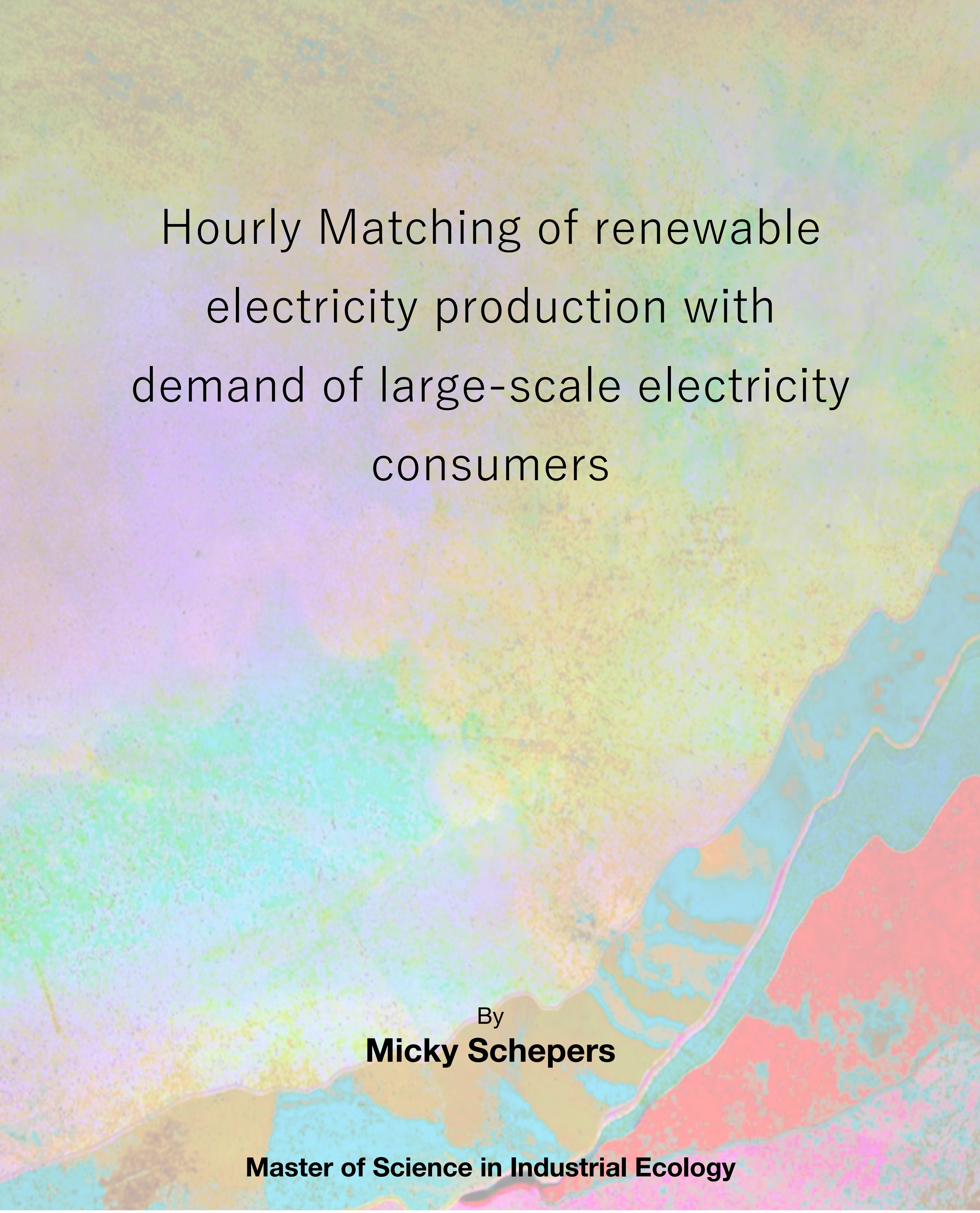

Hourly Matching of renewable electricity production with demand of large-scale electricity consumers

By

Micky Schepers

Master of Science in Industrial Ecology

The front cover of this thesis depicts the annual global carbon emissions from coal, oil, gas, and land use change. Until around 1950 the principal sources of carbon emissions from human activities were changes in land use as a result of agriculture and deforestation. Since then, burning of fossil fuels accounts for most of the anthropogenic (human caused) carbon emissions, and such emissions continue to rise (Environmental Graphiti, 2017).

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In Industrial Ecology

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And last but not least of course my parents, friends and family. I would like to thank my family for their support and encouragement throughout my study and in everything I do. I would like to thank my friends and housemates that I could always ask for feedback and provided me with necessary distractions from my research when needed.

I started this project having a broad background in Industrial Ecology but not an extensive understanding of specifically the energy industry. I had spent a large part of my masters focusing on projects and internships regarding circular economy but realised the energy transition and circular economy intertwined as some of the most exciting sustainability fields for the future. I saw my thesis as a great opportunity to submerse myself in, and gain an extensive understanding of, the energy industry. I have learnt an immense amount since starting my thesis last summer and I am very grateful to have had this opportunity. Although it feels strange to be officially finishing my time as a student, I am looking forward to what the future brings. I am proud of the result that lies before you and hope you enjoy the read.

Micky Schepers,
May 2019

Executive summary

This research aims to provide a method for large-scale commercial electricity consumers to procure towards 100% hourly matched renewable electricity. A problem with the current electricity balancing system is that the energy produced by Variable Renewable Energy sources (VRES), such as wind and solar PV, has a weather-dependent production profile and is thus non-controllable and intermittent. The balance between the total energy demand of the large-scale electricity (LSE) consumer and the production of electricity from VRES in their contract is only based on a yearly scale and not on an hourly scale. At moments when there is little wind, mainly coal & gas-powered plants need to be dispatched to secure uninterrupted power supply.

Procurement of renewable energy is realized with the use of Guarantees of origin (GOs). GOs are an instrument that tracks the origin of electricity generated from renewable resources on a yearly basis but does not differentiate in hourly production profile. Therefore, this system will not be able to address the challenge of balancing VRES and demand on an hourly scale. In the current system GOs are still sufficient as there is limited VRES in the Dutch system. However, in the future, with the ambition of moving towards substantially higher proportion of RES, the balancing on hourly base is needed to decrease the dependency on the conventional plants as backup. Therefore, with the current setup with yearly tracked RES, companies are limited in their role in the energy transition. This research aims to provide a novel method for large-scale commercial electricity consumers to procure towards 100% hourly matched renewable electricity.

Methodology
In this thesis, a techno-economic analysis was conducted to examine possible hourly-matched renewable energy portfolio for Dutch LSE consumers. First, an analysis was conducted of the production and storage technologies that could potentially be used for the application of hourly matching. Secondly, a methodology was developed to analyse the match between an LSE consumer's demand and the production profile. The degree to which these profiles are matched was defined as the green score. The higher the green score, the higher the percentage of the demand that is covered by the portfolio on an hourly base. The demand profile is kept consistent, and a comparison is made of scenarios of different portfolios containing production and storage technologies. Third, using a Levelised Cost of Portfolio (LCOP) the cost per MWh for the whole portfolio is compared for different scenario's.

Conclusion
In the case study analysed 62% of the yearly energy demand (GWh) is currently matched on an hourly base with the electricity production profile of a wind park allocated. The importance of combining wind and solar energy is shown, as a green score of 72% can be reached by adding solar PV generation to the portfolio. Scenarios with different storage technologies are used in the portfolio to show the strong impact of large-scale storage and the importance of decoupling of power and energy capacity of storage. It shows that the with Lithium-ion and Redox flow, added to a combination of solar and wind, a green score just over 80% can be reached keeping a feasible LCOP price increase of 10%. For a 10% cost increase the green score with Compressed Air Energy Storage reaches just below 85% and with Pumped Hydro storage a green score of just over 90% seems feasible. Large scale storage has a lower cost for a higher green score. With these production and storage technologies a green score of much more than 90% will require a large increase in the cost. Figure 1 shows the summarising comparison of scenarios analysed. It allows the comparison of different possible portfolios of technologies for LSE consumers in various coloured curves. The scenarios are evaluated on both the reachable green score and the related Levelised Cost of Portfolio.

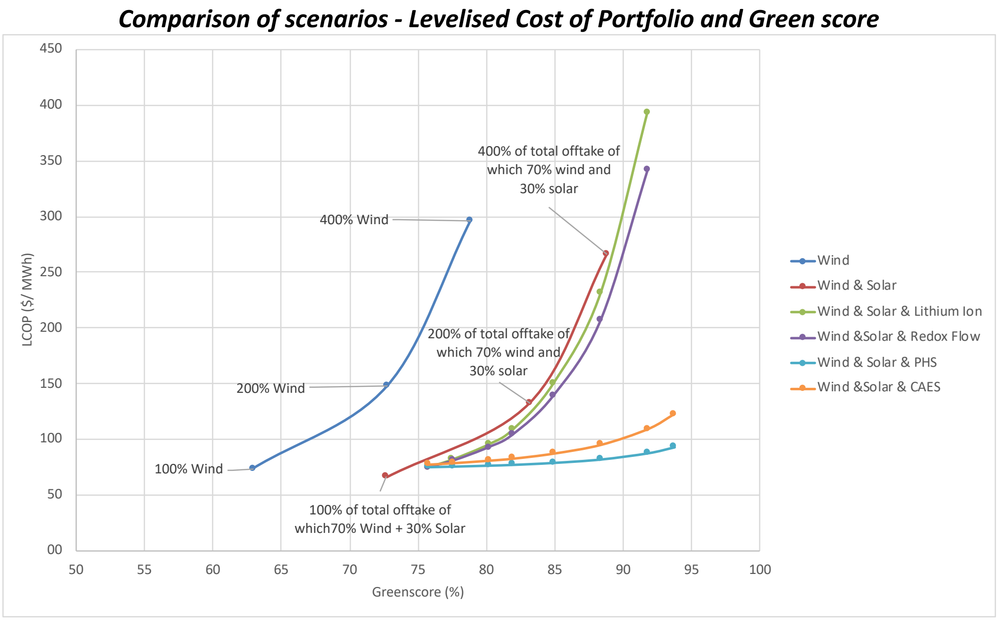

Figure 1: Graph showing the cost ($/MWh) and the green score (%) that is possible with different scenarios of combinations of production and storage technologies, the number for storage is the energy capacity (kWh) of the EES.

Implications

This study shows that the hourly match measured using the percentage green score can be significantly increased by adapting the LSE consumer portfolio, however a 100% hourly match is not shown.

Much of the research to date has focused on national-scale scenarios, but only provides limited incentives and insights into the role that large companies can play. This is an opportunity for stakeholders not often taken into account in design of the electricity market; Large Scale Electricity consumers that want to improve their societal role and are unsatisfied with the current limits of their renewable electricity procurement. This can help in creating a transparent market where empowered consumers can drive the energy transition.

This study provides a tool which is suitable to perform a techno-economic analysis to increase the hourly match of LSE consumers using various electricity production and electrical energy storage technologies. The insights found on the impact of different combinations of technologies in a portfolio can be used to understand a further possible role of these companies in the energy transition.

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Abbreviations

A-CAES	Advanced adiabatic compressed air energy storage
APX	Amsterdam Power Exchange
BES	Battery Energy Storage
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditures
DoD	Depth of Discharge
DSO	Distribution System Operator
EES	Electrical Energy Storage
EV	Electric Vehicles
ETS	European Trading System
GO	Guarantee of Origin
GWh	Gigawatt hour
LA	Lead Acid
LCOE	Levelised Cost of Electricity
LCOS	Levelised Cost of Storage
LCOSP	Levelised Cost of Storage in Portfolio
LCOP	Levelised Cost of Portfolio
LSE consumers	Large-Scale electricity consumers
MWh	Megawatt hour
NaS	Sodium–sulphur
NiCd	Nickel–cadmium
NMC	Nickel Manganese Oxide
O&M	Operation and Maintenance
OPEX	Operational Expenditures
PHS	Pumped Hydro Storage
PPA	Power Purchase Agreement
PV	Photovoltaic
RES	Renewable Energy Sources
RET	Renewable Energy Technology
SCES	Supercapacitor Energy Storage
SDE +	Stimulering Duurzame Energie productie
SMES	Superconducting Magnetic Energy Storage
TSO	Transmission System Operator
VRES	Variable Renewable Energy Sources
VRB	Vanadium-Redox flow Battery

1. Introduction

The dependency on carbon-based fuels needs to be reduced in order to drastically decrease CO_2 emissions. When the Paris climate agreement was adopted in 2015, 195 UNFCCC member countries signed to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels. Furthermore, in October 2018, a report was published by the Intergovernmental Panel on Climate Change (IPCC) in which the importance of limiting global warming to 1.5 °C was stated and called for "rapid and far-reaching" transitions in land, energy, industry, buildings, transport, and cities (IPCC, 2018). The European Union has made firm commitments on behalf of all member states to reduce greenhouse gas emissions by at least 40 % in 2030 compared to 1990 (Rijksoverheid, 2018)

The addition of renewable electricity generation in the Netherlands has however increased slowly in recent years. With only 6.6% of final energy consumption currently from renewables (Bloomberg New Energy Outlook, 2018; CBS, 2018) the Netherlands is lagging behind its EU target to source 14% from renewables by 2020. With 78% of the electricity generated still coming from coal and gas, the Netherlands is heavily reliant on fossil fuels.

The move towards a low-carbon energy system implies substantial changes to the electricity system. First it requires a larger share of electricity from renewable energy, in particular from solar PV and wind. Secondly, the share of electricity in total energy consumption is rising, due to the increasing penetration of demand technologies such as electric vehicles. As a result of these two trends, a greater need for flexibility and system integration is expected (ECN, 2017b).

Commercial and industrial companies have an increasing interest in receiving electricity from renewable energy sources. Currently, they are linked to specific wind farms and solar PV farms through their supply contract with their energy supplier. The energy supplier has Power Purchase Agreements (PPA) with the renewable installation. To trace the origin of the renewable electricity, Guarantees of Origin (GOs) are used which register electricity generated from renewable sources. The yearly offtake of companies is covered through this certification system.

However, on a smaller timescale, hourly and daily, the electricity produced from these renewable sources is intermittent and fluctuates strongly. The profile of the demand of the company does not correlate with the production of electricity from Variable Renewable Energy Sources (VRES). An important next step towards improving our management of green electricity, is matching these demand and supply profiles on an hourly scale.

1.1 Research Motivation & Problem definition

There is a growing body of literature on the topic of optimal renewable energy configurations and Renewable Energy Source (RES) application in the grid, however there is little research into the role that large-scale electricity (LSE) consumers in the current electricity market can play. Increasing recognition exists for more actively involving other actors than countries, for example companies and cities, in defining climate change action could be key to tackling climate change (Krabbe et al., 2015)

One of the most explored related areas of research is the integration of RES on islands. As interconnections are often absent it is highly relevant to develop 100% RES systems on islands. Gioutsos, et al., (2018) analysed a range of island case studies for cost optimal electricity systems with increasing RES penetration and finds that RES penetration in the range of 40% to 80% has optimal costs. Beyond this point, the ability for wind and solar energy to meet higher shares of electricity demand is strained, and the demand for storage becomes more significant due to large over-production. Fuchs Illoldi (2017) also analyses the optimal configuration of hybrid renewable energy systems for islands. He finds wind always being part of the cost-optimal configurations, and favoured in the 0-50% range of renewable integration and PV starting at 30% and up to 70%. De Vos et al., (2013) examine reserve requirements on islands in a case study on Cyprus and finds that without a proper revision of the current reserve policies, the system will not be able to facilitate wind power without high levels of wind curtailment or demand shedding. The previously mentioned work uses (bio-) diesel in the last stages to limit the costs. The Island research uses technologies such as Ocean Thermal Energy that are location dependant. Research on off-grid energy systems and micro-grids is available but analyses stand-alone systems. Centralised production and storage technologies can be used in the setting of Dutch LSE consumers (Mandelli et al., 2016). The research into Electric Vehicles as EES in these systems does provide opportunities for companies with large vehicle fleets (Liu et al., 2010, Hijgenaar, 2017).

In India, 100% RES implications were explored by Gulagi, et al. (2017) on the role and need for storage technologies. In Europe, the residual load and the effects of the increasing amounts of VRES in Germany and the storage capacity required were studied by Schill (2014) who indicated that by 2050, at least 10 GW of storage will be required for surplus integration, of which a sizeable share is seasonal storage. He recommends further research into the optimal mix of storage curtailment and other flexibility option to solve this. Implications of 100% RES were explored by Steinke et al (2013) who examined the backup energy generation required with increasing intermittent power production from solar and wind. They indicated that if solar and wind energy produce an average of 100% of the required electricity, significant dispatchable generation is required. Without grid storage, this amounts to roughly 40% of the demand; with an ideal European grid, 20% would still be required. Connolly et al., (2016) also presented a potential pathway to 100% RES for the EU in the year 2050.

There is limited research on the role that large companies connected to the grid can play with respect to the energy transition. While research has been conducted into the changing business models for energy utilities (Loock, 2012; Richter, 2012, 2013), the role of energy utilities (Frei et al., 2018; Lovins & Lovins, 1982; Sousa et al., 2013) and the development towards product service systems (Hamwi & Lizarralde, 2017; Orellano et al., 2017), very little research is available on how energy utilities and Large Scale Electricity (LSE) consumers procure renewable energy.

To date, mainly data centres have been interested in matching supply and demand profiles. In their research on Goiri et al (2015) analysed data centres powered by a PV solar array and the electrical gird as backup. They reported that scheduling demand load to be dependent on predicted VRES production can increase solar energy consumption by up to 117% and reduce energy costs by up to 39%. This is done by using a scheduler that predicts the amount of solar energy that will be available in the near future. Google, the world's largest corporate buyer of renewable energy, has stated goals on sourcing carbon-free energy for their operations on a 24x7 basis (Google, 2018) and have published insights into their hours of matched electricity. They find that in most locations for which they have signed renewable PPAs, at least 65% matched of the local data centres electricity consumption in 2017 was matched on an hourly basis with carbon-free energy. To ensure that the investments function as a driver for adding new clean energy onto the grid, they insist that all projects be "additional." Although they have stated the goal of achieving 24x7 carbon-free energy, they recognise that it will be challenging and require innovations across policy, technology and business models.

There are limited insights into the role that LSE consumers play or indicators that goes beyond the limits of Guarantees of origin (GOs). The fact that there is currently no methodology for optimising the portfolios of LSE consumers is partially due to the lack of a measuring instrument beyond GOs. It is also due to companies having different criteria for their renewable energy, and that their energy offtake data is not generally accessible.

Companies have different opportunities and barriers to the actors described in earlier studies, therefore it is valuable to further explore the possibilities within the scope of this study. The increasing dependence on electricity from solar PV and wind has strong implications for the electricity grid and requires novel systems thinking regarding the electricity grid of the future and the potential roles of different actors in the electricity system. Moreover, the portfolio of LSE consumers provides an interesting opportunity due to the large electricity offtake (over 100 GWh yearly) in a single contract. Additionally, if a solution can be found for a single LSE consumer contract, this could then be upscaled to multiple consumers.

Lastly, there are increasing numbers of LSE consumers with Eneco as their energy supplier that voice concern about the limits to yearly analysis of green energy. There is a currently a group of these companies that are considering implementing pilot projects with the goal of increasing their hourly match and are interested in working on developing the hourly instead of yearly match between electricity production and their demand further.

1.2 Research questions

The purpose of this research is to investigate the opportunity for implementing an hourly matched energy system in the current market, for large-scale electricity consumers. By analysing the portfolio of large-scale electricity consumers, the demand and production profile can be better matched. The goal of this thesis is to identify how matching electricity demand and supply on an hourly basis can be done. The proposed main research question is:

How can a large-scale commercial electricity consumer procure towards 100% hourly matched renewable energy?

This research question is divided into the following sub-questions:

- What technologies have the potential to increase the hourly match between electricity demand and production?
- What is the impact of different generation and storage technologies on the hourly match?
- What is the cost of improving the hourly match ($/MWh)?

Definition of Hourly Matching

In the context of this research Hourly Matching is the concept of matching the demand profile and the renewable production of a portfolio on an hourly base instead of on a yearly base as is done with GOs. The portfolio is the combination of technologies for production and storage for a specific company contract. This is done within the current electricity market structure. The companies that are taking part in the pilot project are NS, SKU Radboud University, KPN and DSM.

The following graph shows the energy demand of a company (indicated with the black line) and the electricity generated from a specific wind farm that produces the same amount of electricity (indicated with the blue line). The green area is the part of the demand profile that is directly covered by this wind farm. The grey area signifies where the demand is higher than the generation for the specific moment. On a yearly basis there is a balance in the excess energy and the shortage, (as the volume in purple equals the volume in grey). However, there is no balance on an hourly scale. This means that for the grey part of the graph, electricity from the Dutch electricity mix; largely from fossil power plants is used. In this research, the hourly match is calculated by using the green score. The green score indicates the amount of green energy used by a company (represented in Figure 2 with the green volume) over a year, as compared to the total amount of energy used by the company (represented in Figure 2 with the volume under the black line) over a year as a percentage. The exact calculation of the green score will be further elaborated in the methodology in chapter 4.2.

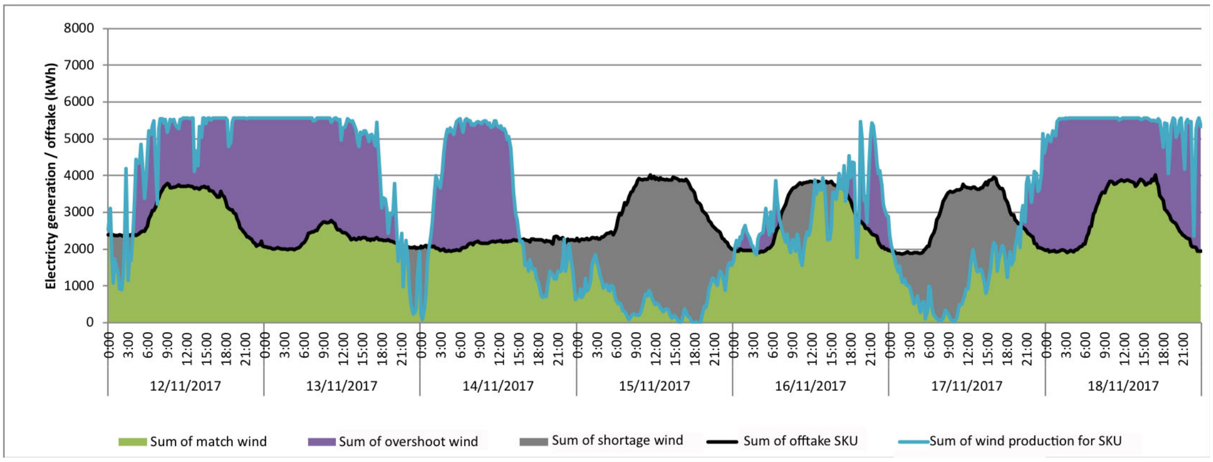


Figure 2: Hourly energy generation from wind in blue and hourly demand of a company.

1.3 Thesis structure

This thesis is organised as follows. Chapter 2 describes the context of this thesis. This brings the research into the context of corporates within the Dutch Energy market, a subject that has not been written about as extensively as the Dutch national outlook. Chapter 3 describes the technology assessment of production and storage technologies in the context of Hourly Matching. It introduces criteria for technologies that are to be used within the given context and for the specific purpose and analyses the possible production and storage technologies. Chapter 4 presents the methodology and model used to optimise Hourly Matching, including the use of the green score and the Levelized Cost of Portfolio. A desired outcome is portfolio with as high of a green score as possible; scenarios are created with the aim of reaching this goal with the selected technologies. Different combinations of technologies in portfolios are described, and how a specific green score can be calculated. Chapter 5 elaborates on the results of the case study selected. A model-driven case study was conducted. The model measures the impact of different technologies in the portfolio on the green score. Using the green score, the costs of a different portfolio options were compared. In Chapter 6 and 7 the results are evaluated in a discussion and conclusions and recommendations are presented.

