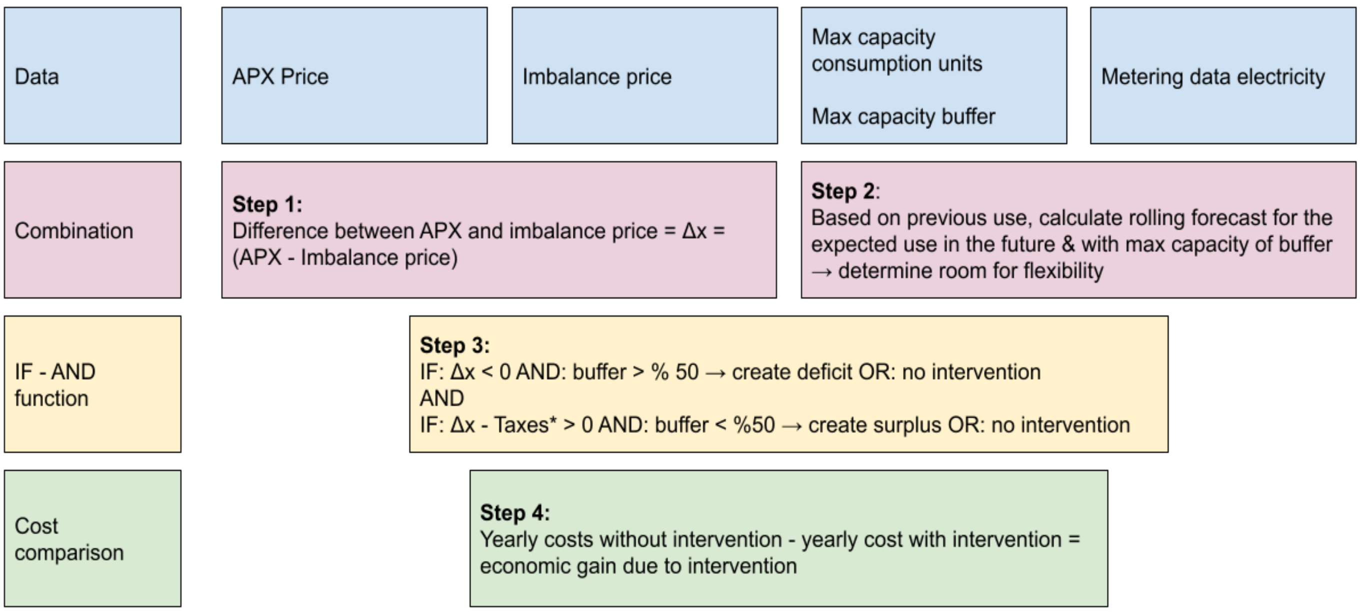

*Figure 15 Steps in the revenue estimation for the case study (*When consuming electricity taxes must be paid: ODE (€30) + EB(€9,42) = €39,42/MWh) as explained in 2.1.2.)*

Steps in analysis

To execute this analysis a model is built in Microsoft Excel. This model uses the electricity prices of certain year and combines this with the energy use data from a company. The steps of this analysis are shown in Figure 15 explained below:

Step 1: Calculate the difference between the APX and the imbalance price for every single 15-minute time frame. For both subtracting from and delivering to the power system. In this step also the different taxes for electrical power use are considered as described in Chapter 2. The sum of these taxes is €0,09428 (energy tax) + €0,0300 (ODE) = €0,039428 (Dutch tax authorities, 2021). Thus, for every MWh that is consumed, a total of 39,42 of taxes must be paid too.

Step 2: Determine the capacity factor of the electricity usage at that point in time. This is done by comparing the amount of usage at that point with the total capacity of the units. This gives an image on the amount usage the units can increase or decrease at that time. Also determine the total power use for that day, this is done with a rolling forecast. So, the model does not ''know'' what the situation in the future will be.

Step 3: Calculate the amount of power the units will increase due to a certain price signal. Then sum up all the energy the units have used more, and subtract the energy that the units used less, on a single day.