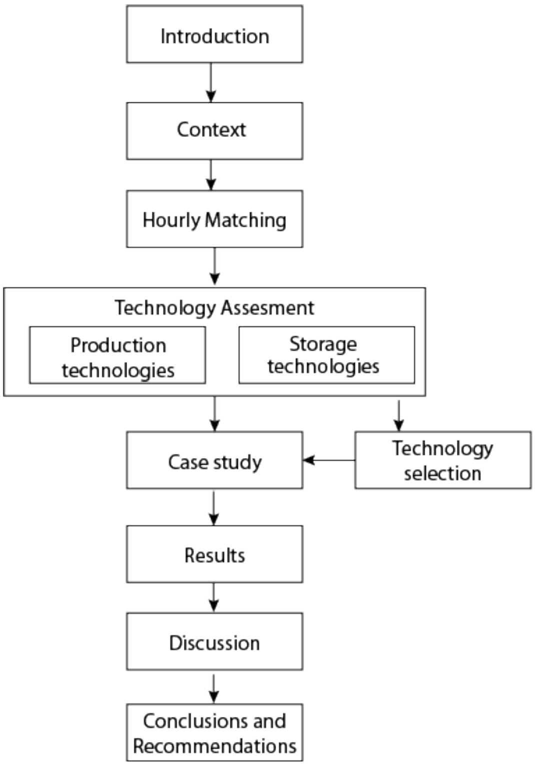


Figure 3: Visual representation of the structure of the thesis.

2. Context

In this section, the current electricity market in the Netherlands including the role of electricity generated from renewable sources is reviewed to gain a thorough understanding of the context. This is initially explored from the perspective of the physical electricity grid, after which it is analysed from a market perspective. This provides an understanding of the study's goal and the barriers and opportunities for the implementation of Hourly Matching.

Furthermore, the role of different actors in the electricity market is investigated. The analysis of the goals, barriers, and opportunities regarding Hourly Matching of the main actors creates a foundation for the social criteria regarding the technologies that are implementable to achieve this.

Information is gathered from a literature search and corroborated through interviews at Eneco and external interviews to gain an in-depth understanding of the present situation.

2.1 The Dutch Electricity system

In this chapter the Dutch Electricity market is analysed, followed by the roles of different actors, in specific the electricity supplier and the electricity consumer as the possibilities within their role is the main scope of this thesis, are further elaborated. Furthermore, the general barriers and opportunities to increase the amount of RES in the grid and implement Hourly Matching at an organizational level are discussed.

Over the last decades an exceptionally reliable electricity system has been established in the Netherlands that is based on a stable network and a clearly developed and regulated market. It has been largely designed in a centralized manner for conventional power plants; gas, oil and coal fired power plants. Natural gas and crude oil have played a prominent role since the second part of the 20th century: around 20% of the state revenues came from the gas and oil industry in 2010 (Donker et al., 2015). Currently the main supply of electricity still comes from coal and gas, with gas supplying 49% and coal 29% of the total electricity (Bloomberg New Energy Outlook, 2018b). These forms of power provide baseload power with a continuous and reliable supply throughout the year. Creating a more low-carbon and sustainable energy system implies a large share of electricity from variable renewable energy (VRE), particularly from solar PV and wind, and a higher need for flexibility and system integration (ECN, 2016). Several methods exist to reduce intermittency power delivered from VRE. These include combining geographically disperse intermittent resources of the same type, using storage, and combining different renewables with complementary intermittencies (Archer & Jacobson, 2003; Archer & Jacobson, 2007).

Organisation of stakeholders in the Dutch Electricity market

Figure 4 shows a simplified diagram of the primary processes and organization of the Dutch electricity market. In the current value chain three main processes can be identified: generation, transport and supply. After the introduction of the Amsterdam Power eXchange (APX, that was later renamed to the current Epex Spot) it also became possible to trade in electricity, adding a fourth role (Buth, 2018), for the sake of simplicity this is not taken up in the diagram as it not in the principal scope of this research. The Transmission System operator is responsible for the security and operation of the national high voltage grid and its maintenance. Electricity is generated by different producers. Producers are responsible for the generation process in the system and do not supply it to the end-user but feed the produced energy in the grid. To a lesser extent prosumers, consumers who also produce electricity, are adopting this role as well (Slingerland et al., 2015). The biggest energy producers in the Netherlands are Nuon (Vattenfall), Orsted, Essent (RWE), Electrabel, Intergen, Delta, Eneco and E.ON (Bloomberg New Energy Outlook, 2018b). Consumers have a contract with an electricity supplier and pay this supplier a fixed price per kWh for their energy, as well as a grid tariff for usage of the grid. Of the total electricity consumption industrial consumption makes up 35%, commercial, 45% and residential 20% of the total electricity use in the Netherlands. "Commercial" includes transport, services agriculture and fisheries, "Industrial" includes the energy sector such as oil refineries. Of sales and retail Eneco has 26% of the total market share in number of end users (Bloomberg New Energy Outlook, 2018b).

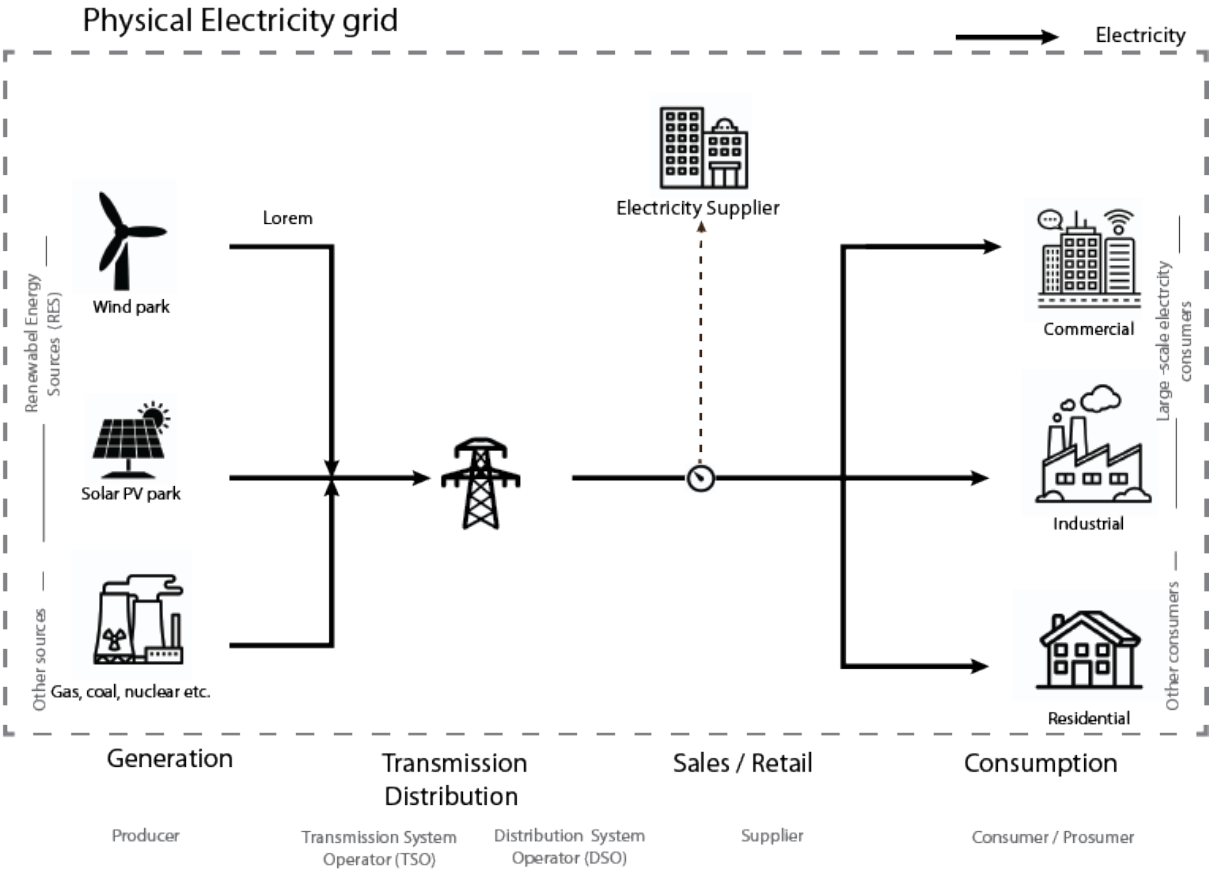


Figure 4: A simplified diagram representing the electricity grid

2.2 The electricity Market structure

Figure 5 shows a simplified diagram of the electricity market structure. The green arrows indicate the RES tracking in the system and the yellow arrows the monetary flows. The energy supplier buys guarantees of origin for their clients and electricity from the wholesale electricity market. The cost that the electricity consumer pays to the electricity supplier consists of both the electricity market price and the GO price.

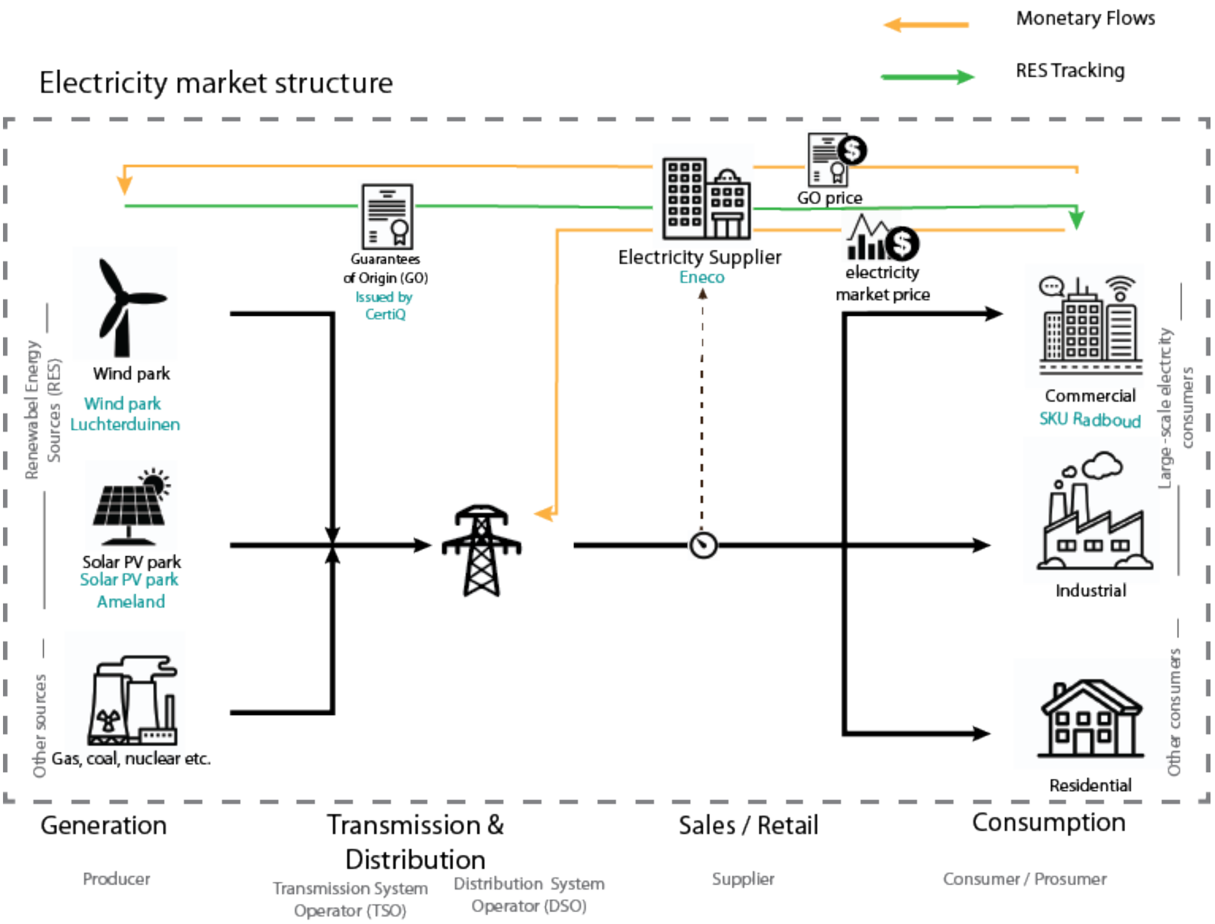


Figure 5: A simplified diagram of the electricity market structure

A power purchase agreement (PPA) is a contract between a buyer and a power producer to purchase electricity at pre-agreed prices. Many wind farms and large solar farms currently operate under a PPA. Renewable electricity producers find that long-term PPAs, which ensure them that a substantial part or all of the produced electricity will be sold, can be a decisive element in whether their projects can be financed (Brinkman, 2017). In general PPAs are are closed between the energy supplier and producer (Staffell & Rustomji, 2016). However, in recent years a global trend has been an increasing number of large industrial and corporate energy consumers wanting to purchase renewable electricity directly from renewable energy producers on the basis of PPAs. These PPAs are signed directly between the purchaser and the renewable electricity producers (Dingenen et al., 2018; Harrison, 2018). Nonetheless, in the Netherlands, electricity suppliers generally still sign these PPAs with producers and sign a supply contract with customers (Brinkman, 2017).

The renewable electricity in these PPAs is tracked using Guarantees of Origin (GO). The trade in GOs is done in a free market. In the Netherlands this market runs almost entirely via bilateral agreements (between, for example, producers and traders, traders and suppliers). Electricity that consumers with green energy contracts use, is identical to the electricity that consumers use that do not have green energy contracts. The difference lies in the addition of Guarantees of Origin.

It is important to realize that it is difficult to label electricity, as it is not a tangible product. Even though there is a difference between it being produced from fossil fuelled power plants or renewable sources and consumers can specifically buy electricity from renewable resources, it is all combined and indistinguishable on the grid. As it cannot be labelled in the grid, this needs to be done in a parallel system as shown in
Figure 5 (Association of issuing bodies, 2017).

The GO is the only and main instrument used to track renewable electricity in Europe. It gives electricity consumers the power to choose renewable power generation over fossil-fuel based. In addition (increasing) GO prices demonstrate to the market that there is a demand for renewable energy (Track My Electricity, 2019).

A GO represents the generation of 1 megawatt hour (MWh) of electricity from an eligible source of renewable power. It contains information on the source of generation, the location of generation and the year of generation. In Europe this trading market currently includes GOs from wind, hydropower, solar PV, geothermal and biomass source.

As trading is done through bilateral agreements, pricing is not transparent to third parties. GOs are traded in a voluntary market and are not connected to the physical delivery of electricity (Track My Electricity, 2019).The GO market and the markets for the electricity commodity (the energy itself) are separate. As a large part of electricity is traded in the APX market this gives an indication of the price, however the price of GOs is not as open (APX group, 2019). The GOs can be issued in the Netherlands or other European countries by producers of renewable electricity (CE Delft, 2016).

Every GO is given a unique number. This is tracked by established authorities as it exchanges hands first from the producer to the broker and lastly to the consumer. In the Netherlands this issuing body is called CertiQ (Track My Electricity, 2019) CertiQ issues GO's for electricity from wind, solar, biomass and hydro (CertiQ, 2018)

Although the volume of academic literature on the role of GOs in the energy transition is rather limited, the GO trade plays a vital role in in how LSE consumers procure electricity.

Companies that procure renewable electricity pay a wholesale price for electricity and additionally for GOs, the cost of which is specific for the technologies they require. The price for GOs from producers in the Netherlands has been increasing in recent years (CE Delft, 2016, Eneco Energy Trade, 2019).

The cost that companies pay is built up of the wholesale price for electricity which is currently between 40€ to 63 € per MWh in the last year (APX group, 2019) and the cost of GOs. The prices of GOs are increasing due to increasing demand for RES and lagging development of wind and solar parks. Where previously the price for GOs was below 1.5 € for Dutch wind and solar, and below 1€ for biomass, hydropower and European wind (Figure 6) they were marginal compared to wholesale electricity prices. GO prices are currently increasing and becoming a more noticeable share of the electricity cost. Dutch GOs have always been more expensive than Scandinavian, and while the costs peak for Dutch GOs they do not as clearly for Scandinavian hydro, Alpine hydro and European wind GOs (CE Delft, 2016). The cost of GOs for Dutch wind is currently between 7 and 10€/MWh and has increased to 2 €/MWh for European wind (Wise Nederland, 2018)

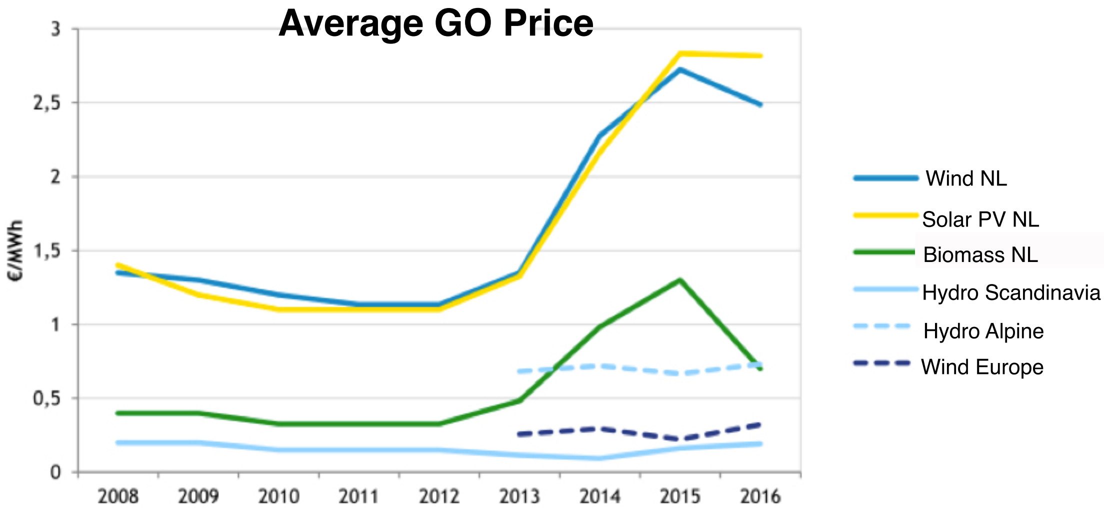


Figure 6: The average price of GOs development (CE Delft, 2016)

In the future the development of platforms connecting consumers and producers of renewable power is required to make new procurement strategies and business models possible (Davids et al., 2015), for example, opportunities of registering renewables using blockchain technology are also being explored (Buth, 2018; Castellanos et al., 2017). The design of a new RES tracking system is outside the scope of this research. The outcome of this research could be seen as a product that can be used in such a future system.

2.3 Limits to current system based on Guarantees of Origin

The workings of GOs have been publicly criticized for not providing an incentive to increase in installed RES with the market mechanisms (Wise Nederland, 2017; Zondag met Lubach, 2018). Although 13% of Electricity in the Netherlands is from RES, 42% of the Electricity is sold as “green” (Wise Nederland, 2017). The Netherlands is a net importer of GOs, the net import of GOs is twice as large as the certified renewable electricity produced internally. This limits the possible stimulation on RES development in the Netherlands through GOs and has allowed for the import of large volumes of GOs with a low price that do not incentivise additional RES implementation from Norwegian and Swedish Hydropower (Wise, 2018).

Therefore, one of the shortcomings is that is easy to import GOs from neighbouring countries. This is possible even though the trans-border grid capacity is not installed such as with Iceland. An example of this was a large number of GOs for Scandinavian hydro being bought, and therefore a substantial part of Dutch electricity being green on paper. However, the grid capacity that would be required for to transport actual electricity was not installed. For this reason, GOs from the Netherlands, are seen by many organizations as the most sustainable option (Wise Nederland, 2017).

Added to this it is it is doubtful whether the trade in GOs current practice incentivizes an increase in green electricity production. The price of GOs has long been too low to incentivize producers or prosumers to increase the RES capacity (Mulder, 2018). Hence the current labelling system for RES is mainly valuable, aside to being an instrument for tracking and tracing renewable energy, as a marketing instrument for electricity retailers (Mulder, 2018).

Moreover, there is a mismatch between the physical nature of electricity and the green energy certifications. An important shortcoming of GOs is that they are tracked on a yearly base and do not take into consideration the intermittency and the generation profile of VRES. The current system does not take into account the mismatch of production profile & demand profile. There is no hourly differentiation in the value of GOs over time. The GOs can be stored, as there is only monthly data available on the origin in time of the GO, however the electricity cannot be physically stored over time. Currently, although suboptimal in the representation of the electricity system, this is not a large problem as conventional power plants create flexibility. However, in a future energy system largely based on VRES, without the balancing capabilities of conventional plants, this hourly matching is crucial in the system.

2.4 Hourly Matching as a possible answer

As a possible improvement to the current limitations of electricity this thesis examines how Hourly Matching could provide a next step in the current ‘green’ electricity system. For Hourly Matching the scale is changed from yearly to hourly, in the analysis of 100% green energy. For doing so the opportunities are explored for adapting the portfolio of large-scale electricity consumers to increase their hourly match, measured as a percentage of the total offtake of energy.

Analysing and improving the match between the demand and production of a corporate consumer on an hourly scale, is significant for various reasons.

First, it can be a logical next step to take the temporal effects into account. The improvement of the sustainability of electricity consumption started with implementation of GOs. It was followed by companies in the Netherlands demanding Dutch GOs and thereby adding geographical criteria, and that the instrument should incentivise new RES deployment rather than existing hydropower from Scandinavia. Furthermore, although the intermittent production profile of VRES and its mismatch with the demand profile is not currently taken into account in the role of companies, it is a situation shows an opportunity for improvement. The balance between total energy demand and the production of electricity from VRES through use of GOs is only based on a yearly scale and not on an hourly scale, and at moments when there is little wind, mainly coal & gas-powered plants are to be dispatched to secure uninterrupted power supply.

Secondly, it is important to give companies insight in the current hourly match of their production portfolio. To make well informed decisions consumers need transparency about the origin of their procured electricity (Davids et al., 2015) and the insight into the green score makes this possible. This increases their opportunities of both adapting their portfolio through their contract with their energy supplier as well as implementing solutions at their own locations. By having a measurable indicator of the influence of different technologies, choices for certain technologies can be better substantiated both in internal and external communication. Targets can be set regarding the match that all internal stakeholders can strive for.

Companies that want to play a role in the energy transition and are not content with the status quo (RE-source, 2018) can work with energy suppliers on developing a novel product that they can implement. By looking at the profile mismatch of a single company and improving this in a scalable concept, companies could potentially play an important role in the Dutch energy transition. Additionally, the companies that are regarded in this thesis have a yearly offtake of more than 100 GWh, that is under a single contract. As they regard long-term contracts, they have designated account managers within Eneco that handle the contract. This gives the opportunity to centrally improve the hourly match for a significantly sized contract. Furthermore, the person responsible within the LSE consumer has an understanding of the build-up of costs within the contract and the use and limitations of GOs. Although it would technically be possible to provide Hourly Matching as a service for smaller companies, with the large-scale companies it is organisationally more feasible.

2.5 Stakeholder interest in Hourly Matching

In this chapter the interest of stakeholders in Hourly Matching is examined. As shown in Figure 5 the most important actors for the sake of this thesis are the large-scale electricity consumer and the electricity supplier. This research is conducted for Eneco BV., therefore the perspective as viewed from this energy supplier is of importance to the approach. This also means that the perspective within the Netherlands is considered, and its implications for the role in the market and the possibilities within the given role.

2.5.1. Interest from large-scale electricity consumers

In the current system, the large-scale electricity consumers can procure 100% RES, matched on a yearly basis from an energy supplier. They contract their energy supplier to offtake a certain amount of "green" electricity – electricity from renewable sources. The energy supplier in turn has Power Purchase Agreements (PPA) with Electricity producers such as a wind farm. One of the advantages for consumers of buying renewable energy in long term contracts is that the price can be fixed for the duration of the contract. They can hedge against rising and fluctuating energy prices in the wholesale market (Brinkman, 2017). Achieving sustainability targets has become an important driver for companies of buying 100% renewable energy (Brinkman, 2017; Krabbe et al., 2015).

There is a growing group of consumers that is increasingly concerned about where the electricity they use is sourced from (RE-source, 2018). In 2018 over 150 companies committed to source 100% of the electricity from renewable sources with RE100, creating demand for 188 TWh of renewable power per year - equivalent to the 23rd largest country in the world (the climate group, 2019). Large scale electricity consumers have the potential to play a larger part in the energy transition than they currently do.

LSE consumers have an interest in renewable energy contracts and Hourly Matching for multiple reasons. Understanding the drivers for implementing Hourly Matching plays a role in the choices, from company perspectives, regarding the types of technologies that can be implemented for goal of Hourly Matching. Firstly, meeting sustainability goals and reducing greenhouse gas emissions are drivers of intent on purchasing renewable energy. For many companies being a front runner in the renewable energy transition is a desirable position. Moreover, proactive compliance to future regulation plays a role as 67 countries are putting a price on carbon (World Bank & Ecofys, 2017). Furthermore, enhancing reputation and keeping up with competitors are additional drivers (Velthuijsen et al., 2018). Intrinsic personal sustainability goals can also play a role (EnecoGroup, 2018a).

One of the criteria that is mentioned by companies are the communication of Hourly Matching, the companies involved favour options that are easy to communicate both internally and externally. The concept must be possible to communicate internally, secondly the concept must be possible to communicate externally. A concept that is simple to communicate and can thereafter be explained in detail to those that are interested is required.

2.5.2. Interest from energy suppliers

Energy suppliers also have interest in matching production and demand profiles of clients and renewable energy producers for multiple reasons. Like LSE consumers, energy suppliers also have internal and external drivers to focus more on sustainability. For energy providers it can become a novel product that can be sold to their clients, energy consumers. The sustainability goals of their customers give and incentive to offer more services and products that support the advancement of the energy transition. As for LSE consumers, creating a novel and innovative product offers marketing opportunities as a frontrunner in renewable energy. It can create a competitive edge over competitors and help the supplier stabilise profits and reduce profit & loss volatility. NGO rankings of energy suppliers such as Greenpeace and Wise also play an important role for energy suppliers.

In specific, Eneco's mission is to maintain a leading role in the energy transition by accelerating and innovating (EnecoGroup, 2018b). As the traditional boundaries between the supplier producer and customer are disappearing their role moves from selling energy to providing services and resources that allows traditional consumers to organise their energy themselves. Eneco is in a unique position to implement a solution for LSE companies as they have a large amount of the data required on the company offtake and production profiles of production locations. It could also offer a premium product on existing long-term current contracts. Added to that Eneco currently has a large and diverse client base. Due to this, if the concept works for LSE consumers, Eneco would be in a position to implement pilot projects with households as well.

2.5.3. Interest from transmission & generation stakeholders

For other stakeholders in the electricity market, interest in Hourly Matching is not determined in detail, however indications of additional benefits are as follows.

For stakeholders involved in transmission, it can bring a novel value to flexibility by introducing LSE consumers into the market due to their interest in matching their profiles on an hourly base. The Transmission System Operator, namely Tennet, is responsible for the transmission system, and therefore for the security and operation of the national high voltage grid and its maintenance (Buth, 2018).Tennet uses a system of balancing responsibility to match the demand and supply of electricity to grid operators. Connected parties are responsible for reporting their planned electricity production, consumption and transport needs. When the actual consumption or production differs from the forecast, imbalances occur, that can affect the reliability of the grid (Tennet, 2019a). As this provides the TSO with a challenge due to the growing shares of solar and wind power, they are looking for means of creating greater flexibility in the grid in the future (TenneT, 2019). With Hourly Matching LSE consumers play a role in reducing the volatility of their portfolio, which is beneficial for the TSO.

For stakeholders involved in generation of electricity, Hourly Matching can play a role in facilitation of growth of RES in the grid and creating a future-proof electricity market. If Hourly Matching can be scaled up to more consumers and can play a role in creating a more robust system based on RES, it could mean that the system becomes less dependent on dispatchable & rampable baseload coal and gas-powered plants and increase the amount of electricity from RES in the Dutch energy system. An example of this are the difficulties for new solar parks that have currently been built in the Netherlands that cannot be connected to the grid due to congestion management issues (Morshed, 2019).

3. Technology assessment

To answer the question regarding which technologies have the potential to increase the match of production and demand in the portfolio of large-scale electricity consumers, possible technologies are analysed in this chapter. In this thesis the opportunities for both generation and storage technologies are discussed. There are other forms of flexibility options such as demand response and grid expansion as indicated previously that can be deployed for the goal of Hourly Matching. In this thesis options for Hourly Matching of electricity production and storage to the demand is analysed as this is the initial steps in optimising the portfolio, it is achievable within the context and it enhances the role played in the Dutch electricity system (Slingerland et al., 2015).

To analyse the technologies, the criteria for Hourly Matching technologies are defined. These criteria differ between production and storage technologies, and are categorised as technical, economic, environmental, and social. They are further elaborated on in the following sections.

3.1 Electricity generation technologies

3.1.1. Electricity generation in the Netherlands

Before moving on to the generation technologies that can play a role in Hourly Matching the current electricity generation in the Netherlands is analysed. This gives a basis for the available technologies and shows the dependence on the main generation technologies. The following graph shows the generation from this installed capacity in the Netherlands (GWh). It clearly shows the high dependency on coal fired and gas fired powerplants. In 2017, 49% of electricity came from gas fired power plants, 28% from coal fired power plants. 11% of the total electricity production came from wind and 5% from biomass & waste, 5% from nuclear, and 2% from solar (Bloomberg New Energy Outlook, 2018b). In 2017, 17 000 GWh was generated from renewable sources, compared to 15 000 GWh in 2016 (CBS, 2018a).

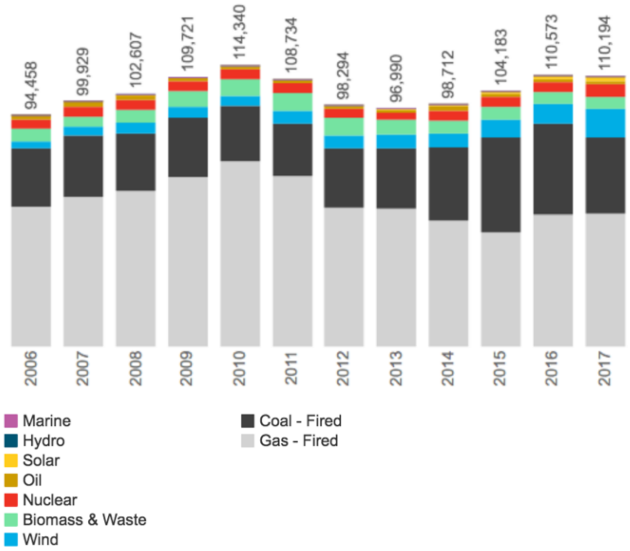


Figure 7: Electricity mix in the Netherlands Generation in GWh (Bloomberg, 2018)

3.1.2. Categorisation of production technologies

First a categorisation is made of renewable electricity production technologies as follows. Although not categorised as renewable energy nuclear energy is taken into account as it is a large-scale, low carbon method of producing electricity.

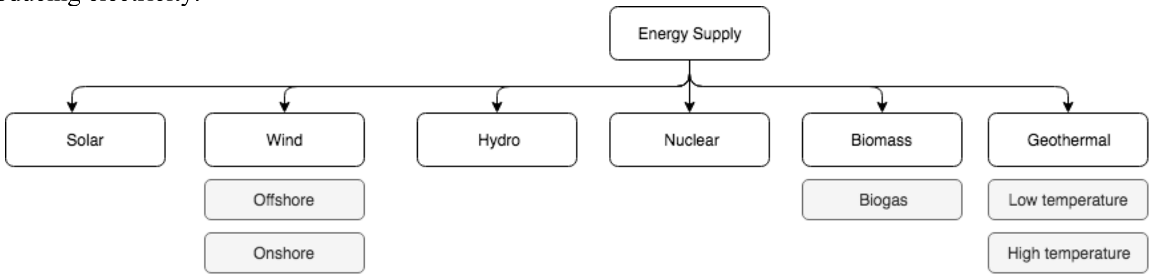


Figure 8: Categorisation of electricity production technologies

In this research the selection has to be made of different electricity production technologies that are relevant in contracts between an energy company and their corporate clients. The possible technologies in contracts between these companies are dependent on the available installed capacity, costs, whether the technology provides baseload or intermittent electricity, and types of energy that the companies are willing to invest in. Furthermore, the choice for specific technologies from a company perspective can be based on their strategy, their goals and their involvement in the technologies.

3.1.3. Criteria for production technologies for Hourly Matching

In this chapter the criteria that are of importance for generation technologies for the goal of Hourly Matching are discussed. To compare the technologies, evaluation criteria are used. A large number of factors (quantitative and qualitative) can be taken into account in the decision-making process. There is vast multicriteria decision making (MCDM) literature on energy issues (Bessette & Arvai, 2018; Demirtas, 2013; Kaya & Kahraman, 2010; Kumar et al., 2017; Mardani et al., 2017). There are various evaluation criteria that can be taken into account in MDMC and these are technical (primary energy ratio, efficiency, safety, reliability, maturity, etc.); economical (fuel cost, net present value, payback period etc.); environmental (CO_2 emission, NO_x emission, SO_2 emission, land use, noise, etc.) and social (social acceptability, job creation, social benefits, etc.) (Kaya & Kahraman, 2010).

For the scope of this research relevant criteria have been selected. These are based on the evaluation criteria for sustainable energy planning by Demirtas (2013) and shown in Table 1. The criteria are further elaborated in the coming chapters as they are specific to production and storage technologies. It is important to note that for an optimal portfolio a combination of technologies is possible, encompassing that not all technologies will score highly on all criteria, but a combination of technologies is possibly required to allow all criteria to be met.

Table 1: List of evaluation criteria for production and storage technologies.

Production Technologies Criteria

Indicator	**Criteria**
Technical	Predictability & Stability
	Steerability Dispatchable & Rampable
	Installed capacity & volume of generation
	Technological Maturity
Economic	Investment cost
	Running fuel cost
Geographic	Applicable to the Netherlands
Environmental	CO_2 emissions
Social	Social acceptability

Predictability & Stability

For the selection of production technologies one of the characteristics of importance is whether the technology has stable and predictable generation of electricity. When there is stable and predictable production it is possible to adapt the rest of the portfolio to it.

Steerability Dispatchable & Rampable

A technology is desirable that can be dispatched and ramped. Dispatchable indicates powerplants with manageable output. The speed at which a generator can increase (ramp up) or decrease (ramp down) generation is a criterion as its importance is increasing in an electricity system increasingly based on RES (Slingerland et al., 2015).

Installed capacity & volume of generation

The capacity of the technology installed needs to be interesting for large scale corporate offtakes. This means that wind and solar are taken into account and Ocean energy is not as there is a plan for installing 100 GW in 2050 throughout the EU. For Hourly Matching production technologies are required that have enough possible production capacity for LSE consumers in the Netherlands. Technologies that have a large installed energy production capacity are favoured as this increases the scalability of possible solutions. Production technologies are required that can be used in the portfolio for multiple LSE consumers.

Technological maturity

The technology has to be matured at the moment of implementation, it needs to be possible for an energy company to invest in the technology without a large amount of research into the technology, and insecurity about the feasibility and cost. As this research is done on the case study of an energy company and their client, the technology needs to be mature. Although they invest in start-ups, for the case of hourly matching technologies are desired that are feasible to implement.

Investment Cost of technology

One of the economic subcriteria is an investment cost of technology that is feasible for an energy supplier and electricty consumer or a consortium of companies. The Capital Expenditures (CAPEX) indicate initial investments required to install an asset. If the CAPEX is extremely high it lowers the possibility that the technology will be invested in.

Running fuel cost

Technologies with a low running fuel cost are desired. If the fuel cost of a techology is acceptable this increases the feasibility of implementing the given technology.

Applicable to the Netherlands

The technology is required to be located in Europe, favourably in the Netherlands.

CO_2 emissions

Of the environmental criteria CO_2 the capability for emission reduction is considered crucial as compared to impact on environment and land requirement sub-criteria (Ahmad & Tahar, 2014). Although companies indicated that this is not the direct first aspect that is measured it is a general measurement of environmental impact.

Social acceptance

Public opinion towards a certain type of technology is notably important in the scope of this research. As stated in the context and from the interviews, due to the fact that Hourly Matching is to be an improvement to the current 100% "green" electricity, is needs to be possible to communicate it as such (Beekhuis, 2018; Sonnemans & Buiting, 2018).

3.1.4. Cost of Electricity production (LCOE)

To take into account the economic characteristics the cost of needs to be compared. To compare the production technologies the Levelised Cost of Electricity (LCOE) is used in this research. For quantifying and comparing the costs of electricity generation technologies the LCOE is a well-established measure (Bloomberg New Energy Outlook, 2018b). It represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generation plant during and assumed financial life and duty cycle. Main inputs include the financing costs, capital costs, fuel costs, fixed and variable operations and maintenance costs (O&M), and assumed utilization rate for the plant type. It is used as a summary measure of the overall competitiveness of different generating technologies (Energy Information Administration, 2019). It allows for the comparison of different technologies that have dissimilar lifetimes, a range in project size, different capital costs, risk, return and capacities (Energy Information Administration, 2019). Due to the fact that this research aims to compare specific technologies, and different market structures are not taken into account the cost is simplified to using the LCOE and does not into account the influence of the market on the cost.

Current costs

The following costs are given by Bloomberg New Energy Outlook (2018a) The costs are given for the Netherlands and the current LCOE is given. It must be noted that these costs are unsubsidised.

Table 2: Current LCOE for Production technologies specified to the Netherlands adapted from (BNEF 2017)

Production LCOE	**Mid**	**Source & further information**
	$/MWh	
Wind Offshore	74	(BNEF, 2017) Netherlands
Wind onshore	51	(BNEF, 2017) Netherlands
Solar PV	49	(BNEF, 2017) Netherlands, based on non-tracking PV
Hydro	347,5	Based on costs for Germany LCOE as this is most likely where Hydro would come from - or France or Belgium due to geographical location (BNEF, 2017)
Biomass	196	Based on costs for UK Biomass as the Netherlands is most comparable to European country costs (BNEF, 2017)
Nuclear	301	Bases on costs for France LCOE as this is most likely where nuclear energy would be imported from as there is no planned increase of Borssele Nuclear power plant in the Netherlands (BNEF, 2017)
Open cycle gas turbine	225	(BNEF, 2017) Netherlands Although these technologies are not RES, they are added in this table to indicate the cost in comparison.
Closed cycle gas turbine	79	(BNEF, 2017) Netherlands
Coal	131	(BNEF, 2017) Netherlands
Marine energy	-	-

3.1.5. Description of technologies

In this chapter a general description it given of the possible generation technologies and their accompanying characteristics. A summary of advantaged and disadvantages per technology can be found in the appendix.

Wind energy

As one of the most mature renewable energy production technologies to date, wind energy is one of the generation technologies with most potential in the Netherlands. Currently, '100% renewable energy' on a yearly base that companies use generally consists of electricity generated from wind parks. Its production profile is intermittent,

In 2017 offshore wind parks generated 0,57% of the final energy consumption of the Netherlands. (Energieopwek, 2019). With In 2018 10.8 TWh of energy was generated by wind turbines, of which 6.9 TWh came from land and 3.9 TWh came from offshore wind. An ambitious offshore wind programme has a target of 49 TW in 2030 (Clean Tecnica, 2019). The installed capacity currently in operation in the Netherlands is 1 GW, by 2030, 12 GW is planned to be installed offshore (Velthuijsen et al., 2018). Further information on the plans can be found in the appendix. The LCOE of offshore electricity production in the Netherlands is between 66 and 88 in 2017. The cost in the Netherlands is relatively low compared to surrounding countries.

In 2017 onshore wind generated 1.08% of the final energy consumption in the Netherlands (Energieopwek, 2019). Limited public support is slowing down growth in the long and short term for onshore wind. Where the target was 6000 MW of installed capacity, this has now been adjusted to 4750 MW in 2020 (ECN, 2017b).

Solar PV

Solar PV is the other of the most mature renewable energy technologies that is being implemented in a rapid pace. In 2018 Solar PV production in the Netherlands grew from 2.2 TWh to 2,47 TWh, about 3% of the total electricity consumption (Clean Tecnica, 2019). It has a predictable production profile with peaks at midday (Energieopwek, 2019).

Biomass

The production of electricity from biomass in the Netherlands grew from 4.7 TWh to 5.8 TWh in 2018 (Clean Tecnica, 2019). 5% of the electricity in the Netherlands comes from biomass. Of which a significant part also comes from waste incineration.

Electricity from biomass is baseload. The most dominant forms in which energy is generated from biomass are from industrial wood pellets, from agri-residues and in the form of woodchips. In the Netherlands a large amount of biomass for power is co-fired in coal-fired plants. Eneco largely uses their biomass plants for heating, and as the Netherlands has to decrease their gas consumption over the coming years, the use of biomass is expected to play an important role in heating before being used for power. The use of biomass is associated with increased competition with food and feed production and loss of forests and there (Better biomass, 2015; Dornburg et al., 2008). The sustainability criteria for specific biomass plants are specific to the plant and certification such as Better Biomass is required per case (Eneco, 2015).

Electricity generated from waste is often incorporated in the categorisation of biomass. The incineration of waste by waste processing plants produces heat that is used to generate electricity or in heat networks. Waste consists partly of biomass ('biogenic') and residual waste. The biogenic part is counted as renewable energy and in 2017 this was 0.96% of our final energy consumptions (Energieopwek, 2019).

Biogas

Biogas is created by fermentation or gasification if biomass. This can include sludge from wastewater treatment, deposited waste, vegetables, fruit and garden waste (GFT), manure, maize or waste flows from agriculture. In 2017 0,50% of the final energy demand in the Netherlands came from biogas (Energieopwek, 2019). Biogas is expected to be used for heating purposes before being used for power generation (Roelofsen et al., 2018)

Ocean Energy (Wave, thermal, tidal)

A number of technologies are possible in the ocean energy sector that are designed to utilise the power in the oceans and convert it to renewable low-carbon energy. These consist of tidal energy, wave energy, ocean thermal energy conversion (OTEC) and salinity gradient. Currently, tidal and wave energy are the most advanced ocean energy technologies, and those assumed to become commercially viable in the short-medium term (Magagna & Uihlein, 2015). Where ocean thermal ocean energy (OTEC) is more suited to tropical water (Bluerise, n.d.), research is being done into wave and tidal energy implementation in the Netherlands.

Tidal and wave energy represents two of the most advance types of ocean energy. In 2050 the EU aims to reach a combined 100GW of installed capacity for wave and tidal, and 66 MW of ocean energy projects are expected to become operational by 2018 in the EU (Magagna & Uihlein, 2015). However, according to (Sgobbi et al., 2016) wave energy does not become cost-competitive in Europe by 2050 with current expectations and assumptions. They state that tidal energy could be cost-effective in 2050, although substantial technology improvements are required to realise earlier placement.

There is a Tidal energy project that has been started by Tocardo at the Afsluitdijk (Magagna & Uihlein, 2015). In Den Oever in 2008 the initial version was installed in the drainage of sluices. The pilot project was started with 100 kW (Holland Trade and Invest, 2018). A combination of Tidal stream turbines have been placed at the Oosterscheldekering, these have been operational since 2015 with a capacity of 1,2 MW but this is only possible at existing large scale reservoirs (Tocardo, 2018). According to the company they plan to install 100 MW of tidal energy until 2020.

Nuclear

Nuclear power plants can produce large amount of baseload electricity and have a small external impact. However, the future of nuclear energy is uncertain because of public apprehensions and subsequent government policies. Although it is virtually carbon-free, public opinion on safety and nuclear waste disposal are hurdles in implementation (Suman, 2018). For this reason, that the technology has extremely high investment costs and that the Netherlands is densely populated it is difficult to implement new nuclear plants and there are currently no plans for new ones. Despite high interest in nuclear energy in the Netherlands at times in the past, only one commercial nuclear reactor was installed in Borssele. Technical and economic setbacks but also societal concerns that started to emerge in the 1970's meant that nuclear energy never took off in the Netherlands (Hölsgens, 2019; Lagaaij & Verbong, 1999; Verbong, 2001). Although not optimal for the goal of hourly matching due to the societal acceptance being an important criteria, it does provide (Brook & Bradshaw, 2015)

Hydropower

Hydro power has almost no emissions during use and can generate large scale and stable electricity. It can function as a balancing power and has no fuel costs. Hydro power plants have a long lifetime. However, the technology has a significant impact on the environment and the river ecosystems. Moreover, construction of new hydro requires substantial investment. For generation of electricity from hydro the Netherlands has little potential due to the flat topography. However, using the large volume of water that passes through its rivers electricity can be generated. The total capacity small scale hydro installed in the Netherlands is 35 MW which produces 99 GWh. Due to limited border grid capacity, electricity from hydropower in Norway and Sweden in the form of GOs has suffered critique in the past (Milieucentraal, 2018).

3.1.6. Comparison of production technologies

To make a selection for production technologies that have a theoretical potential for Hourly Matching the following table shows the criteria for different technologies. The criteria in this summary have been adapted from Demirtas (2013).

Table 3: Analysis of electricity generation technologies regarding the application of Hourly Matching

		Wind offshore	Wind onshore	Solar PV	Biomass	Biogas	Ocean Energy	Hydro	Nuclear	Gas	Coal
Technical	Predictability & Stability	-	- -	-	+	+	+	+	+	+	+
	Steerability – dispatchable & rampable	- -	- -	- -	+	+		+	-	-	-
	Installed capacity & volume of generation	++	++	+	+	-	- -	-	-	++	++
	Technological maturity	++	++	++	+	+	- -	++	+	++	++
Economic	Investment cost	+	+	+	+	-	o	-	--	o	o
	Running fuel cost	++	++	++	-	-	++	++	- -	- -	- -
Geographic	Applicable in the Netherlands	++	+	++	+	+	- -	- -	- -	++	++
Environmental	CO_2 emissions	+	+	++	-	-	++	+	o	- -	- -
Social	Social acceptability	++	++	++	-	+	++	-	-	- -	- -

The technologies are evaluated with a linguistic scale as very good, good, neutral, poor or very poor (Kaya & Kahraman, 2010)

++	Very good
+	Good
o	Neutral
-	Poor
- -	Very Poor

The further indications are elaborated on of the following page.