Step 4: Multiply the usage with the prices at that 15-minute time frame with the power use. Sum this up for the whole year and compare to the scenario with no intervention.

6.3 Result

In this section the main results are described. First the electricity prices of 2019 are described in 6.3.1. Then an example day is given to show how the model works. The 28th of January is a good example because on this day the model frequently intervened with the normal pumping activities. Secondly, the baseline profile of the water pumps for one day in that year are described in 6.3.2. Thirdly, the effect of the market price on the water pumping activity are presented in 6.3.3, the estimated economic gain in **Error! Reference source not found.**., and finally the final results in **Error! Reference source not found.**.

6.3.1 APX price and imbalance prices 2020

In TABLE X the electricity prices for 2020 are shown. Based The average APX price in that year was €32,24. Where at the lowest the APX was €-79,19 and the highest was €200,04. The range of the imbalance prices in 2019 was between €-561,17 and €797,23. The biggest difference between the APX price and the imbalance price was for downward bidding €550,00 and for upward bidding €670,85.

Table 15 Key values electricity prices 2020

	Value
Average APX	€ 32,24
Min APX	€ -79,19
Max APX	€ 200,04
Min imbalance price	€ -561,17
Max imbalance price	€ 797,23
Max difference APX and imbalance price (downward)	€ 550,00
Max difference APX and imbalance price (upward)	€ 670,85

6.3.2 Baseline profile

As shown in Figure 16 the baseline profile of the water pumps is visualized. The data is per PTU, so the values that are shown are the amount of MWh those pumps used per fifteen minutes. The pumps operate based on water levels between the lower and the higher ground. This metering data is provided by water board Scheldestromen on the 28th of January.

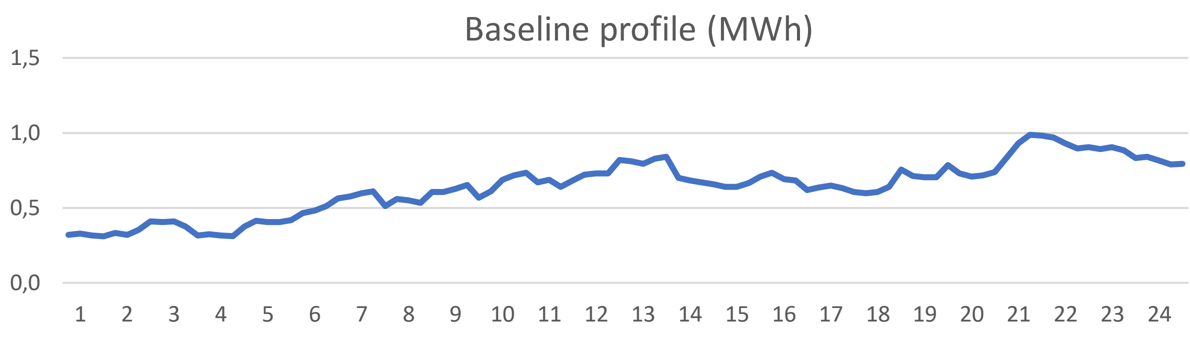

Figure 16 Baseload profile pumping activities for an example day

Figure 17 shows the development of the APX price and the imbalance price on the 28th of January is shown. The black line is the APX price, the blue line is the imbalance price. The bar chart shows the difference between the APX and the imbalance price where the green bars indicate that the price is positive and red bars mean it is negative. This difference determines whether the model decides to consume more or less than without an intervention at that moment. When the difference in price is positive the imbalance price is higher than the APX price, so the model decides to sell the at a higher price, and not turn on the pumps. Therefore, a deficit is created compared to the expected pumping estimation. If the difference is negative, the model decides to pump more than it was planned to do, and therefore creates a surplus.