Conclusion

Solar PV and wind energy are at present two of the most mature renewable energy production technologies. Furthermore, it is recognised that the more predictable production of solar PV can be complemented by the more unpredictable and variable wind energy production. One of the negative aspects of solar and wind are dependent on the weather and cannot be dispatched or ramped. However, these technologies are expected to largely increase coming years. Solar and wind have low costs that are expected to fall further in the future. Electricity generated from Wind and Solar PV therefore provide a base for future RES in the Netherlands and is therefore also significant for the scope of Hourly Matching. The other technologies analysed (nuclear, biomass and hydro) have either low social acceptance or low installed capacity, such as ocean energy. Although there is some installed, biomass is still largely used for heating or for co-firing with coal. In terms of social acceptability fuel input for biomass and biogas are complex and need to be tracked extensively to ensure sustainability. Compared to solar PV and wind, it is more controversial, however in specific case its can be further explored. The installed capacity of ocean energy is small and still in a development phase, as with biomass, in specific cases this could be used. However, for the scope of this thesis relatively little general data is available on the technologies and differs per installation. Hydro production would have to come from neighbouring countries, which is less desirable for the case of production. Although various production technologies could potentially be added to the portfolio, the acceptance per technology is partially dependent on the consumers preference for technologies that the want to be associated with. For example, one LSE consumer could want to invest in novel technologies such as tidal energy and another could base their preference on a focus on lowering carbon emissions.

3.2 Electrical Energy Storage technologies

Following the initial analysis of electricity generation technologies, in this chapter the selection of different Electrical Energy Storage (EES) technologies are analysed. EES is a process of storing electrical energy in other forms of energy to be converted back when required (Argyrou et al., 2018).

There are a large number of energy storage forms that have characteristics that make them suitable for diverse applications (ECN, 2017a). To select technologies that have potential for Hourly Matching, first the different applications and categorizations of Electrical Energy Storage are analysed. Secondly, the technical operation of storage technologies and their characteristics are further discussed. Thirdly, the criteria for the selection of storage technologies for Hourly Matching are defined. The criteria define the potential shortlist of technologies that are taken into account in the model.

3.2.1. Applications areas of Electrical Energy Storage

Although there is no single application of EES that can be found that describes the goal of storage for the goal of Hourly Matching, existing applications in literature are investigated to gain a better understanding of current categorisation of application areas. This gives insight to specify the aspects of EES that are important for Hourly Matching. It is well recognized that no single EES technology can meet the requirements for all power system applications and therefore there is no unambiguous EES solution (Luo et al., 2015). Comprehensive There is a large variety of categorisations of application areas and suitable technologies. (Aneke & Wang, 2016; Luo et al., 2015; Mahlia et al., 2014; Zhang et al., 2018). Moreover, no unambiguous categorisation of applications of storage can be found in existing literature.

There are many different categorisations of energy storage available in literature, the important ones are the following. The first categorisation of application areas of storage that is often mentioned, is based on time. Examples include storage for 4-6 hours for solar energy shifting and 4-10 hours for wind energy shifting *(Navigant, 2018)*. Secondly, the function and the nature of the problem resolved is often mentioned. Examples are transmission and distribution, asset optimisation or peak shaving or improvement of power quality (*Navigant, 2018,* Luo et al., 2015). Other named applications are; power quality, frequency regulation, peak shaving, load levelling, load following, seasonal storage, integration of renewable energies and emergency backup generation. (Argyrou et al., 2018; Luo et al., 2015). Third, storage applications can be analysed from a market perspective, if it provides a service on the day-ahead market and intraday market or on the frequency reserve market (Eneco, 2018). Additionally, storage can be categorised based on power and capacity rating amongst other technical characteristics.

Over the past decades, the stationary energy storage development has been mainly focused on short duration energy storage applications and grid services (Navigant, 2018). Hourly Matching has a specific goal of storing electricity to balance out the production and demand to reach 100% match on an hourly scale. Therefore, the desired discharge duration is hours rather than seconds. Additionally, seasonally balancing is a potential application for EES, however hourly balancing is the initial step. Although there are many different applications of storage also desired in an energy system based on (V)RES, this is not the initial focus of Hourly Matching and this research.

Globally, the largest amount of storage currently is Pumped Hydro Storage (PHS), with 98% of the energy storage. The largest number of operational projects are battery Energy Storage projects, the second largest is PHS and third largest number is thermal energy storage projects (Aneke & Wang, 2016).

3.2.2. Categorisation of Electrical Energy Storage Technologies

Storage technologies can be categorised by storage duration (long-term to short-term technologies) or by other criteria such as capacity, efficiency, environmental impact or capital cost. EES may be divided into 5 main categories such as chemical, electrochemical, electrical, mechanical and thermal energy storage (Guney & Tepe, 2017). Within the scope of this research Thermal energy Storage (TES) is not further analysed as it is assumed that as there is a large demand for heating, this form of storage will be largely allocated to heating purposes.

Figure 9 shows the categorisation of technologies that are taken into account in this analysis.

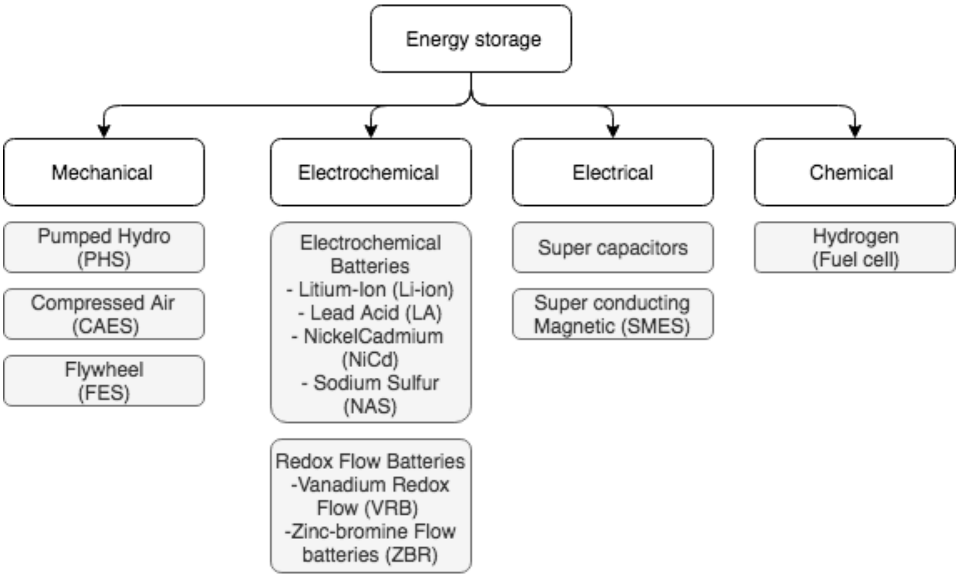


Figure 9: Different categorisations of energy storage (Adapted from Aneke & Wang, 2016; Argyrou et al., 2018)

3.2.3. Criteria for storage technologies

In this chapter, the criteria that are defined for Hourly Matching are further elaborated after briefly showing the relevance of different characteristics for the choice for technologies.

Storage technologies can enable an increasing share of variable renewable energy generation in the system by reducing the mismatch between generation and demand over time (Slingerland et al., 2015). To analyse these storage technologies, two storage ratings are essential to time-shift of electricity to loads (Belderbos et al., 2017). The first is electric power, or capacity (W). The power capacity of a storage technology refers to the highest level of electricity that the utility can supply at any one time. The second is electric energy, or power generated over time (Wh) (Belderbos et al., 2017). Energy refers to the total amount of electricity that the storage utility supplies throughout the year and is measured in Wh.

In Table 4 the criteria used for the selection of EES and the characteristics that influence these criteria are given. The characteristics of storage technologies that impact the criteria are given in the last column.

Table 4: List of evaluation criteria for production and storage technologies.

Indicator	**Criteria**	**Impacted by characteristics**
Technical	Suitable application rated power & energy capacity	• Power rating • Discharge time at rated power • Discharge duration • Response time • Cycle life
	Suitable application storage for hours	• Suitable storage Duration • Response time • Self-discharge Rate
	Efficiency	• Efficiency
	Technological Maturity	• Technological maturity
Economic	Installation cost – power & energy	• Energy installation cost • Power installation cost
Geographic	Applicable to the Netherlands	
Environmental	CO_2 emissions	
Social	Social acceptability	

Characteristics of storage technologies

The following characteristics are given in Table 4 of storage properties (Argyrou et al., 2018; International Renewable Energy Agency, 2017):

Table 5: Properties of technologies that are used in the analysis.

Characteristics found in Literature	**Indicator**	**Explanation**
Power rating	(MW)	The rate of energy transfer per unit of volume.
Discharge time at rated power		The time that the EES can discharge with the above power rating
		Can store electricity for long enough
		Can store enough electricity
Suitable storage duration		The potential duration of storage
Response time		The response time is the duration of time for the transition from no discharge state to full discharge state.
Self-discharge rate	(%/day)	The continuous loss of stored energy as a result of leakages (PHS, CAES), internal processes (Battery Energy Storage Systems) or friction (flywheels).
Cycle life	(equivalent full cycles)	The total number of cycles possible before it becomes unusable for the application (i.e. that the capacity decreases severely).
Round-trip efficiency (η)		The ratio of energy output (kWh) to energy input (kWh) of a storage system during one cycle.
Depth of discharge	(%)	How much energy is cycled into and out of the EES on a given cycle, expressed as a percentage of the total capacity.
Lifetime	(years)	The shelf life of a battery system under given conditions, stated in years.
Technical Maturity		Maturity of the technology
Applicable to the Netherlands		Applicability in Europe, preferably Netherlands

Economical Characteristics

A difference in the cost structure generally used from literature and practice. In business and investing in storage technologies, the cost is usually broken down, as a business case, into:

- Capital Expenditures (CAPEX)
- Operational Expenditures (OPEX)
- Efficiency

In literature the cost of Electrical Energy Storage is often split into

- Energy Capital cost $ / kWh - The levelised cost of providing storage services during the system lifetime, expressed in $/ per kWh
- Power Capital cost $ / kW - The levelised cost of providing storage services during the system lifetime, expressed in $/ per kW (Akinyele & Rayudu, 2014; Aneke & Wang, 2016)
- $/ kWh/ cycle (Luo et al., 2015)

The cost structures for Electrical energy Storage systems will be further discussed in the Methodology in chapter 4.

Summary of Costs

The following graphs show the energy installation cost ($/ kWh) and the power installation cost ($/kW) of different technologies. The energy installation cost is the the cost per installed kWh of storage capacity in real 2017 USD ($), the power installation cost is the cost per installed kW of capacity. To analyse the costs of storage both the cost of the installed power and installed energy need to be taken into account in the calculations. Flywheels are excluded from the graphs as the cost is relatively high (and hence this technology is not regarded as suitable for the application of Hourly Matching). The reference case indicates a realistic cost, the high and low indicate the range of costs. It shows the decrease in cost for most EES, except for Pumped hydro storage (International Renewable Energy Agency, 2017). The accompanying table can be found in the Appendix.

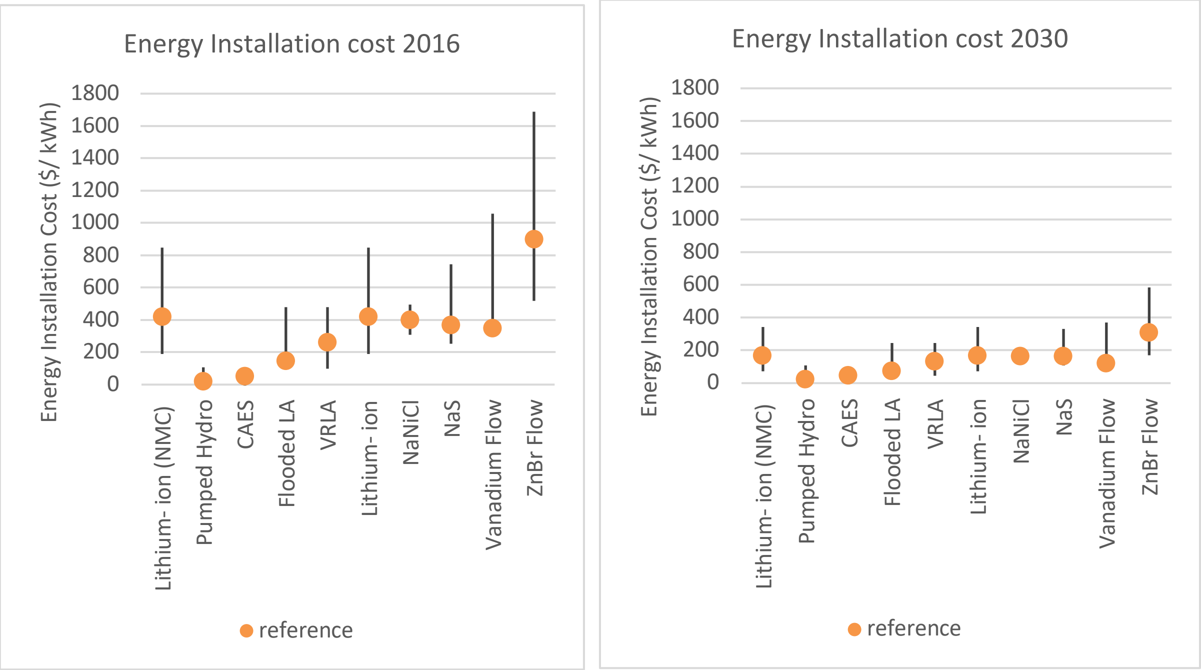


Figure 10: The energy installation cost in 2016 and in 2030, the reference cost is indicated with the marker and the range is indicated with the line

The following graphs show the power installation costs It shows that PHS and CAES have higher power installation costs, these are also the technologies that have the lowest energy installation costs.

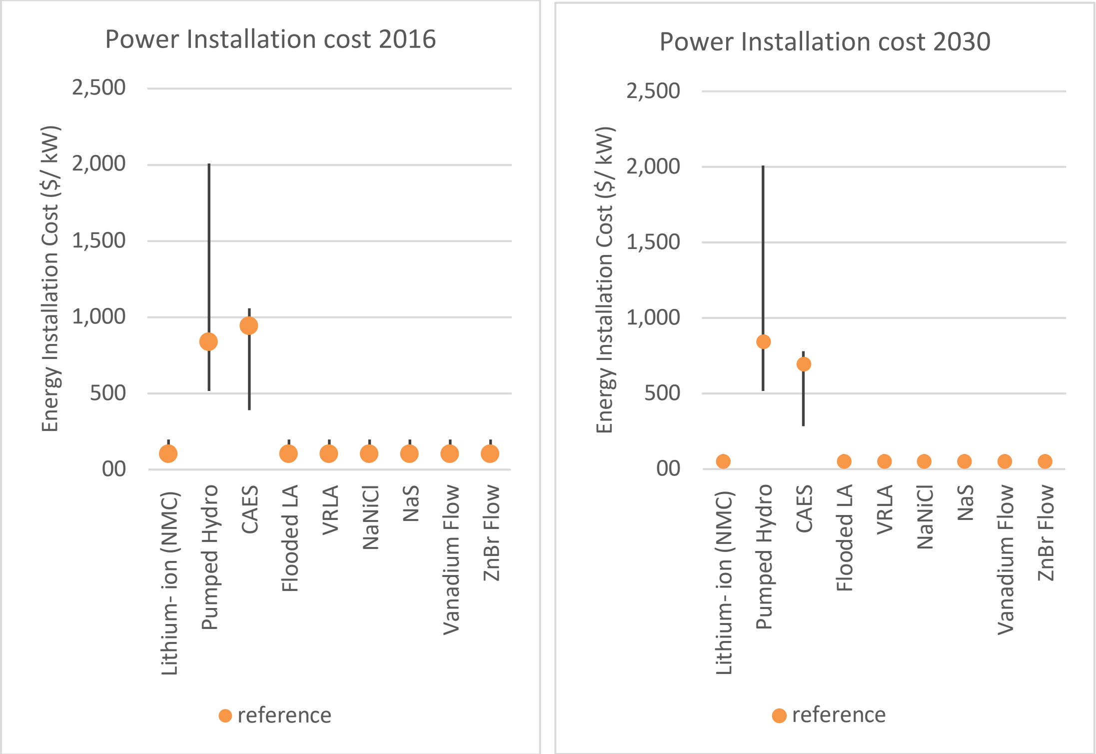


Figure 11: The Power installation costs in 2016 an 2030, the reference cost is indicated with the marker and the range is indicated with the line.

3.2.4. Description of electrical energy storage technologies

This section contains a detailed description and discussion of each type of energy storage technology.

Pumped Hydro Storage (PHS)

Pumped Hydro Energy Storage is one of the most common, mature and popular energy storage systems. The largest capacity of global energy storage is in the form of PHS with 96% and 169 GW over 300 PHS plants. The first storage system was built in 1929 in the USA. The largest PHS plant has a power capacity of 3GW and a discharge time of 10 hours at rated power.

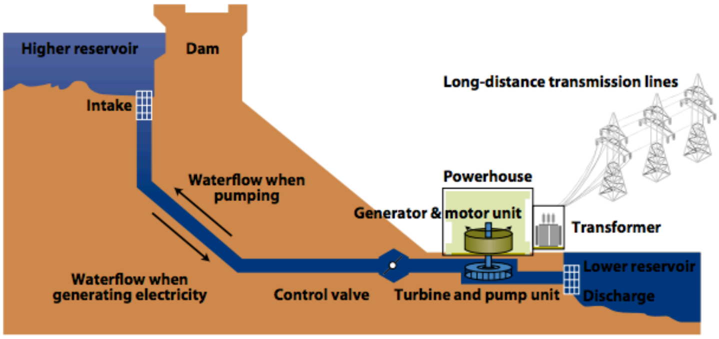


Figure 12: Schematic of a typical Pumped hydro storage system (Luo et Al, 2015)

PHS makes use of potential energy stored in water pumped up to a higher reservoir. The water can be pumped from the lower to the upper level or can flow from the upper to the lower level. When electricity is needed water from the upper reservoir is released and activates the turbines for electricity generation. When energy needs to be stored water is pumped to the upper reservoir (Argyrou et al., 2018). As shown in Figure 12 the system consists of two water reservoirs, and a unit to pump water to the higher reservoir and a turbine to generate electricity. The energy is stored in potential energy, therefore the amount of energy that can be stored is proportional to the difference in height between the reservoirs and the amount of water that can be stored ($E = m \cdot g \cdot h$). Advantages of PHS include the long lifetime of 30-60 years, a relatively high efficiency at 65-85%, and a fast response time of less than a minute. Added to that, a large power capacity is possible with 100-5000MW, energy can be stored for a long period of time and cycle costs are low. PHS can also be incorporated in existing Hydropower systems.

However, disadvantages are that there is a high capital cost, a large amount of land is required and therefore the environmental impact is large, and projects usually have a long lead time of around 10 years. Furthermore, finding an area that is topographically suitable is difficult as projects often are only feasible from a height difference of 300m (Poullikkas, 2013).

PHS is not directly available in the Netherlands. However, it is available in a number of neighbouring countries and there are options for implementation that might be feasible closer or in the Netherlands. The first options would entail contracts with small scale PHS systems in surrounding countries. This could be done with largescale PHS in Switzerland, Germany, France or Belgium. The second option is not available yet but could entail the Delta 21 plan to make use of water near Brouwers Meer (Delta 21, 2018). This plan consists of a system which would initially be to be able to pump excess water out to sea in case of flooding risk, however this would only be required in extreme cases, on shorter term it could also be used to as energy storage. The water level in the water reservoir can rise or fall 17.5 m, respectively. Emptying or filling the pool with an average height difference of water of 14 m. The reservoir would have an installed power capacity of 1.8 GW, which can supply energy for 12 consecutive hours (Delta 21, 2018). The third option would be to create PHS in underground caverns for which height difference from mountains is not required. For the scope of this research the costs of these different implementation options for PHS are assumed to be equal.

According to the International Renewable Energy Agency (2017) PHS has an energy installation cost of 21 $/kWh and a power installation cost of 840 $/KW. This falls within the large range of the capital cost also given by Poullikkas (2013) $500-4600$/kWh. The price for PHS is expected to decrease very little over the years, as there are no large innovations being done for this technology (International Renewable Energy Agency, 2017)

Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage is another technology for large scale energy storage. By compressing air in natural or mechanically formed caverns, energy can be stored mechanically. As it can store and supply energy for days it is seen as long-term energy storage (Argyrou et al., 2018). The power capacity of a CAES plant is generally between 100 and 300 MW. There is currently 640 MW of CAES set up globally. A CAES plant in Germany (in Huntorf, 290 MW since 1978) and in USA (Alabama, 110 MW since 1991) are the only two large scale CAES installations at the moment. By 2020 there are two large scale plants expected in Texas (317 MW) and California (300 MW) (Mahlia et al., 2014).

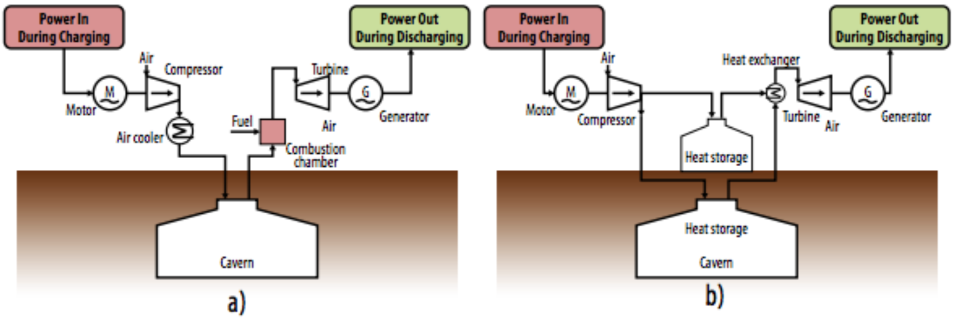


Figure 13: Schematic diagram of a diabatic (left) and adiabatic (right) compressed air storage system (International Renewable energy agency, 2017)

Figure 13 represents a schematic diagram of a basic CAES system. It consists firstly of a motor to charge and a generator to discharge. An air compressor with an air cooler is required for compression and to decrease the moisture content of the compressed air. Following that there is a recuperator and a low and high-pressure turbine. The compressed air is stored in a cavern or container underground. Lastly there are equipment controls and auxiliaries such as heat exchanger units and fuel storage. CAES plants lack the maturity that some other electrical energy storage systems have although the equipment used in the plants is well proven and mature (Argyrou et al., 2018).

As previously mentioned, there are two main types of CAES, adiabatic and diabatic. Diabatic CAES is combined with a gas turbine plant. The Adiabatic CAES does not require a connection with a gas turbine plant. As it does not need to be combined with a gas plant it is more sustainable than the diabatic storage. By integrating thermal storage, it is operated at expansion mode. The heat created from the compression process is stored and can be used to reheat the air during the expansion. This entails that there is no need for a combustion process. As fuel consumption is limited and the system is more efficient and environmentally friendlier it is seen as a promising technology. In 2016 the first pilot A-CAES system was built in the Swiss Alps with a 4hr autonomy and capacity of 500kWh. The estimated overall efficiency is around 63-74% and an unused tunnel functions as the air storage cavern and for thermal storage a packed bed of rock is used (Argyrou et al., 2018). Further data on this technology and its characteristics is not available. New companies continue to innovate such as Hydrostor (Navigant, 2018)

Benefits of CAES are the low capital cost stated as being energy installation cost of 53 $/kWh and a power installation cost of 945 $/kW according to the International Renewable Energy Agency (2017), the fact that it brings few environmental problems as it makes use of underground storage, has a lifetime of around 40 years. It has comparable benefits to PHS with long energy storage duration at more than 1-year, high power capacity, relatively high efficiency with 60-80% and relatively quick start up. The self-discharge rate of the system is low (0.1% / day). However, with 12 kWh/ m^3 they do have a low energy density (International Renewable Energy Agency, 2017; Argyrou et al., 2018).

Disadvantages of CAES include the dependence on gas for recovery of stored energy in the case of diabatic CAES. One of the biggest barriers arise from geographical restrictions as traditional underground storage requires either natural underground caverns or underground tanks (Navigant, 2018). Abandoned gas reservoirs and particularly salt caverns are suitable for installing CAES facilities, in the Netherlands there are a large amount of these (Slingerland et al., 2015).

CAES is seen as a suitable storage technology for large-scale power and high energy storage applications. It is also seen as a viable technology to mitigate wind variability with the purpose of wind levelling and energy management (Beaudin et al., 2010).

Flywheel Energy Storage (FES)

Flywheel Energy Storage makes use of kinetic energy of a rotating mass. During charging it acts as a motor, and as a generator from the rotational energy during discharging. The energy storage is dependent on the moment of inertia and the angular velocity. The amount of energy stored can be increased by rotating the wheel faster. (Argyrou et al., 2018)

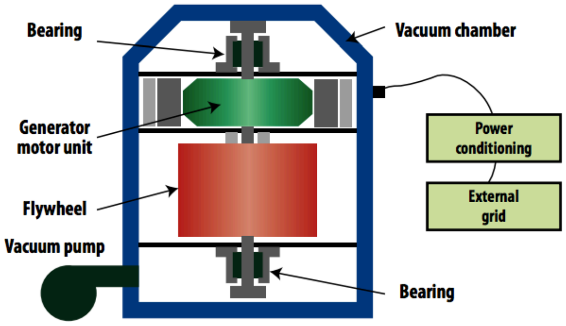


Figure 14: Key components of a high-speed flywheel storage system (International Renewable Energy Agency, 2015)

FES is categorised as short-term energy storage as the discharge time is between minutes and up to 1 hour. Figure 14 shows the flywheel storage system. It consists of a motor/ generator two magnetic bearings that rotate a mass in order to decrease friction a high speed and the vacuum to reduce wind shear.

The benefits of FES include a high efficiency (90-95%), long lifecycles (10,000 – 100,000 cycles) and a long lifetime (15-20 years). However, disadvantages of FES include that they have a self-discharge rate of 20% / hour, therefore they do not allow long-term energy storage. The energy density is also low, and the capital cost is high.

This type of energy is therefore more suitable for short term storage and balancing the grid for frequency regulation. It is not suitable for the goal of increasing the % of hourly matched RES in this research.

Battery energy storage (BES)

Battery energy storage (BES) refers to electrochemical energy storage technologies that convert electricity to chemical potential storage and then back to electricity. A battery storage system consists of a battery pack and a power conversion system.

Batteries can be categorised in the following sub-categories:

- Conventional: (eg. lead acid, lithium-ion) Are composed with cells that contain two electrodes.
- High temperature batteries: Use molten salt to store electricity (eg. NaS)
- Flow batteries: Make use of electrolyte liquids in tanks (e.g. ZnBR and FECr Redox flow batteries) (Slingerland et al., 2015)

The prices of batteries have fallen largely in the past decade and the pack prices are expected to fall until 2030. (BNEF, 2018). The historical average prices joined with the volume of Lithium-ion battery shipments provide a learning rate of around 18%. However, currently there are few batteries commercially available for flexibility services, and are currently only interesting for short term flexibility and balancing (Slingerland et al., 2015).

Lead acid batteries (LA)

Lead Acid batteries are the oldest form of BES. LA batteries have been popular in microgrids or isolated power systems, and for power quality. They are a mature technology with a round trip efficiency of 75-85% (Luo et al., 2015)) They are not favourable for time shifting purposes due to the fact that they have limited life cycles (2500), short discharge time, and low energy density (50Wh/ kg) (Zakeri & Syri, 2015).

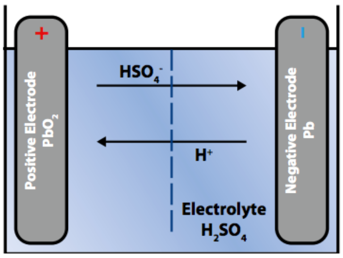


Figure 15: Operating principle of a lead-acid battery (ISEA, 2012)

Sodium Sulphur batteries (NaS)

Sodium Sulphur batteries were introduced in the 1960's. They are a form of molten salt batteries. Their characteristics include a high energy density (150-240 Wh/ kg), high power density (150-240 W/kg), high rated energy capacity (up to 245 MWh), low maintenance costs, fast response time and high energy efficiency (75-90%). Materials used in the battery are also about 99% recyclable) However, the batteries have a high initial capital cost and some safety issues (explosions are possible under high temperatures) (Argyrou et al., 2018). They have an expected lifetime of 15 years and are one of the most proven electrochemical storage technologies in MW scale (Zakeri & Syri, 2015). Figure 16 shows the Operating principle of a sodium sulphur (NaS) battery (ISEA, 2012)

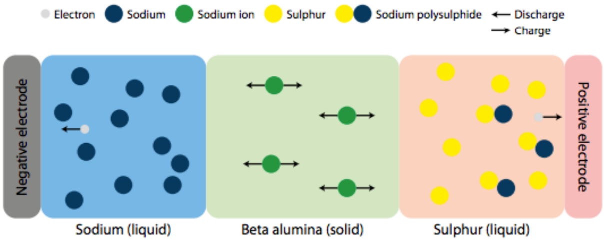


Figure 16: Operating principle of a sodium sulphur (NaS) battery (ISEA, 2012)

Lithium-ion batteries

Lithium–ion batteries are gaining a large part of the storage market. The technology has currently achieved significant penetration. It is transitioning into the hybrid and electric vehicle market and has opportunities in grid storage.

Lithium-ion batteries were commercialised in 1991. They consist of a cathode composed of lithium-based compounds (such as LiCoO2, LiMn02, LiFePO4) and an anode made from graphitic carbon (C) The electrolyte is usually a non-aqueous liquid organic solvent mix with dissolved lithium salts. (Argyrou, M., 2018).Figure 17 shows the Main components and operating principle of a lithium metal oxide cathode and carbon-based anode Lithium-ion cell (ISEA, 2012)

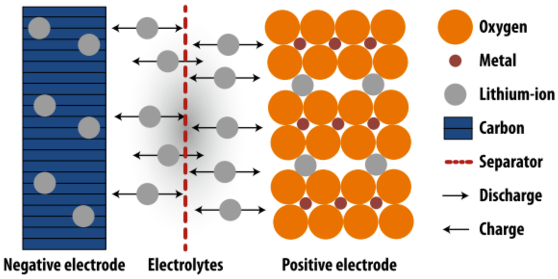


Figure 17: Main components and operating principle of a lithium metal oxide cathode and carbon-based anode Lithium-ion cell (ISEA, 2012)

The advantages of Lithium-ion batteries compared to NiCd and LA batteries are the higher energy density (80-200 Wh /kg) and high energy efficiency (90-97%), a low discharge rate (<5%/month) and very low maintenance required. Lithium-ion batteries also have a fast response time (<5ms) high power density (500-2000 W/kg) wide operating temperatures (-20 to 60 C for charge and -40-65C for discharge) and more than 1000 to 10,000 life cycles (Wen et al., 2017). The prices have fallen rapidly in previous years. Between late 2015 and late 2018 the decrease was 35%, this is much faster than many in the industry had predicted and is seen as a reason why other long duration energy storage companies have gone bankrupt (Navigant, 2018).

However, there are also disadvantages to Lithium-ion batteries, the lifetime of the batteries depends on the temperature and for that reason they are not suitable for backup applications in which they need to be completely discharged. Another disadvantage regards their safety. The metal oxide electrodes which are thermally unstable can decompose when temperatures rise and release oxygen and thermal energy. Because of this problem there is a maximum charge and discharge cunt limit on most batteries (Argyrou, M., 2018). The initial capital cost is one of the factors limiting extensive application of these batteries in grid energy storage (Wen et al., 2017).

Lithium-ion batteries technically provide an option for storage to increase the number of matched hours of RES production and demand of a company.

The sales of Lithium-ion batteries are expected to strongly increase in the future, of which a large proportion for passenger EVs. This widespread deployment of EVs will lead to rapid decrease in the costs. According to the re-using and repurposing of Lithium-ion batteries after the end of life in Electric vehicles, as stationary storage will contribute to cost reductions (Tsiropoulos I et al., 2018; BNEF Long-term Energy storage outlook, 2018).

Flow batteries

Flow batteries are another promising storage system and relatively new technology. They are classified as long-term storage for large-scale applications.

Flow batteries convert electrical energy into chemical potential energy by charging two liquid electrolyte solutions and releasing the stored energy. In tanks these electrolytes are stored externally which are pumped through the electrochemical cell that converts chemical energy directly to electricity and vice versa. The energy capacity is easily scalable as the number of electrolytes are easy to replace or increase their amount (Luo et al., 2015). Figure 18 shows aA schematic diagram of the flow battery system (Argyrou et al., 2018)

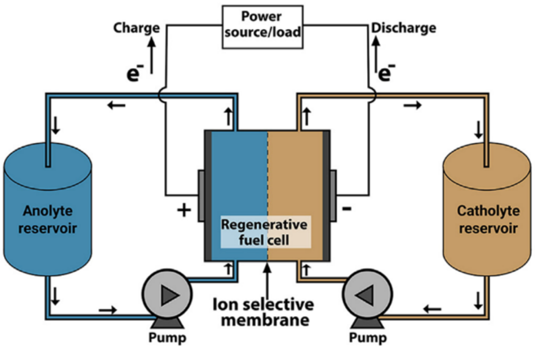


Figure 18: A schematic diagram of the flow battery system (Argyrou et al., 2018)

The benefits of Redox flow batteries are the fact that there is no discharge rate, low maintenance requirements, it has a long lifetime and no degradation of depth of discharge. Flow batteries have electrochemical recharging capabilities that can be compared to other rechargeable battery technologies. With flow batteries however, the power and energy are decoupled which is more comparable to fuel cells. Because of this decoupling it is possible to create flexibility in the independent design of the power output unit and the energy storage unit. This entails cost and time advantages and the possibility of simplified upgrading in the battery system in the future (Qi & Koenig, 2017). The disadvantages include that there are technical development issues and high investment costs. For large scale EES systems (19 kW- 10MW) Redox flow batteries offer an interesting option (Argyrou, M., 2018).

Vanadium Redox flow Battery (VRB)

Vanadium redox flow is one of the most mature flow batteries and has a lower cost than Zebra flow batteries (Luo et al., 2015). Vanadium redox flow batteries have fast responses (faster than 0.001 s), can operate for 10,000–16,000+ cycles and have a high efficiency, of up to 85%. VRBs can be used in a large number of applications, including enhancing the power quality for stationary applications, improving load levelling and power security, balancing the intermittent nature of RES-based electricity generation (Luo et al., 2015)

Super conducting Magnetic Energy Storage (SMES)

Superconducting Magnetic Energy storage makes use of the magnetic field to store energy. To reach a temperature below its superconducting critical temperature it is cryogenically cooled. Due to the high cost of superconducting wire and the energy requirements of cooling, SMES have a high cost and are mainly used for short term energy (Mahlia et al., 2014) Due to the fact that they have a discharge time up to 30 minutes this is technology is not suitable for the application of Hourly Matching as this requires longer storage duration.

Super Capacitor Energy Storage (SCES)

Super capacitors consist of electrochemical capacitors with relatively high energy density. High efficiency and long lifecycles makes the technology attractive, however the short discharge time and low power rating make it a technically unsuitable technology for the goal of this research (Mahlia et al., 2014).

Hydrogen Energy Storage

Power-to-fuel storage systems produce hydrogen by ectrolysis. Hydrogen can be used directly as fuel, as chemical feedstock or converted to other fuels, and can be converted back to power (Sternberg & Bardow, 2015). Compared to the other technologies analysed however, hydrogen for a power-to-power application is inefficient with only 20-35 % efficiency for a fuel cell and 40-50% for a gas engine (Aneke & Wang, 2016; Steinke et al., 2013). It could potentially increase up to 50% if more efficient technologies are developed (Energy Storage Association, 2018) but is therefore much lower than other storage technologies. The costs are also This low efficiency is due to multiple conversion from electrical to chemical energy and heat losses for the case of Electrical Energy Storage (Navigant, 2018). Overproduction of energy from RES in the Netherlands is limited and therefore low efficiency rates for power-to power applications are undesirable. Added to this the technology is developing, and there is currently a still a great demand for hydrogen as a resource in industry, an application that would be favoured to produce from green energy before using it as electrical energy storage (Sternberg & Bardow, 2015).

3.2.5. Summary of Storage technologies

	Technology	Power Rating [MW]	Discharge Time at rated power	Suitable storage duration	Response time	Self-discharge Rate [%/ day]	Cycle life [equivalent full cycles]	Efficiency [%]	Lifetime [years]	Maturity
Mechanical	PHS	100-5000	hours-days	hours-months	min	0,01	50,000	65-85	30-60	Mature
Mechanical	CAES A-CAES	5-300	hours-days	hours-months	sec-min	0,1	50,000	60	50	CAES commercialised AA- CAES developing
Mechanical	Flywheel	0.01-10, 0.1-20	seconds-minutes	seconds-minutes	sec-min	60	200,000	85-95	15-20	Early commercialised
Mechanical	LAES	0.35-5	1-24 hours	hours-months	5 min			50-70	20+	Demonstration
Electrochemical	LA	0-20	seconds-hours			0,25	1500	75-85	12	Mature
Electrochemical	NiCd	0-40	seconds-hours							
Electrochemical	NiMh	0.01-1	hours							
Electrochemical	NaS	0.15-10	seconds-hours	second-hours	5 ms	0,05	5000	75-86	15	Demonstration
Electrochemical	Li-Ion	0.1-50	minutes-hours	minutes-days	5 ms	0,15	2000	90-97	12	Demonstration
Electrochemical	Redox flow (VRB)	0.3-15	seconds- 10 hours	minutes-months	5 ms	0,15	10,000- 16,000	68-85	12	Demonstration, early commercialised
Chemical	Hydrogen Fuel Cell	0.001-50	minutes- hours	hours-months	5 ms	0.003-0.03	1000	20-35 40-50	5-15	Developing
Electromagnetic	SCES	0.01-1	seconds-minutes	seconds-hours	5 ms					Developing
Electromagnetic	SMES	0.1-10, <100	seconds-30 min	minutes-hours	5 ms		100,000+	95-98	20+	Developing
Thermal	TES (High Temperature)	0.1-300	hours		min					Developed
		(Argyrou et al., 2018)	(Argyrou et al., 2018)	(Aneke & Wang, 2016)		(International Renewable Energy Agency, 2017) (Bocklisch, 2016) (Aneke & Wang, 2016)	(International Renewable Energy Agency, 2017)	(International Renewable Energy Agency, 2017) (Zhang et al., 2018) (Luo et al.,2015) (Bocklisch, 2016) (Aneke & Wang, 2016)	(International Renewable Energy Agency, 2017)	(Argyrou et al., 2018)

Table 6: General characteristics of storage technologies

Comparison of Storage technologies

To make a selection for technologies that have a theoretical potential for Hourly Matching the following table shows the criteria for different technologies. The criteria are explained below. The criteria have been adapted from Demirtas (2013). The technologies are evaluated with a linguistic scale as very good, good, neutral, poor or very poor (Kaya & Kahraman, 2010)

Table 7: Analysis of ESS regarding the application of Hourly Matching

		PHS	CAES	AA-CAES	Flywheel	Lithium-ion Battery	LA Battery	Other BESS	Redox flow	Hydro gen	Electromagnet Supercapacitor	SMES
Technical	Suitable application storage for hours	++	++	++	- -	++	++	++	++	+	- -	- -
	Suitable application rated power & energy capacity	++	++	++	-	o	o	o	++	+	- -	+
	Efficiency	++	+	+	+	++	++	++	++	- -	++	++
	Technological maturity	++	+	-	+	++	++	++	-	- -	+	+
Economic	Installation cost – power & energy	++	+	+	- -	+	+	+	+	- -		
Geographic	Applicable in the Netherlands	- -	+	+	+	+	+	+	-	+	+	+
Environmental	CO_2 emissions	++	-	+	+	+	+	+	+	o	++	++
Social	Social acceptability	-	o	o	+	+	+	+	+	o	+	+

The further indications are elaborated on of the following page.

++	Very good
+	Good
o	Neutral
-	Poor
- -	Very poor

Conclusion

Suitable for hours

For Hourly Matching storage needs to provide storage for a number of hours. Due to its fast-self-discharge, flywheels are not suitable for improving the Hourly Matching score based on this criterion. For most other technologies this is possible although NaS, Supercapacitors and SMES are up to hours, all others can store energy for a longer period of time.

Suitable application in size

The technology needs to be able to store enough electricity to be able to backup for hours in which there is not enough RES to supply a corporate, this means that the rated power and energy capacity of storage needs to be relevant for the size of a corporate. The energy capacity of storage in flywheels is not applicable as they have a rapid self-discharge and therefore cannot store electricity over time. PHS and CAES can provide high capacity and long-duration storage.

Technology efficiency

An efficiency of at least 60% is taken as criterium in this theoretical selection. In the case of Hourly Matching technologies are required to be efficient as the cost of the system increases if they are inefficient. Additionally, as the Dutch energy mix currently only contains 6.6% renewable energy it is not desired to use inefficient technologies as these waste renewable or fossil energy from the grid.

Technological maturity

The technology has to be matured at the moment of implementation; it needs to be possible for an energy company to invest in the technology without a large amount of research into the technology. As this research is done on the case study of an energy supplier and an LSE consumer, the technology is required to be mature. Although the energy company analysed in this research, Eneco, invests in start-ups, for the case of Hourly Matching technologies are desired that are implementable on a reasonably short timescale. PHS and LA batteries are the most matured EES. Technologies such as NaS, NaNiCl, Flow batteries Lithium-ion, SMES, Flywheels and supercapacitors are generally in demonstration projects, applications in large-scale energy storage are not common (Aneke & Wang, 2016).

Energy installation cost

The CAPEX of the technology needs to be possible to pay by a company. While for PHS in cases where it is located in neighbouring countries, the cost would be in the form of a contract with the PHS, for the case of Lithium-ion batteries it would be possible to locate them on site, and buy them in smaller numbers and scale up

Applicable in the Netherlands

The technology needs to be feasible in Europe, in countries that have enough grid capacity with the Netherlands. This makes Germany, Belgium, France and Norway options for storage to be placed. Technologies are favoured that can be implemented in the Netherlands. This is difficult for large scale storage such as PHS, however in this case due to large scale possibilities, PHS is kept in the selection. Although CAES is difficult in certain countries, it is feasible in old salt caverns in the Netherlands.

CO_2 emissions

The technology should have the potential to run without using a fuel that has carbon emissions. While Diabatic CAES uses gas, A- CAES does not have this requirement, it is therefore seen as neutral.

Social acceptability

The technologies used are required to be non-controversial as the companies that are interested in the product need to have a story that they can communicate, both internally and externally. Although for production technologies social acceptability is of high importance, there is less discussion about storage technologies as these are less well known (see Appendix for further details).

Figure 19 gives a visual representation of the Electrical Energy Storage technologies that are feasible for the goal of Hourly Matching.

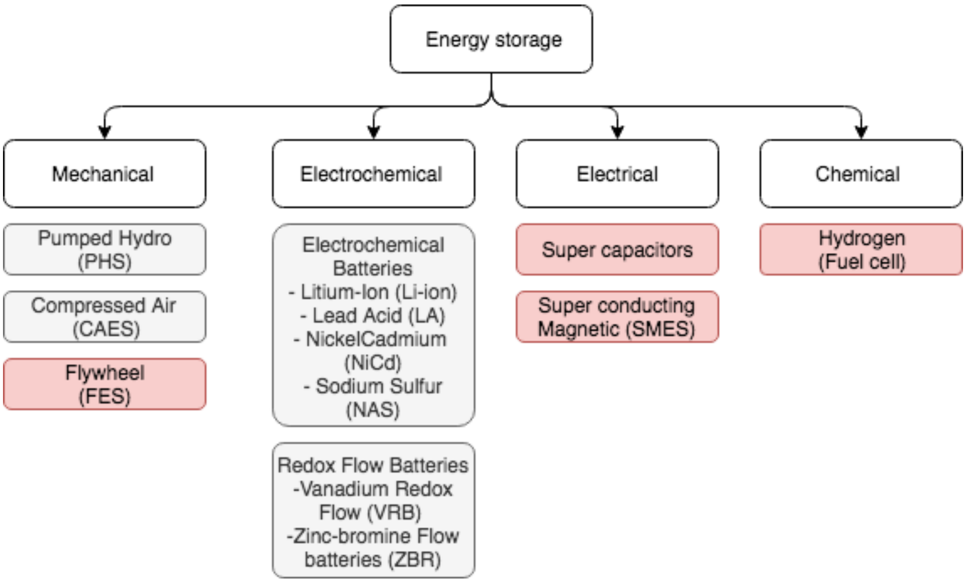


Figure 19: A visualisation of the technologies that are feasible for the goal of Hourly Matching due to characteristics regarding the function.

4. Methodology & Model

In this chapter, the methodology of the research and the model development are described. The model's underlying components, assumptions and calculations are presented. First, an overview of the model is given, and the method of determining the hourly match of a portfolio using a green score. Secondly, the methodology for analysing and comparing the costs within the given context of a client portfolio, the Levelised cost of Portfolio (LCOP) is introduced. Thirdly, the input for the model is explained. Following the analysis of technologies in Technology assessment chapter 3, the selection of generation and storage technologies analysed in the model is given.

4.1 Model overview

To analyse the effect that different production and storage technologies have on the hourly match, the following methodology is used. For the quantitative aspect of the research, an Excel model is used. To do this an existing model, developed by Eneco, is further developed, that can be used to indicate the green score of a combination of solar and wind production. The scope of the model has been extended to include additional storage technologies and a cost structure, the Levelised Cost of Portfolio. A case study is analysed of a large-scale electricity consumer.

First, the percentage of wind and solar PV as input in the model are studied. This is the percentage of the total volume of the offtake in a year in the benchmark. First this model is used to analyse the current situation using input from an existing wind park. Following this, the portfolio of technologies is used as input for the model, the effect of different technologies in a portfolio, on the hourly match is analysed. In this the ratio of production can be allocated to different production technologies. Last the methodology to analyse the cost of the portfolio in the case of the LSE consumer that is used for the case study is explained. Figure 20 shows the general schematic overview of the model. The final output is the green score and a Levelised cost of portfolio.

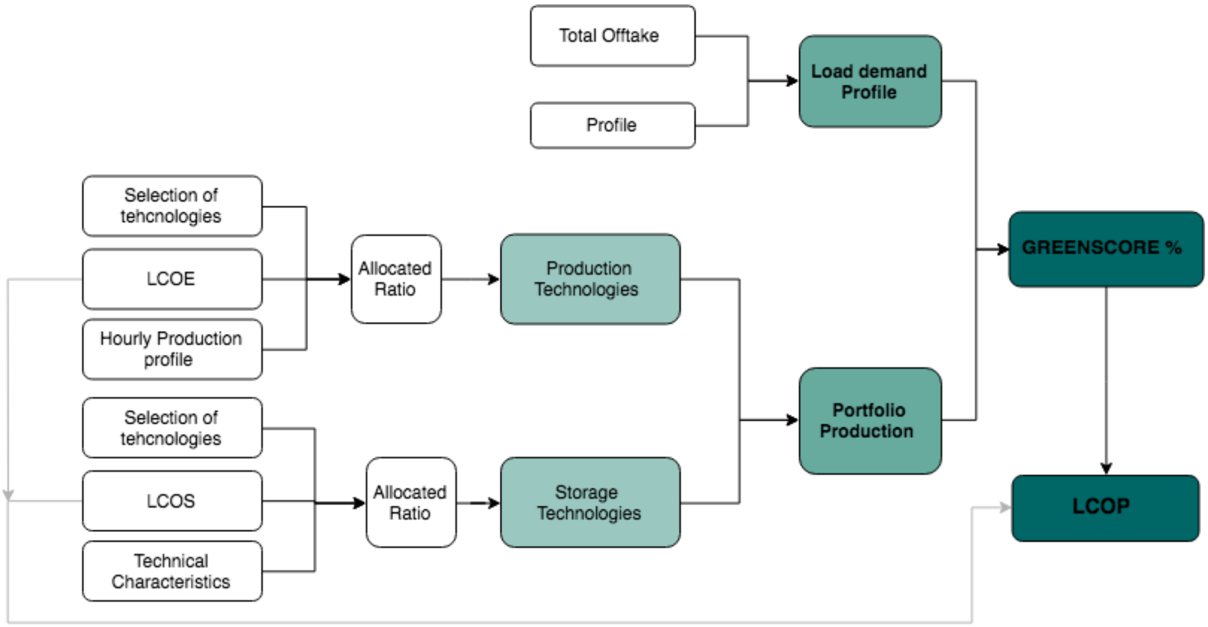


Figure 20: General schematic overview of the model

4.2 Green score of portfolios

In this chapter the green score that is used to analyse influence of different technologies on the hourly match is elaborated on. First this a conceptual description is given after which the methodology for calculating the green score is further elaborated on.