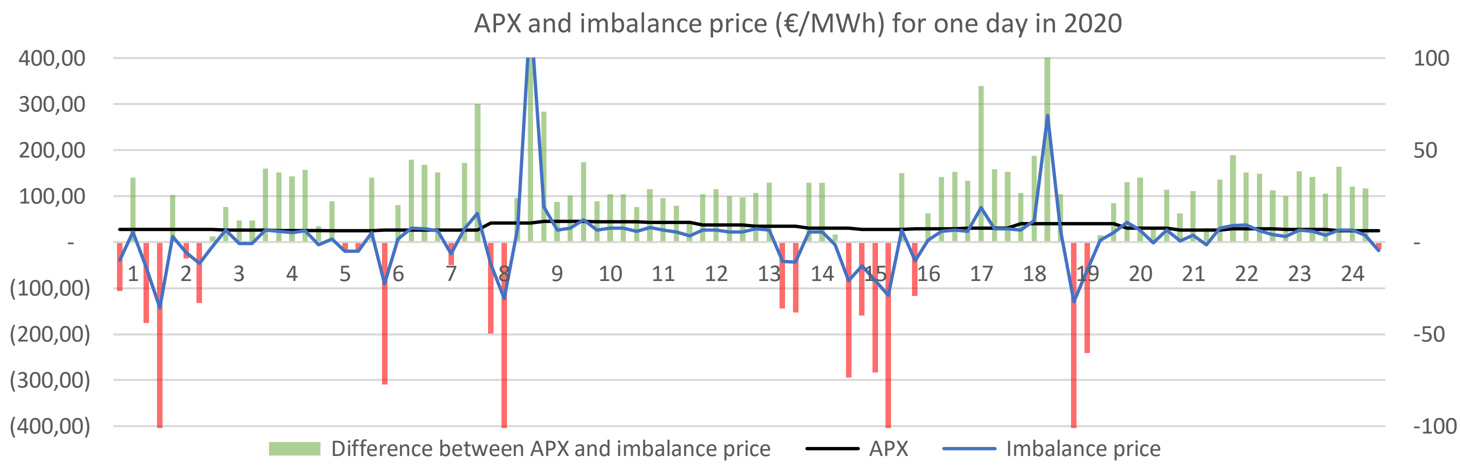

Figure 17 APX and imbalance price for one day in 2020

6.3.3 Effect of energy market price on electricity use

The model uses input from the electricity prices in Figure 17 and the baseload from Figure 16Figure 18 to determine if it needs to adjust the normal pumping activity. This is shown in Figure 18. The baseload, and the adjusted energy use is visualised in the same graph, together with the electricity prices. This shows that the model decides for every PTU how much power it will consume. On every PTU the model chooses the most cost-effective option, this leads to a revenue of €770. The model does the same calculation for every day. When added up the total revenue recording to the model is €104.257, which is very high compared to the estimated total electricity costs of €226.000, this revenue is very high.