Conceptual description of green score

Step 1- Electricity from wind

In this thesis the portfolio indicates the combination of electricity production and storage technologies allocated to a company. The green score is a percentage that indicates the amount of green electricity used by a company

(represented in Figure 21 with the green volume) over a year, as compared to the total amount of energy used by the company (represented in Figure 21 with the volume under the black line) over a year.
The base of the model is electricity produced from wind parks, this is done as this is the current “100% renewable electricity” that is delivered. The first production technology is added is solar PV. This is relatively cheap, and, in the portfolio, wind can easily be replaced by solar PV.

Figure 21 shows the offtake, as a black line of the case study, and the electricity generated from the allocated wind contracts.

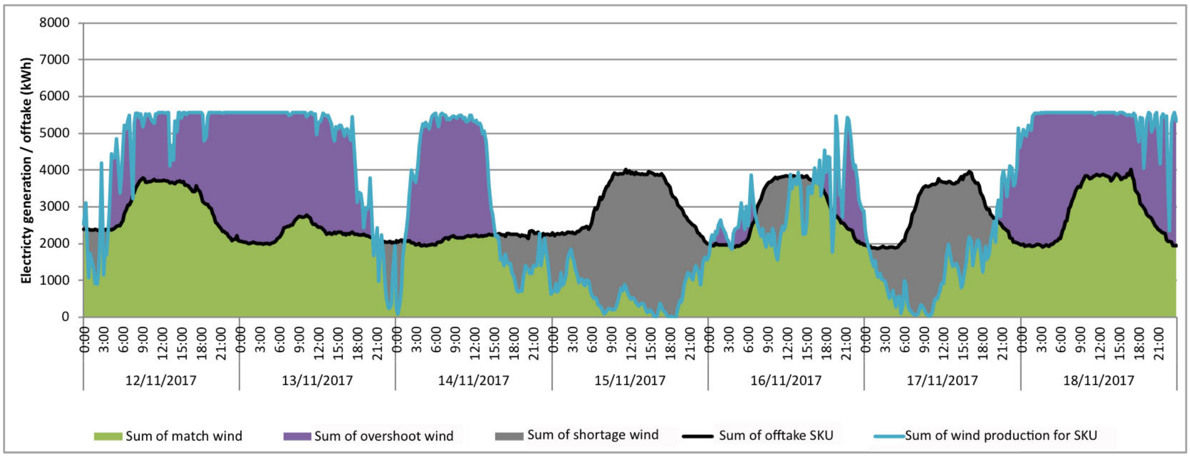


Figure 21: A weekly profile of the case study that is used for the Hourly Matching model.

The first step that is taken is to reach a combination of solar PV and wind electricity production. For these different ratios of the two data sets are added to the model. When an optimum is found in the combination of solar PV and wind production, Electrical Energy Storage is added to the portfolio.

Step 2 - Electricity generated from Solar PV and wind
The following graph shows an example of the possible combination electricity generated from solar PV, and wind. The blue line shows solar PV production for the company and the orange line shows the wind production for the company. This partially increases the electricity offtake that is covered by the portfolio of technologies allocated to the company.

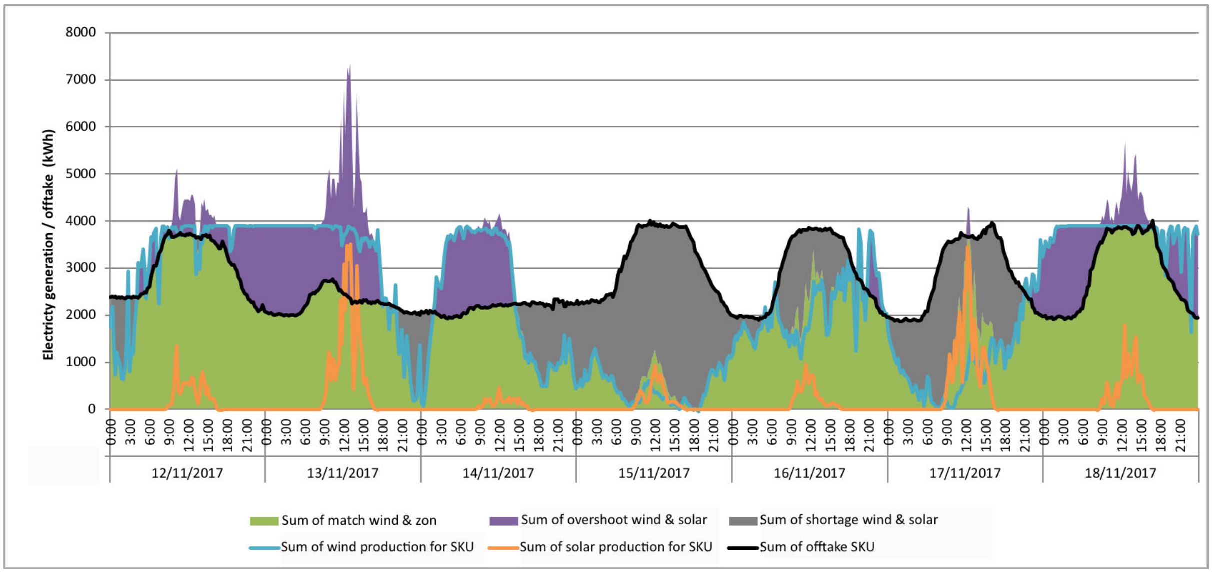


Figure 22:Hourly production for wind, solar and the match with the offtake of a company

Step 3 - Electricity from wind, solar and electrical energy storage
The last step is that storage technologies are added to the selected combination of solar PV and wind. The maximum power and installed energy desired of the storage is selected based on total offtake of the company.

In this phase the effects of adding storage to the portfolio on the hourly match percentage are analysed. The following graph shows an indication of the profile of the combination of solar PV, wind and storage.

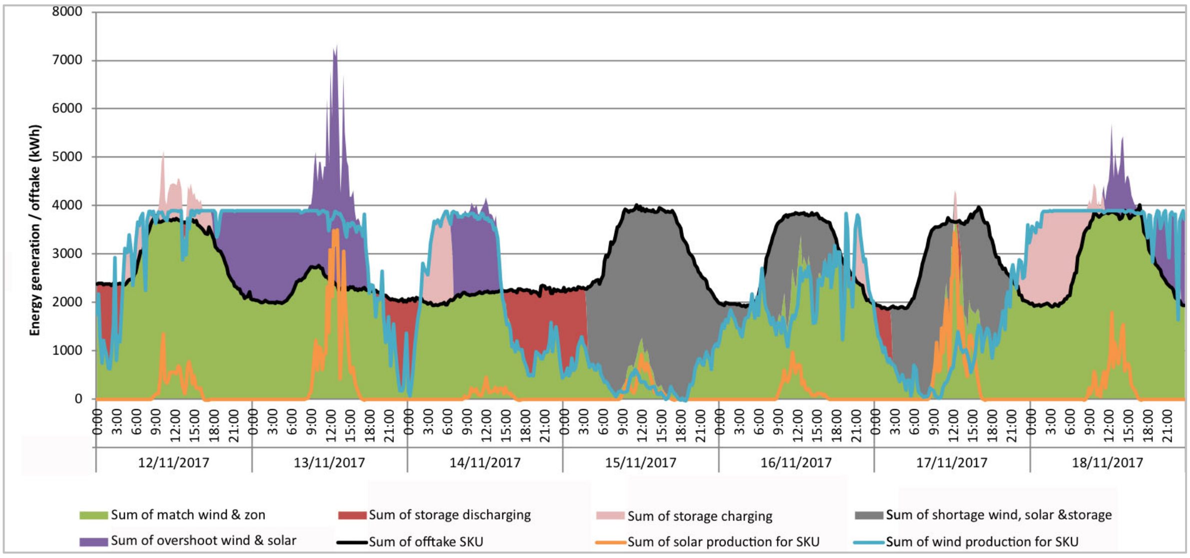


Figure 23: Hourly production for wind, solar PV and batteries and the match with the offtake of a company

Calculation of the green score

As described above, the green score gives the percentage of the total annual demand of the company, that is produced from renewable production in the portfolio. To calculate the green score of the portfolio the following formula is used, which will be further elaborated in the following section:

$$Green\ score = \frac{E_{Total\ Demand\ Company}\ [kWh] - E_{Total\ shortage\ company}\ [kWh]}{E_{Total\ Demand\ Company}\ [kWh]} \cdot 100 \tag{4-1}$$

$E_{Total\ demand} =$ *Total electricity delivered to the company, is the total offtake of the company in a year (kWh)*

$$E_{Total\ demand\ company} = \sum_{t=1}^{n} E_{demand}\ (t) \in \{1,2,\ldots,n\} \tag{4-2}$$

First the momentary balance is calculated with the following formula:

$$E_{Balance}(t) = E_{Production}(t) - E_{Demand}(t) \tag{4-3}$$

Portfolio of Wind

To calculate the momentary overproduction or shortage between the production portfolio and the demand of the company the following formula is used. The $E_{Wind\ Balance}(t)$ is calculated every 15 minutes.

$$E_{Wind\ Balance}(t) = E_{Wind}(t) - E_{Demand}(t) \tag{4-4}$$

$$E_{Wind}(t) = C_w \cdot E_{produced\ total\ windpark} \tag{4-5}$$

Where:

$E_{Wind}(t) = Electricty\ generated\ at\ time\ t\ from\ percentage\ of\ wind\ park\ allocated\ to\ company$
$E_{Demand}(t) = Electricty\ demand\ at\ time\ t\ of\ company$
$E_{Total\ demand} =$ *Total electricity delivered to the company, is the total offtake of the company in a year (kWh)*
$C_w = Allocation\ factor\ of\ windpark\ for\ specific\ company$
$E_{produced\ total\ windpark} =$ *The hourly production profile of the wind park used in the case study (kWh)*

To calculate the momentary shortage at a given moment the following formula is used. There is a shortage if the demand is higher than the production from the portfolio. If the offtake of the company subtracted from wind production is negative, there is a shortage, there is not enough production to cover the offtake at that moment. To calculate the total shortage, all momentary shortages are summed.

$$E_{Shortage}(t) = \begin{cases} E_{Wind\ Balance}\ (t) & E_{Wind\ Balance}(t) < 0 \\ 0 & E_{Wind\ Balance}(t) > 0 \end{cases} \tag{4-6}$$

$$E_{Total\ shortage} = \sum_{t=1}^{n} E_{Shortage} \in \{1,2,\dots,n\}$$

Portfolio of Wind and Solar combination

With the combination of production from solar and wind the formula becomes as follows. The production of the allocated solar and wind energy of the portfolio are summed, and the demand is subtracted from this momentary production.

$$E_{Wind\ Solar\ Balance}(t) = [E_{Wind}(t) + E_{Solar}(t)] - E_{Demand}(t) \tag{4-7}$$

Where:
$E_{Solar}(t) = C_s \cdot E_{produced\ total\ solarpark}$
$C_s = Allocation\ factor\ of\ solar\ park\ for\ specific\ company$

When 100% of the electricity demand on a yearly basis is met with renewable production.

$$C_s + C_w = 1 \tag{4-8}$$

When there is overproduction, more than 100% of the electricity demand is produced by renewable energy and $C_s + C_w > 1$

$$E_{Shortage}(t) = \begin{cases} E_{Wind\ Solar\ \ Balance}\ (t) & E_{Wind\ Solar\ Balance}(t) < 0 \\ 0 & E_{Wind\ Solar\ Balance}(t) > 0 \end{cases} \tag{4-9}$$

$$E_{Total\ shortage} = \sum_{t=1}^{n} E_{Shortage} \ \in \{1,2,\dots,n\}$$

Portfolio of Wind, Solar PV and storage

When the production is higher than the demand there is overproduction, and electricity is stored. When there is less production than demand, electricity is discharged from the storage, taking into account minimum and maximum rated power and energy capacity. When storage is added in the portfolio the final $E_{Storage\ Balance}(t)$ becomes

$$E_{Storage\ Balance}(t) = E_{Wind\ Solar\ Balance}(t) + E_{Storage} \tag{4-10}$$

$$E_{Shortage}(t) = \begin{cases} E_{Storage\ Balance}\ (t) & E_{Storage\ Balance}(t) < 0 \\ 0 & E_{Storage\ Balance}(t) > 0 \end{cases} \tag{4-11}$$

$$E_{Total\ shortage} = \sum_{t=1}^{n} E_{Shortage}(t) \quad \in \{1,2,\dots,n\}$$

Where:
$E_{Storage} = Electricty\ discharged\ from\ storage.$
$E_{installed} = C_{installed} \cdot T_{depth\ of\ storage}\ (kWh)$
$T_{depth\ of\ storage} = \ hours\ of\ storage\ (h)$
$C_{installed} = installed\ capacity, is\ the\ maximum\ amount\ od\ power\ that\ can\ be\ stored\ or\ discharged\ at\ a\ moment$

4.3 Levelised Cost of Portfolio

One of the objectives of this thesis is to give insight on the economic implications of improving the green score of a company. Therefore, after the green score is calculated for the different scenarios, the costs are calculated. To do this a levelised cost of portfolio (LCOP) is developed. The definition introduced in this thesis for the LCOP is the cost of all technologies combined within the portfolio of an electricity consumer, divided by their total electricity offtake. This makes it possible to compare different scenarios of portfolios using different technologies as the final cost per kWh offtake by the consumer is given. It takes into account the cost of the production of electricity and the cost of storing the electricity as well as the application of Hourly Matching as the cost is based on the selected size of storage. The methodology to calculate the cost is explained in this section.

It should be noted that the cost structure that is used by energy suppliers is not used (as described in the Context in Chapter 2). For the scope of this research this cost structure is not used for the following reasons. The wholesale electricity price is the market price and fluctuates based on market mechanisms. For Hourly Matching this would make the influence of the hourly production profile unclear and undefinable. Secondly this research analyses future developments of the technologies and therefore a cost structure is needed that does not combine these costs with the market effects. Lastly, as the cost of GO's is confidential, as the price for GO's is created in an un-transparent bi-lateral market, these numbers are not used.

Steps to the Levelised Cost of Portfolio

To reach the Levelised cost of portfolio, several steps have to be taken. Figure 24 gives a visual representation of the steps that are taken to approach the Levelised Cost of Portfolio;

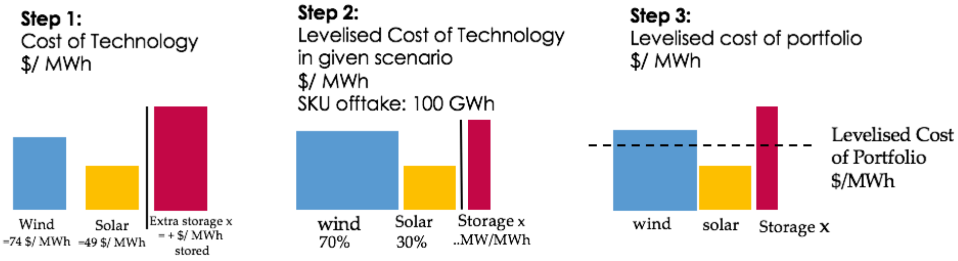


Figure 24: Steps in the decision of the cost of electricity.

Step 1:
First the cost per MWh of technologies is found from literature research, the Levelised Cost of Electricity (LCOE) of production can be compared between technologies, however the cost of storage and production cannot be compared due to the fact that the cost of storage technologies depends on the application of the storage. The cost of storage technologies is made up of two components, the energy installation cost and the power conversion system cost. At this stage the cost can give an indication in comparing different technologies but cannot be used to draw any conclusions for the specific case study.

Step 2:
Secondly, the rated power and energy capacity of storage is selected, and the allocated ratio of different production technologies used in the portfolio. The cost of electricity per MWh of the section of the whole portfolio that is provided by the technology, can now be reached.

Step 3:
The third step is to reach a cost that approaches the cost that LSE consumers pay to the electricity suppliers. As these consumers do not pay for all technologies separately, but in cost per final MWh, it is important to take the costs of the total portfolio into account . This is the cost that should be optimised as a company pays per MWh consumed. It should be as low as possible for a high a green score as possible.

Calculating the LCOP

The cost that is used to analyse the system for the goal of Hourly Matching is the following

$$LCOP = \frac{Discounted\ sum\ of\ production\ costs\ over\ lifetime\ (\$) + Discounted\ sum\ of\ storage\ costs\ \ oover\ lifetime\ (\$)}{Discounted\ sum\ of\ electricty\ delivered\ from\ storage\ [kWh]} \tag{4-12}$$

$$LCOP = \frac{(LCOE\left[\frac{\$}{kWh}\right] \cdot E_{Total\ produced}\ [kWh]) + (LCOS\left[\frac{\$}{kWh}\right] \cdot E_{Total\ delivered\ from\ storage}\ [kWh])}{E_{Total\ delivered}\ [kWh]} \tag{4-13}$$

Where:
$E_{Total\ produced}$ = Total electricity produced for the company portfolio
$E_{Total\ delivered\ from\ storage}$= Electricity that is delivered from storage, is output from the green score model.
$E_{Total\ delivered}$ = Total electricity delivered to the company, is the total offtake of the company in a year
The approach of the LCOE and the LCOS that are used in the LCOP are further elaborated after this section.

LCOP Takes into account:

- Approaches the commercial case in which an energy supplier and an LSE consumer sign and electricity contract.
- The $E_{Total\ produced} = E_{Totaldemand}$, the total amount of kWh equals the total amount of kWh demand.
- The ratio between different production technologies in the portfolio.
- Added to the production, that equals the yearly demand, the cost of storage is taken into account, this is based on the specific application of Hourly Matching and the selected the Power installed ($P_{storage\ installed}$) and energy installed ($E_{storage\ installed}$).
- The different costs of storage between different technologies. The Energy installation cost and Power installation costs differ per technology.

The Levelised cost of Electricity

For the model first the Levelised cost of electricity is used. This is used as it gives an indexed cost and makes it possible to compare different technologies and different scenarios with various technologies added together.

The levelised cost of energy is the net present value of the unit-cost of energy over the lifetime of a generating asset (BLIX Consultancy BV & partners, 2018)It is often used as the average price that a generating asset has to receive in the energy market to break even over its lifetime.

The following formula therefore represents the LCOE:

$$LCOE = \frac{Discounted\ sum\ of\ production\ costs\ over\ lifetime\ [\$]}{Discounted\ sum\ of\ total\ production\ over\ lifetime\ [kWh]} \tag{4-14}$$

When the discounting of cash flows is taken into account, the following detailed formula is used:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Produced\ electricty_t}{(1+r)^t}}$$

Where:
n= total number of years
t= year
r = Discount rate
CAPEX= Capital expenditures (Investments)
OPEX= Operational Expenditure (Operational Costs)
Produced electricity= Electrical energy produced in year t

It is important to note that caution must be taken for the levelised cost, these may be specified in real or nominal cost, neglect effects like taxes and contain assumptions.

Cost of Electrical Energy Storage

Although there is general agreement on the use of levelled energy costs (LCOE) to compare different energy generation technologies, such as solar PV parks and wind farms, there is no universally applied metric for the calculation of energy storage costs. It can therefore be difficult to assess and compare the costs of different energy storage solutions (Beushausen, 2016).

As opposed to electricity production technologies, which have a single application (i.e. electricity generation), energy storage technologies serve a variety of applications, including both front-of-the-meter applications (e.g. reserve power supply, black start support, dispatchable PV), and behind-the-meter applications (e.g. increased self-consumption, peak shaving). These different use cases have different operating parameters, which influence the costs. Every technology suits these parameters differently depending on the relative strengths and weaknesses. For this reason, comparing energy storage costs only makes sense in a common and clearly defined and specified use case. In addition, the costs need to be related to the added value of storage in the specified case, such as energy (kWh, MWh) or power (kW, MW) (Beushausen, 2016). Furthermore, the amount of energy discharges as well as the cost of electricity have an influence on the cost of storage (Jülch, 2016).

In the available literature multiple levelised costs of storage are also found. Unlike the levelised costs of energy for production technologies, the metrics for storage are not yet established and as new ones are being proposed the methodologies vary (Schmidt et al., 2018). Where the Levelised cost of Storage (LCOS) is used but has shortcomings (Jülch, 2016; Schmidt et al., 2018; Zakeri & Syri, 2015), Lai & McCulloch (2017), propose the Levelised cost of Delivery (LCOD) Furthermore the Levelised cost of system (LCOS) is used (Fuchs Illoldi, 2017; Gioutsos, 2016) and the Levelised cost of energy storage technologies (LCOEST) (Schmidt et al., 2018). Some organisations use a levelised cost of energy storage that takes into account the service provided by the battery such as Lazard (2017b) and International the Renewable Energy Agency (2017). Alternatively new metrics are proposed such as the Levelised Cost of Electrical Energy Storage that capture the economic break-even price required to charge and discharge electricity in N cycles per year (Comello, 2018).

There are various aspects in which all these approaches to the cost of Electricity Energy Storage show differences. While academic studies are often limited to a small selection of storage technologies, industry reports are often not transaparent about the LCOS methodology (Lazard, 2017b). While some studies neglect cost parameters such as replacement or disposal, others exclude performance parameters such as capacity degradation (Schmidt et al., 2018). (Belderbos et al., 2016) analyses the shortcomings that neglects the cost due to efficiency losses, which in turn depend on the cost of the input energy. Additionally, usage of the storage is highly dependent on the profile of energy production that it is used for. Moreover, the LCOS if often based on the amount of cycles that can be made and the Depth of Discharge and take into account the maximum amount of energy that can be stored yearly. However, in the case of this research the amount of energy stored is dependent on the specific production profile.

Based on the previously analysed theories, the levelised cost of storage (LCOS) within the LCOP is presented as follows and the input parameters that are taken into account are further elaborated on.

$$LCOS = \frac{Discounted\ sum\ of\ storage\ costs\ over\ lifetime\ [\$]}{Discounted\ sum\ of\ electricty\ delivered\ from\ storage\ [kWh]} \tag{4-15}$$

When the discounting of cash flows is taken into account, the following detailed formula is used:

$$LCOS = \frac{[USD]}{[kWh]} = \frac{CAPEX + \sum_{t\,=\,1}^{n} \frac{+OPEX_{\,t}}{(1+r)^t}}{\sum_{t\,=\,1}^{n} \frac{E_{Stored\ t}}{(1+r)^t}}$$

Where:

n = *total number of years*
t= *year*
r = *required return*
CAPEX= Capital expenditures (Investments)
OPEX= Operational Expenditure (Operational Costs)
$E_{Stored\ t}$ = *Electricity discharged from storage in a year*

There are various parameters that influence the LCOS. The following factors are taken into consideration.

Capital Expenditures (CAPEX):

Capital Expenditures are taken into account as in the case of the LCOE. The following formula is used.

$$Capex = (installed\ power\ [kW] \cdot power\ installation\ cost\ [\$/kW]) + (installed\ energy\ [kwh] \cdot energy\ installation\ cost\ [\$/kWh])$$

Where:

Power installation cost = The cost per installed kW of capacity (IRENA, 2017), in \$/KW
Energy installation Cost = The cost per installed kWh of storage capacity, in real 2017 \$ (IRENA, 2017), in \$/kWh

Operational Expenditures (OPEX):
These include operation and maintenance costs; periodic minor and major servicing is required for storage technologies. In mechanical storage, such as redox flow parts such as pumps require extra maintenance that is not required for battery storage for example, however these are not (Beushausen, 2016). O&M costs are taken as 1.5% of the capital investment costs, and fuel costs are not further taken into the calculations (IRENA, 2017).

Charging Costs:
The charging costs are in some cases taken into account as the cost of energy stored. Due to efficiency losses in a complete charge-discharge cycle, more electricity has to be purchased than can be discharged.

In this research the LCOE of the energy stored is known, and the charging costs are taken into account as the additional cost of energy due to efficiency losses during storage. In the hourly matching model, round-trip efficiency of storage is not taken into account in the calculating of the green score, as it has limited direct impact However, in the LCOP the efficiency is taken into account to calculate the costs. More electricity needs to be produced as input for the storage than the electricity demand due to efficiency losses of the storage unit. This is done because the total amount of energy stored is the output of the first model that is used to calculate the green score.

The round-trip efficiency of the storage technology that is used is

$$\eta = \eta_P \cdot \eta_E$$

Where:

$\eta = Roundtrip\ efficicency\ of\ storage\ unit$ (%)
$\eta_P = \ Roundtrip\ efficiency\ of\ power\ installation\ unit$ (%)
$\eta_E = \ Roundtrip\ efficiency\ of\ energy\ installation\ unit$ (%)

As they are the round-trip conversion, they take into account the charge and discharge efficiency (See appendix for further details)

Net present value (NPV):
Is used to take the net present value of an investment based on a discount rate and a series of future payments and income. The net present value is taken into account for the Operational Expenditures, these are future costs and therefor the depreciation if money is taken into account. The Capital Expenditures are assumed to be made in the first year and therefore the depreciation does not play a role. The Net present value is also taken into account for the total electricity delivered to take into account the future value of electricity. In the model the lifetime of the storage technology is taken into account in the calculation of the NPV.

The net present value is the sum of the present value of a series of present and future cash flows. It provides a method that helps in comparing products that have cash flows spread over many years in, as is the investment in storage technologies.

Each cash inflow/outflow is discounted back to its present value (PV). Then all are summed. Therefore, NPV is the sum of all terms;

$$\frac{R_t}{(1+r)^t}$$

In which:
t = the time of the cash flow
r = the discount rate, i.e. the return that could be earned per unit of time on an investment with similar risk
R= the net cash flow i.e. cash inflow – cash outflow, at time t.

Therefore, the total NPV is given as:

$$NPV(r,n) = \sum t = 0 \, n \, \frac{R_t}{(1+r)^t} \tag{4-16}$$

$n = the\ total\ number\ of periods\ the\ net present\ value$

Discount rate:
The discount rate refers to the interest rate used in discounted cash flow analysis to determine the present value of future cash flow.

A uniform discount rate of 7% is taken for all technology options for the calculation of cost annuities. This value is stated by Sensfuss & Pfluger (2014) as a uniform discount rate used to create in the EU long term scenarios.

In this study no intertemporal discount rate is taken into account for the cost function. This entails that the at every time step, regardless of the period in which they occur, the cost has the same weight in the overall cost function (Sensfuss & Pfluger, 2014).

Assumptions

- It is assumed that for storage the CAPEX is made in year 1. The OPEX is discounted over the production lifetime. It is assumed that these costs are are paid in one year and are not spread out over the lifetime of the asset.
- Duration of storage of 1,2,4,6,12,24,48,72 hours were investigated. In this study, the energy storage capacity is optimized while the power capacity is assumed fixed (Belderbos et al., 2017).
- This formula contains the assumption that the stored energy is equal in every year. In reality this is different every year due to different production portfolios.
- No differentiation is assumed between the charging and discharging power capacity and efficicency (Belderbos et al., 2017).
- In the calculations the Depth of Discharge is not taken into account.
- The storage is not calculated in the number of cycles as the electrical energy stored is based on the hourly matching model, no assumption is made of a specific number of cycles in a year. Therefore cycle life is not taken as one of the input parameters. From the model the electrcity stored is used.

4.4 Model input

In this section the choice for the input used in the model is further elaborated. The input data in the model consists of the selection of the case study and its demand profile, the technologies used, and the corresponding cost data for these technologies.

4.4.1. Selection of case study and demand profile

In this research the Electricity demand or load is not altered. This section describes the load used in the case study.

Although different corporates that are interested in the concept of Hourly Matching could have been selected, the case study is based on the Stichting Katholieke Universiteit (SKU) Radboud University. This case study is used for the following reasons. First, the company represents a commercial off taker and has a corresponding profile, which means the research could potentially be scaled up and still give an indication of the role that commercial companies could play in the energy transition in the Netherlands. A comparison to the Dutch load profile can be found in the appendix. Additionally, data was available on the offtake load of the company.

The graph in Figure 25 shows the offtake of the casestudy. It clearly shows 5 high peaks (weekdays) and 2 low peaks (in the weekend). It should also be noted that there is a large baseload offtake (Appendix).

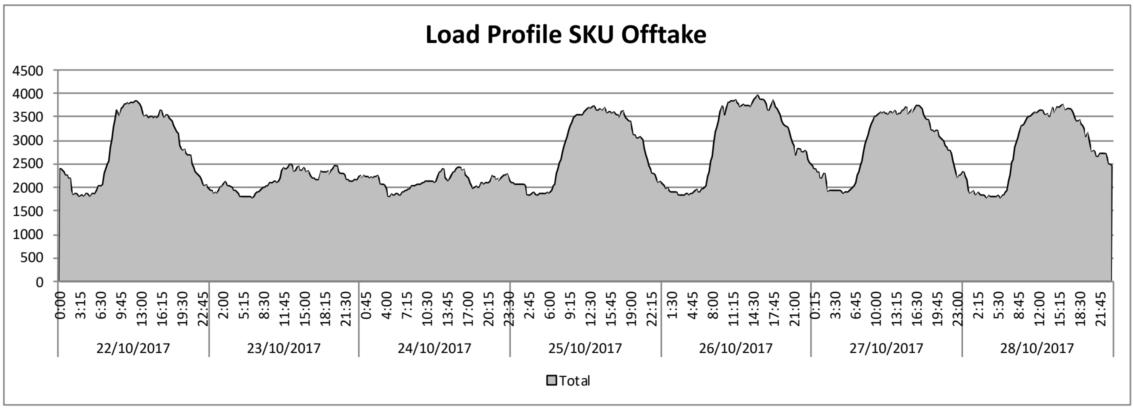


Figure 25 : Load Profile SKU Radboud University

In the Radboud University, there is a large-scale magnet in the system, for the research this very different profile is not incorporated in the data.

Data Collection

Data about production and storage technologies was gathered from literature to compare the technical specifications of technologies. Furthermore, hourly production data is used from energy production facilities, and the hourly demand of one of the clients of Eneco is used as input data in the model. This provides the input to analyse the different possibilities for increasing the match between hourly demand and hourly production

The following specific hourly data is used as input data in the model.

Input data	Specified case study
Electricity offtake profile	SKU Radboud offtake
Hourly Wind production for 2017	Offshore wind park Luchterduinen
Hourly Solar PV production profile for 2017	Solar PV park Ameland

4.4.2. Technologies used in model

In chapter 3 production and storage technologies have been analysed and their potential to be used for Hourly Matching. The following production and storage technologies are used in the model.

Wind and solar PV

Wind and solar PV are used as initial input technologies in the model. They are renewable and have a large capacity. They are available in the Netherlands and the installed capacity is expected to increase strongly in the future, with decreasing costs. Furthermore, it is recognised that the more predictable production of solar PV can be complemented by the more unpredictable and variable wind energy production. The other production technologies that are analysed in the literature review, are not used in the model as they are debatable or will not be producing enough electricity in the near future. As the base case of this research is 100% RES on a yearly basis from wind energy, well known production technologies that are taken into account in the research need to have a higher or comparable social acceptance to wind. Additionally, analysing wind and solar PV takes into account the dynamics of the current energy transition. as the increase in RES in the Netherlands is generally expected to come from wind and solar PV.

Lithium-ion Batteries

As the technical characteristics are within comparable ranges for the BESS, Lithium-ion batteries are used in the model and are indicative of battery storage costs. Furthermore, the price of Lithium-ion batteries is decreasing.

Redox flow batteries

The decoupling of energy and power provide interesting possibilities for the application of Hourly Matching. It makes it possible to design the power based on the peaks in the hourly fluctuations, the energy can then be based on the number of hours that Electrical Energy Storage is required.

CAES

Compressed Air Energy Storage is suitable for large-scale storage power and high energy storage applications. CAES is potentially a low-cost technology for short term storage.

PHS

PHS is suitable for large-scale storage power and high energy storage applications. It is possible to sign contracts for on a large scale. PHS is also potentially a low-cost technology for short term storage.

The other analysed technologies have initially less favourable characteristics for the goal of Hourly Matching or are not expected to deliver additional insights in the effect of the portfolio on the green score. This range of storage technologies is seen as initially indicative of the range of possibilities of technologies.

Production cost input

The following table contains the input LCOE's that are used for production of electricity. This data for the levelised costs reflects the subsidy-free cost of electricity for a new power plant.

Table 8: LCOE of Production technologies (Bloomberg New Energy Outlook, 2018a)

Production technology	**$/MWh (2017 real)**
Offshore wind	74
PV	49

Storage cost input

The following characteristics will be used as input in the model .

Table 9 contains the input characteristics of different storage technologies for the model. After extensive literature research, the input data was used from IRENA (2017). Although there are various literature reviews on the characteristics of storage technologies that have been analysed for this research (Akinyele & Rayudu, 2014; Aneke & Wang, 2016; Argyrou et al., 2018; Lazard, 2017b, 2017a; Luo et al., 2015) the input data for energy installation cost and power installation cost from IRENA (2017) is used. Articles were found to cite relatively old articles (from before 2014), contain large ranges in costs, and contain various different ranges. The data from IRENA was seen as relevant and accurate. Data about different storage technologies was available and therefore comparable. The lifetime and efficiency are taken from the same source. The following characteristics will be used as input in the model .

Table 9: Characteristics of Electrical Energy Storage systems in 2017 (adapted from International Renewable Energy Agency 2017)

	Lithium ion	**Redox flow**	**CAES**	**PHS**	
Energy installation cost	420	346,5	52,5	21	$/kWh
Power installation cost	105	105	945	840	$/kW
Efficiency	93,1	68,6	60,0	80,0	%
Lifetime	12	12	50	60	years

4.4.3. General Assumptions

For the model in this research a number of assumptions were made in order to model the use of storage and production technologies for the case study. The relevant implications are considered in the discussion.

- In the model one year is analysed. This means that the hourly production data of the wind and solar allocated to the case study, and the load of the case study are taken for a specific year (2017). This data could differ in a different year.
- Data is used from specific wind and solar PV parks. By allocating production from different wind and solar PV locations, a first step can be made combined to create a better green score.
- Depth of Discharge and cycles are not used as input in the model, as the input of the cost scenarios is the output of the Hourly Matching model. The total electrical energy stored (from the Hourly Matching model) is taken into account when calculating the cost of portfolio. It therefore does not take into account the change in efficiency of storage over time due to wear.
- It is assumed that a Lithium-ion battery is used is nickel manganese cobalt oxide (NMC) battery as this is an industry standard Lithium-ion battery.
- As this research aims to show the implications of different technologies on the green score, the LCOE LCOS and then LCOP are used to indicate the costs, and by doing this market-based fluctuations are not incorporated in costs. It should be noted that, although indicative of the cost, the cost that companies pay for the technologies are based on the market price for wholesale electricity and the price of GO's as stated in chapter 2.2 The electricity Market structure. This does not mean it is the exact price that a company would pay for the electricity. In this research dollars ($)/ MWh are used, as according to most literature reviewed regarding technologies.
- The technologies used in this research are based on literature research and indicative of what the impact of a range of technologies is on the green score and the cost. Although in the literature research, there was a focus on technologies that are possible in the Netherlands, the exact costs for PHS and CAES would have to be made for a specific case in a collaboration with a specific company in a certain location, to improve the accuracy of the costs.
- The market for energy storage is developing rapidly and there is difficulty in obtaining up-to-date data for every technology analysed. For this analysis care was taken to gather data as recent as possible and where of importance, relevant to the location and to the case of businesses, however it should be taken into account that the costs that are relevant in the case of companies are likely on the low side of the reference cost scale, as energy suppliers negotiate to get the best possible price for contracts.

5. Results

This chapter describes the impact implementation of different electricity production and storage technologies in the portfolio on the green score and LCOP of a Large-Scale Electricity consumer. This will be provided in sections that contain:

- The effect of over production on the green score
- The effect of overproduction of wind and solar PV on the green score and LCOP
- The effect of wind solar PV and various storage technologies on the green score and LCOP
- Combined results on the relation between the green score and the LCOP

5.1 Effect of over production on green score

The results clearly show the implications of different technologies on the green score of the company and the impact of the use of different technologies within the portfolio on the cost of the portfolio.

5.1.1. Overproduction of wind

For the first analysis the adjustment of the energy production ratio of wind allocated to the company is shown. The production profile of an offshore wind park is used.

Figure 26 depicts the green score dependant on the percentage of the total offtake of energy in a year by the company. It shows the strong improvement on the green score up to 100%. The grey dotted line indicates where 100% of the yearly electricity offtake is allocated to wind. However, it shows that after this point the improvements to the green score are limited. However, it is notable that with the increase allocation of wind generated electricity it is feasible to reach a green score of 72%.

The accumulated cost in this case is directly dependant on the allocated energy production, and therefore increases linearly. It is important to note that in the case of a company the surplus electricity can potentially be sold on the market, thereby making the total cost lower. However, as the impact of this market-based cost on the LCOE cost is not clear, this possible decrease in the cost is not shown.

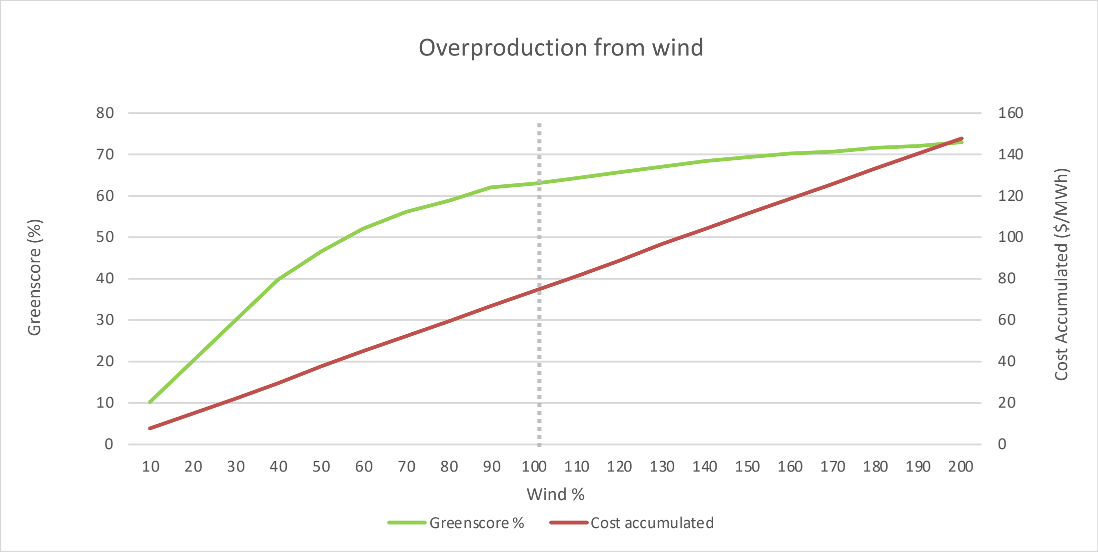


Figure 26: The effect of different percentages of electricity from solely wind generation, as percentage of the total offtake of the case study, on the green score

5.1.2. Effects of combining Solar PV and wind

After evaluating the impact of overproduction from wind, the influence of the ratio of electricity generated from wind to solar PV is analysed.

Figure 28 shows the results of the combination of solar PV and wind energy in the portfolio. The optimum ratio of electricity production of wind: solar lies around 70%: 30%. At this point the green score is 62,92% with just wind and becomes 72,67 % with solar added to it. When the optimum point is analysed this results in 68% wind, at which point the Hourly match score is 72.71 %.

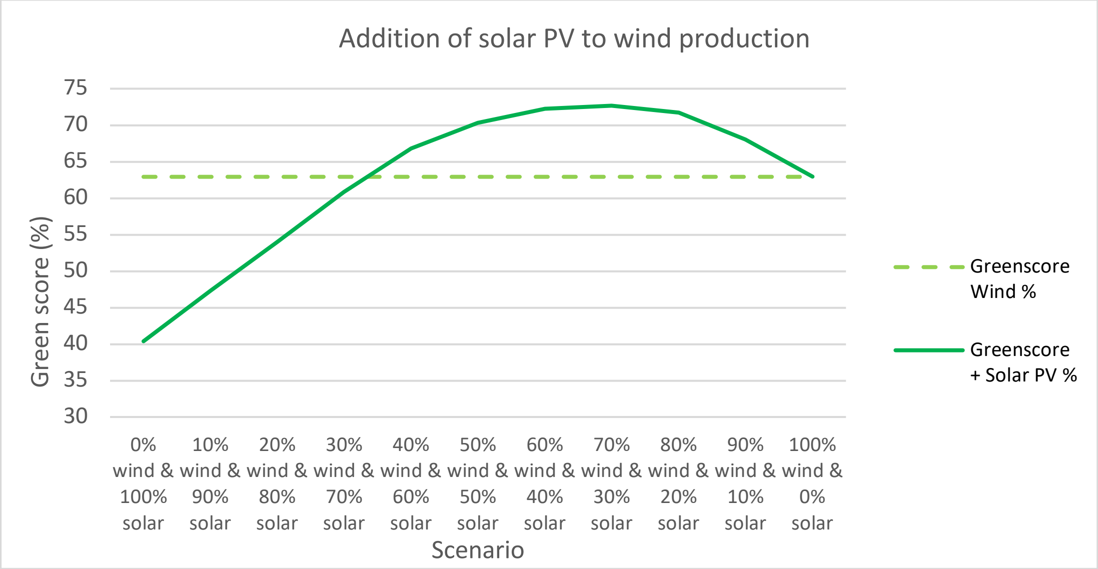


Figure 27: Different ratios of wind and solar PV electricity production, with 100% offtake of the total energy demand.

5.2 Wind, Solar PV and storage

Battery of 500 kW

Implementation of a battery with a relatively small power capacity of 500 kW, comparable to Lithium-ion in an EV give the following graphs. The improvement in the green score is limited. It reinforces that the EES for Hourly Matching is required to have a significantly larger power rating and energy capacity.

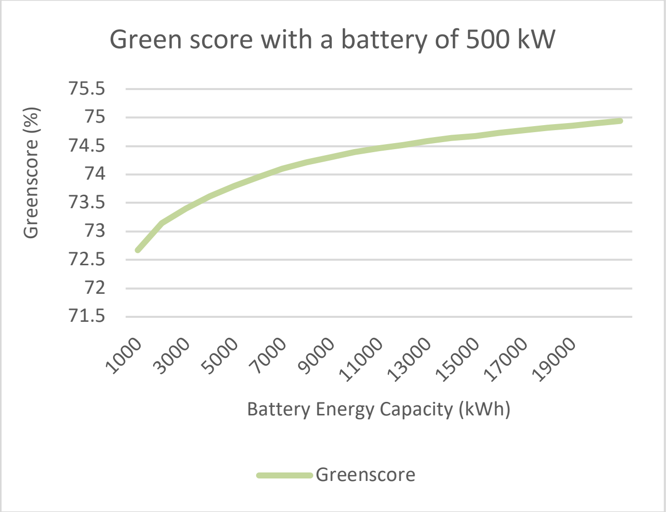


Figure 28:Green score with solar PV, wind and storage of 500 kW

Selection of storage scenario to reach maximum green score %

The size of storage is based on SKU Radboud University use of 100 GWh which when taken for 8760 hours a year gives an average offtake of 11 MW per hour (Not on the industry standard storage energy/power ratios of Lithium-ion for the example). The power capacity of the storage used is given at 11 MW and then the energy capacity (or the number of hours storage is required) of the storage is adapted. This is done as the energy capacity of the storage has a larger impact on the green score rated power of the storage.

With this addition of storage, the green scores of the portfolios are calculated for different energy capacities of storage added to the system. This is done based on 1, 2, 4, 6, 12, 24, 48, 72 hours of storage. Although storage of above 24 hours (and also above 12) is extremely long it is added to show the limits and boundaries of the system.

The average power needed for the case study at 11 MW is evaluated. In Figure 29 the option of decreasing the power capacity by half is examined. This gives an incremental difference in the green score. The following runs of the model therefore take into account storage of 11 MW.

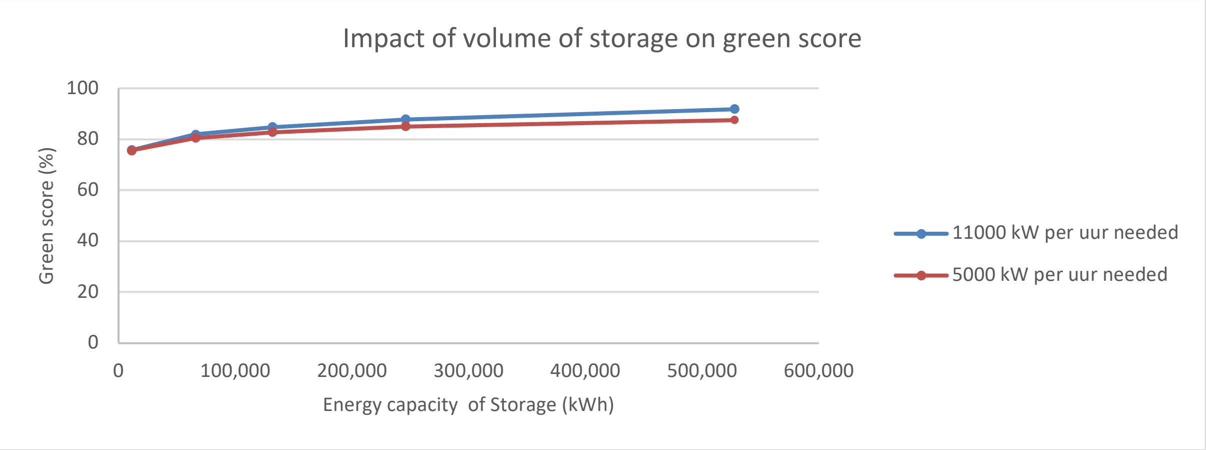


Figure 29: The impact of the energy capacity of storage on the green score

5.2.1. Green score comparisons

In this section first the results of the green score of different scenarios are be compared. In Figure 30 the implications of extreme additions of wind are shown, where costs are not taken into account. By allocating a larger amount of wind production, relative to the demand, to the portfolio it shows the green score can already be improved as previously in Figure 26. Figure 30 shows the extreme addition of up to 400 and 600% of the total offtake.