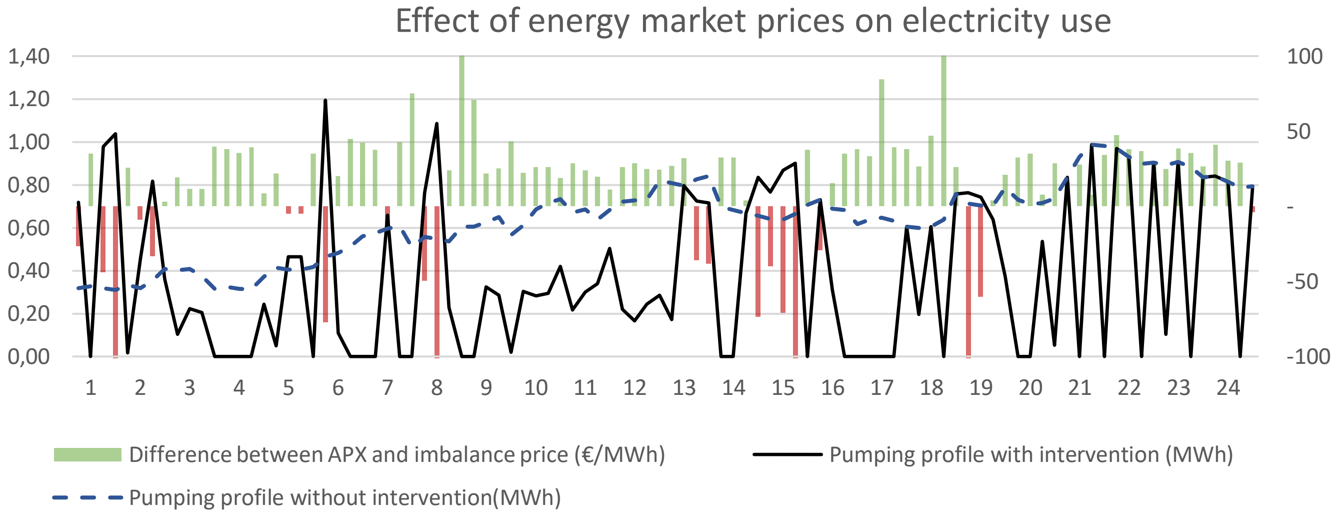

Figure 18 The effect of electricity prices on electricity use

6.4 Conclusion and recommendations case study

This economic gain is only an upper bound of the possibilities of demand side management. With a more sophisticated model, with more constraints, this upper bound can only be lower. However, looking at the results from the analysis, unlocking the flexibility of water pumping companies can prove a useful source of income. However, in this analysis many assumptions are done due to time constraints and complexity of the pumping process. With interpreting the outcome of the case study, caution should be taken.

7 Discussion

7.1 Discussion of results

The share of VREs will continue increasing in the next decades, associated with additional challenges. The disbalance of electricity production and consumption comes with intermittency problems. This thesis contributes to addressing this problem by providing an overview of large players in the energy market that can contribute to the flexible power system through an aggregator company. This is done by exploring energy load profiles of companies and opportunities of utilising flexibility. Bidirectional communication infrastructures will enable demand response and unlock flexible power from end users. Peak shaving and load shifting are the two most important demand response concepts for flexibility. Flexibility can take many forms and still be both valuable for the consumer in an economic way, while at the same time suitable for contributing to the stability of power system.

This research finds that large energy consumers in the Dutch industry, especially present in manufacturing sectors, with processes that use both large amounts of electricity and heat, are suitable candidates of containing unlocked flexible power. Also, industries that use large amount of compressed air are a suitable candidate for flexible power demand. Compressed air can be stored easily and it is possible to add storage capacity for further load shifting. However, further research is strongly advised to identify challenges that arise in implementing this technology, such as valve leaking. According to Stadler & Bukvić-Schäfer (2003), compressed air investment costs are 180 euro per kWh. As described by various scholars, compressed air could be used to store energy, which is in a later stage is converted back to electricity (CAES). In the industry sector, many applications for compressed air are present where the conversion in a PCS back to electricity is not necessary (Stadler & Bukvić-Schäfer ,2003), especially in WWTPs and the paper and pulp industry. It is important to assess efficiency loss implications like higher pressure band, or higher compressor wear-out, but it is likely that this will not weigh up against the conversion losses to electricity is CAES (Beier et al., 2015).

Due to new technological developments in power to heat technologies, and with the support of subsidies, an increase in electric boilers in the coming decades cannot be ruled out. This increase in electric boilers creates many opportunities for flexible demand response, where consumers in the industry sector can choose between gas or electricity for heating their water to produce steam. The availability of an electric boiler also increases the potential of factories to contribute to the stability of the power system. Therefore, subsidies might work in two ways. Even though the implementation of an e-boiler requires high investment costs, it also creates opportunities for creating extra revenue with the increase of flexibility. If a company decides to install an electric boiler, it is important that the flexibility can be used for their own balancing program through an aggregator company, instead of outsourcing this to a large energy supplier. This way, the company will not miss out on economic revenue.

Demand side management based on production processes, where processes are stopped, slowed down, or turned up for a certain amount of time, remains a challenge. The availability of any form of storage is critical to make a production process flexible. This is the case in the paper industry as well in as in the animal feed industry.

For the stability of the power system, production processes in industry are an important balancing factor. However, the knowledge and technology to benefit from flexibility is still limited. With the increasing need for flexibility, and the increase of companies that need to contribute to balancing services, aggregators fulfil a key role. Flexibility works best when combined in a large ''pool'' where the disadvantages of deviating from normal activities is not needed due to the diverse load profiles of other agents in the pool.

The water board sector that has been analysed on a deeper level resulted in the following key findings. With a total electricity cost of €226.000, a revenue of €104.257 is estimated. However, the activities of water pumping companies are difficult to generalise, due to the large difference of topographic factors.

7.2 Limitations & recommendations

A number of limitations are worthwhile to consider regarding the findings of this thesis. In the process of gathering interview data from participants, some form of bias could be present. This can be in the form of self-selection bias. Approached interviewees that agree on conducting an interview will usually be more interested in the sustainability topic than people who did not answer. Therefore, it is possible that the outcome of this thesis is overestimated.

The limited time frame of this research could have also played a role in the depth. Not all sectors that are determined in the preliminary analysis are interviewed, and therefore could not be included in this research. The companies that have replied and agreed on conducting an interview have however proved to be suitable for flexible power. Therefore, it is essential that in further research also the other sectors should be approached and spoken to on the same way that has been done in this interview, see appendix A.3 for example questions.

The results of the case study on a water pumping company are very positive. However, caution must be taken in interpreting these results. This research did not take all constraints and factors into account when executing the analysis. Examples of these constraints are the effect of water levels on the ecological or agricultural processes and the fact that institutions like water boards may not be willing to take risks on the energy market. In this case study, only the possible economic revenue was assessed, to determine an upper bound to be considered for further research.

Regarding the results and the limitations of this research, some recommendations can be made. The method of finding flexibility in industrial sectors proved effective as there were new flexibility options revealed in most sectors. If this study is executed more extensively, with more sectors, it is possible that more new flexibility is unlocked. Also, awareness on the presence of flexible power could be increased. This could involve either market-based stimulation, by informing industrial sectors of the existence of financial compensation when contributing to the balance of the power system, or by implementing some form of reward for being flexible, either economically or based on reputation. This way, flexibility could provide tangible and intangible benefits for both energy consumers and aggregator companies.

Further research should not only be done in exploring the possibilities in other sectors that are not included in this research, but also deeper insights are needed into the sectors that are included in this research. Flexibility options revealed in this thesis still must be proven based on feasibility and economic efficiency when deployed in real life.

This research only focussed on the possibility of demand response in the industrial sector in the Netherlands. In other countries the same intermittency problem is rising, and therefore this thesis can also be of use in other countries. Demand response in only one of four pillars that ensure flexibility next to *dispatchable power plants*, *energy storage* and *interconnections (Okur, 2021)*. Therefore, this research only contributes to one part of the solution to the intermittency problem.

8 Conclusion

The current trend in the development of the energy transition, with the increasing share of VREs, puts pressure on the stability of the electrical power system. With the increase of electrification in the Dutch industry, together with subsidy policies, new chances of adding balancing resources to the power system are rising. The objective of this research was to identify to what extent the flexible power from large energy users can contribute to solving the increasing intermittency problem from RES penetration in the Dutch electricity system. This question was answered with extensive literature and semi-structured interviews, data research, and further analysed through the lens of a case study. Many different sectors in the Dutch industry have been investigated. The interviews resulted in useful insights in the possibilities of flexibility from the Dutch industry. This study found that looking at specific industrial processes revealed opportunities for unlocking flexible power to the power system, through the use of an aggregator company. In some cases, this flexibility can be utilized immediately. In other cases, an adjustment, either in the process or in equipment, is needed. The method of approaching companies within energy intensive sectors, for both heat and electricity, proved to be successful. In sum, this research finds a range of opportunities to unlock flexibility in the power system, especially within the industry sector, which provide valuable insights into opportunities to address the emerging intermittency problem.

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Appendix

A.1 Interview data

Function	Sector	Sub-sector	Date	Time	Place
Environmental Manager	Edible oil and fat industry		19-4-2021	13:00	Online
Chief Operating Officer	Paper and board industry		1-4-2021	14:00	Capelle aan den IJssel
Energy and Environment	Paper and board industry		26-5-2021	10:00	Online
Manager technology and engineering	Paper and board industry		27-5-2021	11:00	Online
Project Coordinator	Paper and board industry		19-4-2021	15:30	Online
Energy policy	Water Management		28-4-2021	14:00	Online
Coordinator Energy	Water Management		28-4-2021	15:00	Online
Energy transition and circular economy	Water Management		30-4-2021	12:00	Online
Energy Coordinator	Water Management		19-5-2021	10:00	Online
Energy Consultant	Water Management		19-5-2021	13:00	Online
Energy Consultant	Water Management		19-5-2021	14:00	Online
Energy Consultant	Water Management		08-6-2021	16:00	Online
Energy Performance Manager Electricity	Iron and steel industry		29-3-2021	12:00	Capelle aan den IJssel
Plant Manager	Animal feed industry		15-4-2021	11:00	Online
Plant Manager	Animal feed industry		4-5-2021	13:00	Online
Plant Manager	Beer industry		13-4-2021	16:00	Online
Manager Technical services	Potato processing industry		21-4-2021	10:00	Online

A.2 Results MCA

	Electricity use	Electricity production	Gas use total	Gas for electricity	Heat Use	Heat production	Suitability
Vegetable and fuit processing	1	1	1	1	1	1	6
Edible oil and fat's	1	1	1	1	1	1	6
Dairy	1	1	1	1	1	1	6
Grain mill products and strarches	1	1	1	1	1	1	6
Paper and pulp	1	1	1	1	1	1	6
Industrial gasses	1	1	1	1	1	1	6
Other inorganic basic chemicals	1	1	1	1	1	1	6
Other organic basic chemicals	1	1	1	1	1	1	6
Fertilisers and nitrogen	1	1	1	1	1	1	6
Iron and steel	1	1	1	1	1	1	6
Sewage water collection and treatment	1	1	0	1	1	1	5
Animal feed	1	1	0	0	1	1	4
Beverages	0	1	0	1	1	1	4
Pharmaceutical products of preparations	0	1	0	1	1	1	4
Concrete	0	1	0	1	1	1	4
Waste treatment	0	1	0	1	1	1	4
Wood industry	0	1	0	0	1	1	3
Dyes and pigments	1	0	0	0	1	0	2
Ceramics and clay	1	0	1	0	0	0	2
Collection, purification and distribution of water	1	1	0	0	0	0	2

Figure 19 Preliminary multi criteria analysis of target group

A.3 Questions semi-structured interviews

Interviews are conducted in a semi structured way. The same questions are asked, these are listed below. All interviews are recorded via Microsoft Teams transcribed and stored on a hard drive, and can be provided on request, due to privacy reasons the interviews are not made publicly available.

- Is there a general PowerPoint that you can share on how the process of the company works?
- What are the different steps in the production process?
- What amount of energy is used in these different steps?
- On what frequency is this capacity needed, and for what extend of time?
- How much time do these processes take?
- On what level can these processes be turned higher or lower, without losing product quality?
- Are there buffers available in the process. Is there any kind of storage possible in the process?
- What is the capacity of this buffer, and between what levels does the buffer needs to be to not influence the process?
- To what extent can the process be turned up or down, to let the buffers increase in capacity?
- Is there a possibility to implement a form of storage between process steps without influencing the process?
- Are there other machines to do the same process step?
- Did you ever calculate the possibilities of adjusting the process or equipment?
- Did the company look at changing the equipment based on the changing electricity needs?
- Did the company look at options to store electricity for short term use?
- Until what level is the company/sector willing adapt changes in the process to increase their flexibility?