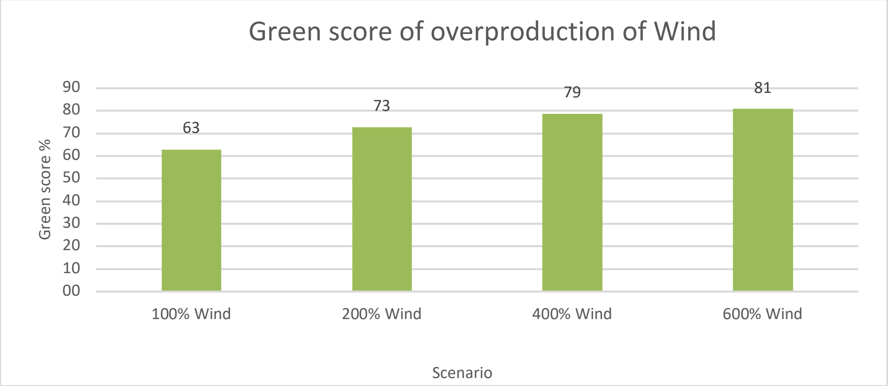


Figure 30: The green score of over-production of Wind

In the following Figure 31 the green score for different scenarios is shown with a combination of both overproduction and a combination of Solar PV and wind. To show the limits that are possible a scenario was also used in which 20 times the offtake was allocated. In this case a green score of 92% is possible.

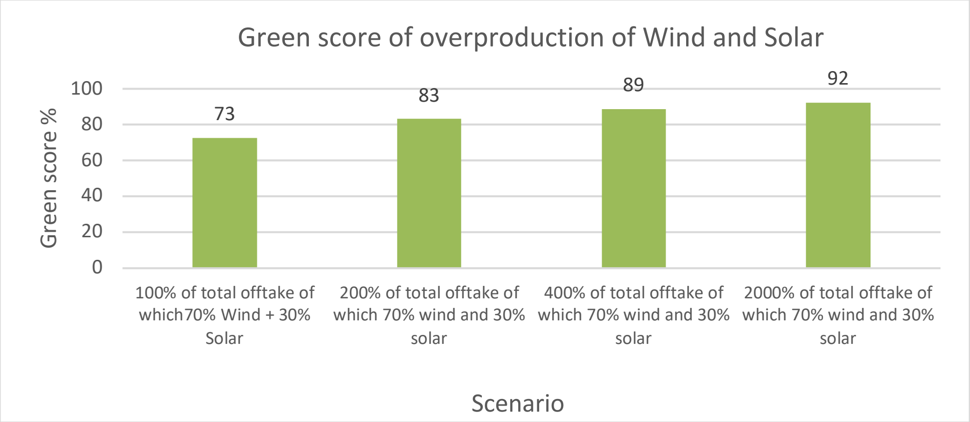


Figure 31: The green score of over-production with Wind and Solar PV

Figure 32 shows the improvement of the green score with 70% wind, 30% solar PV and energy storage. In this case the energy capacity is kept the same and the depth of the battery is adapted.

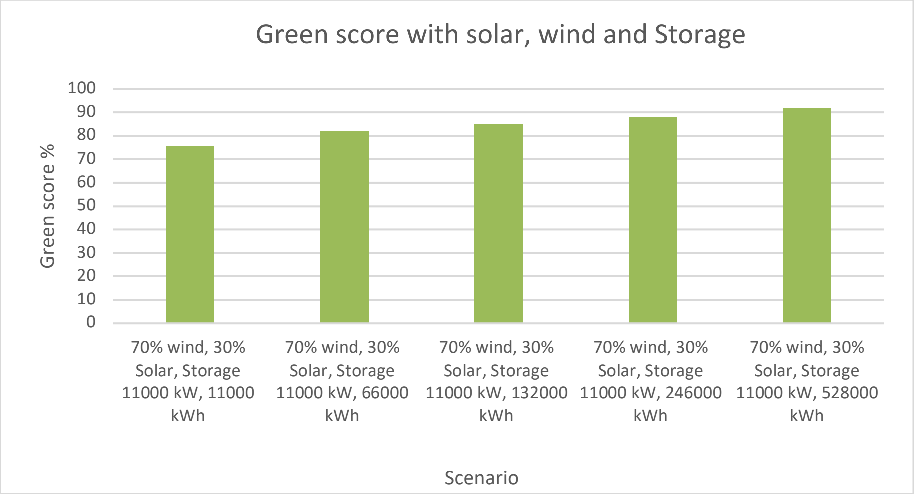


Figure 32: Green score with solar PV, wind and energy storage

Figure 30 to Figure 32 show that comparable green scores are feasible with different additional solar PV as with additional storage. They show that the first steps with new technologies create the largest improvements in the green score.

Moreover, they show that large scale storage is required to improve the green score and when taking Lithium- ion batteries into account, these need to be relatively extremely large and the size of the storage needs to be decided based on the offtake of the company if the significant improvements in the green score are desired.

Levelised cost of portfolio for different combinations of technologies

Figure 33 to Figure 36 show the green score compared to the LCOP of the different storage technologies. They show the initial steep increase in the green score after which it rises slightly. The blue line indicates the LCOP and the green dotted line the green score. The graphs show the difference in LCOP per storage technology added to the portfolio. Where Lithium-ion and Redox flow reach towards 600$/ MWh and 500 $/ MWh, CAES reaches towards 150 $/ MWh and PHS towards 100 $/ MWh.

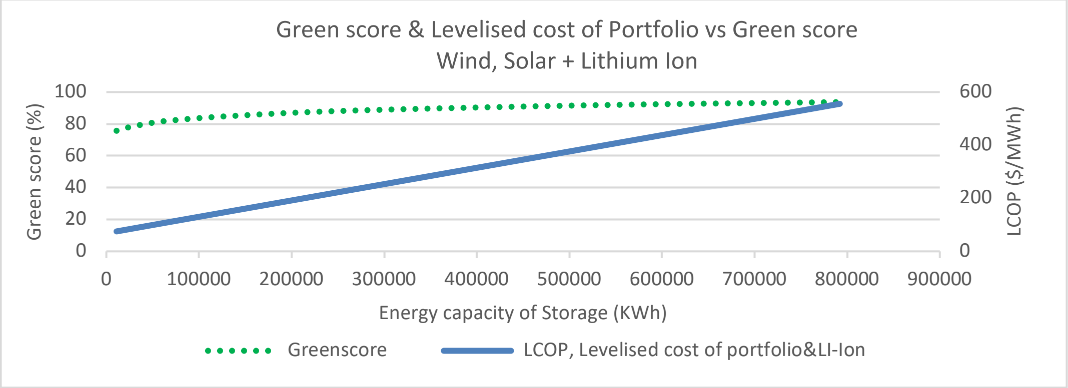


Figure 33: The LCOP vs Green score of Wind, Solar + Lithium-ion

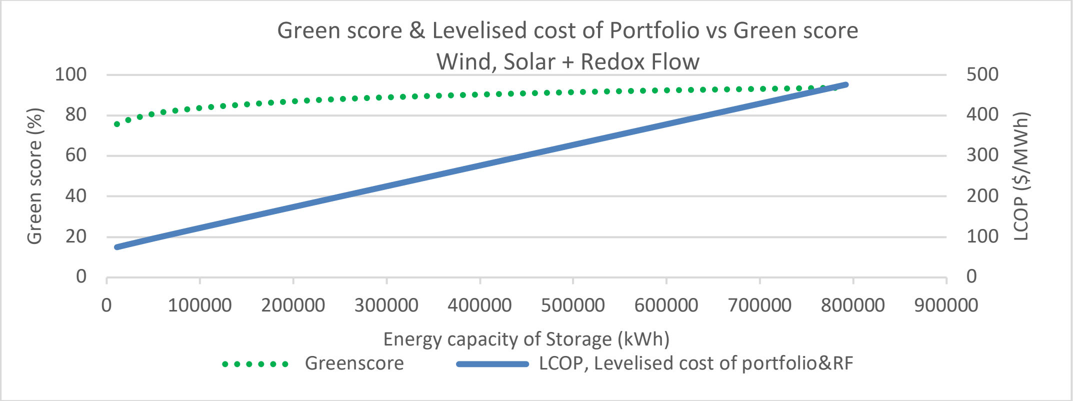


Figure 34: The LCOP vs Green score of Wind, Solar + Redox flow

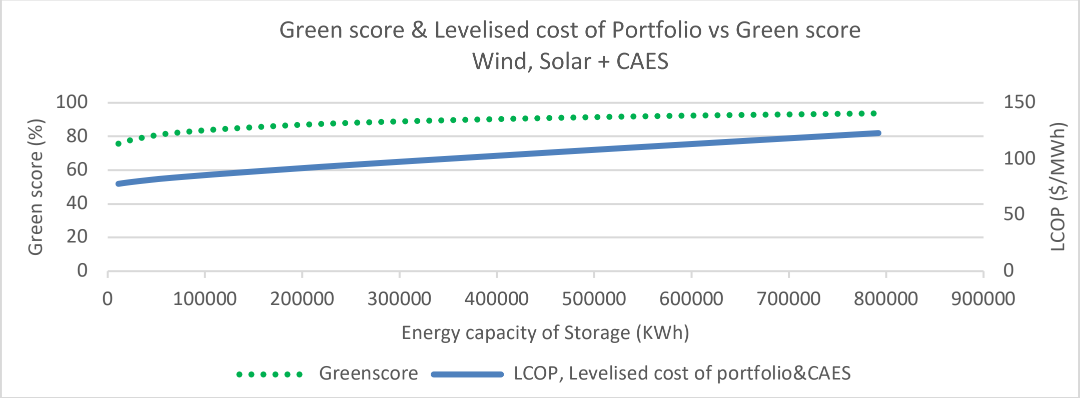


Figure 35: The LCOP vs Green score of Wind, Solar + CAES

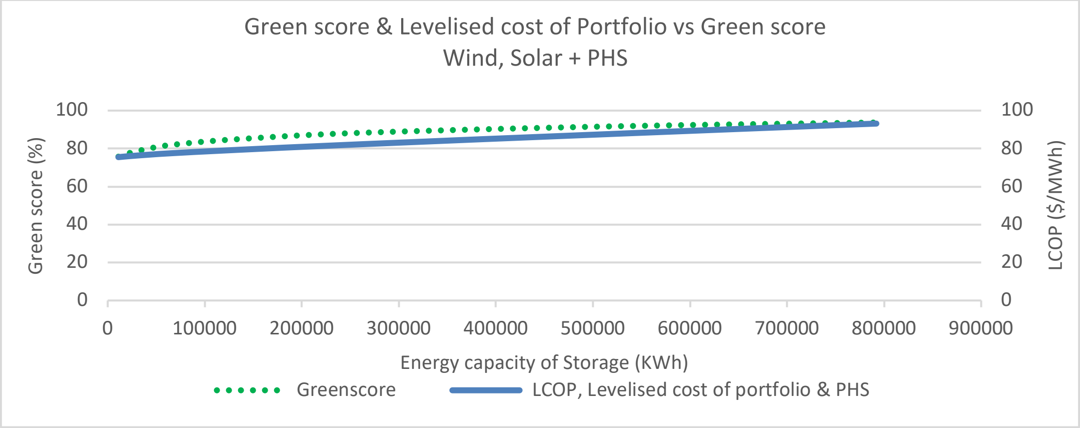


Figure 36: The LCOP vs Green score of Wind, Solar + PHS

Depicted in Figure 37 below, are the combinations of the costs different EES added to the portfolio and the accompanying Levelised Costs of the Portfolio, to increase the hourly match. The green dotted line indicates the green score and the other lines indicate the Levelised Cost of Portfolio per MWh, for the different technologies that are added to the portfolio. It should be noted that the horizontal axis does not give level steps, this is done in Figure 33. It clearly visualises the increasing cost of storage to continue to increase the green score gradually.

The graphs show the cost of lithium Ion and Redox flow increases strongly where the cost of CAES and PHS increase marginally. This is due to the fact that CAES and PHS have a high power installation cost and a relatively low energy installation cost, whereas Lithium ion and Redox flow have a relatively high energy installation cost and an average power installation cost.

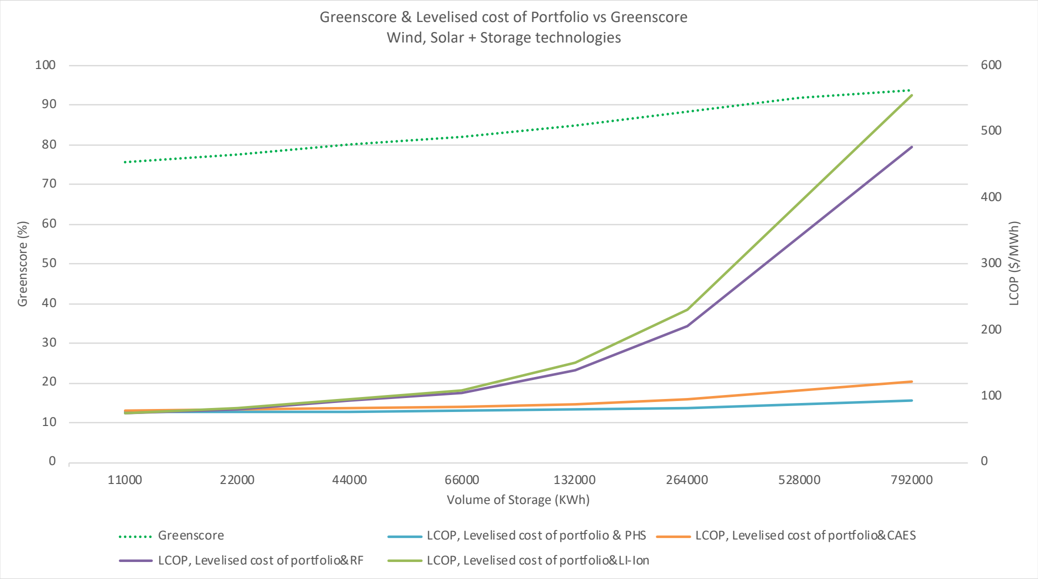


Figure 37: Green score & levelised cost of portfolio vs green score of wind, solar PV and different storage technologies

The following Figure 38 uses an equal distribution on the horizontal axis. The number of hours of storage have been indicated on the green score curve.

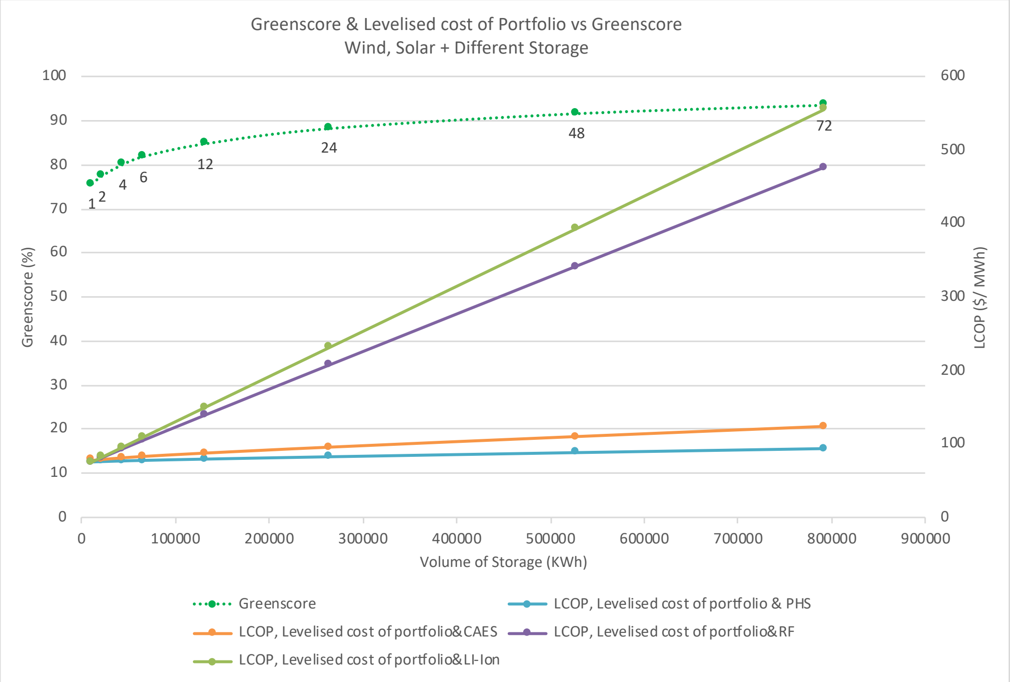


Figure 38: Green score & levelised cost of portfolio vs green score of wind, solar PV and different storage technologies

The previous graphs shows that the addition of storage to the portfolio increases the green score sharply initially but only marginally after a certain point. The largest increase in green score is achieved between 0 and 20 000 kWh, these are the E/ P ratio up to 20. To show the impact of the initial storage, in the following graph, a more detailed version is given. Figure 39 shows the detailed view of the graph and depicts the initial storage added giving the largest improvement in the green score.

Figure 39: Green score & levelised cost of portfolio vs green score of wind, solar PV and different storage technologies

It is noteworthy that the following percentage increase in green score is possible for the following number of hours of storage. Between the first and 6th hour, a 1.67%/ hour is seen, between 6-12 hours a 0,5%/ hour increase is seen and from 12-24 hours only a 0.29% increase is seen.

Size of battery	% increase/ hour of storage
1-6 hours	1,67%/hour
6-12 hours	0,50%/hour
12-24 hours	0,29%/hour

Final comparison of all scenarios

The results combined and depicted in Figure 40 showing the cost per MWh and the green score. It gives insight in the choices in creating a portfolio for the case study using multiple technologies to improve the green score.

In the graph in Figure 40, towards the bottom right depicts the optimum point to reach. Here the Levelised Cost of Portfolio would be 0 $/MWh, and the green score is 100%.

In reading the following graph it is important to note the following.

- The y axis depicts the LCOP in $ per MWh. The 100% wind starting point of the wind curve gives an indication of the current price that is paid for electricity by LSE consumers.
- The x axis depicts the green score (%). There are no criteria for a specific percentage increase in green score that is demanded by LSE consumers. As this gives novel insight into the portfolio there are no hard limit for this in the graph. The additional value for a company per % increase does not give a specific limit to the graph.

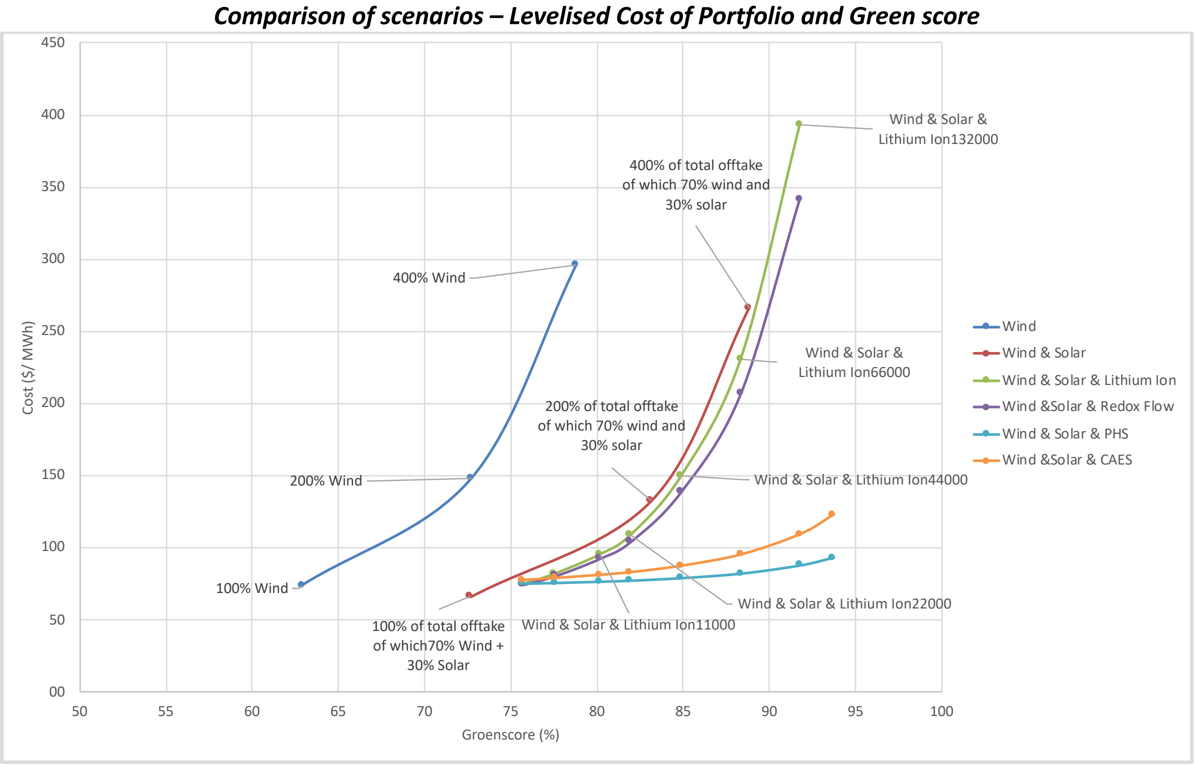


Figure 40: Graph showing the cost ($/MWh) and the green score (%) that can be achieved with different scenarios of combinations of production and storage technologies, the number after storage indicates the installed energy capacity (kWh) of the EES.

Based on the results of the model in Figure 40 the following is shown.

Firstly, as can be seen in the blue line the use of overproduction from wind improves the green score up towards 80%. However, for a price increase of 10% a green score of around 65% would be possible. It should be noted that in this case the surplus of electricity generated for the portfolio is not resold.

Secondly, the addition of solar PV further improves the green score. An initial 72% green score is feasible with a combination of solar and wind without overproduction on a yearly base. By adding solar to wind production, a substantial improvement to the green score is achieved, without increasing cost.

A portfolio including electrical energy storage shows a better performance than with solely production. A green score of up to around 80% is possible with a combination of wind, solar and storage. Storage for multiple hours gives a substantial improvement on the green score. Furthermore, the graph also gives insight in the attached costs. In a commercial setting, a choice would have to be made about what are feasible costs to improving a green score. It shows that the combination of wind, solar PV and PHS have the lowest cost per MWh and the highest possible green score.

Wind, solar & Lithium-ion and Redox flow storage are close together. These scenarios have a combination of 30% solar and 70% wind as basis of electricity generation. On the one hand the portfolio using storage can be beneficial as it can potentially be used for further applications besides hourly matching. This could generate additional income and investing in new storage can be communicated well as it is additional to the current energy system. On the other hand, adapting the portfolio by adding solar is easier due to the replacement of GOs, with batteries the LCOP contains more assumptions than is the case for production technologies. Except for Hourly Matching, there is no generally accepted certification system for battery storage.

From the graph PHS and CAES come out as the best options. The green score for lithium ion and redox flow only rises incrementally although the LCOP steeply increases.

A green score of up to 90% seems feasible, but unrealistically expensive. The difficulty in reaching a green score above 90% can be explained due to the following reasons. First of all, the cost of storage is high. For the last percentages, the additional energy capacity of the EES needs to be large compared to the amount of time that it is used to store electricity. Without the addition of baseload, the storage is dependent on intermittent production to charge, when there is limited production there is no electricity to store. Another possible reason is that the model takes into account the production profile of a solar and wind park from January to December, for the year. There is however more wind production in the winter than in the summer. Therefore, although matched on a yearly basis, it is not possible to shift overproduction from December to previous time in the model used.

Sensitivity analysis

In order to gauge the influence of the inputs to the model, a sensitivity analysis was carried out based on expected development of specific parameters. To do this the LCOP of a portfolio including storage technologies is taken as the reference case. To conduct an in-depth sensitivity analysis, input variables are used for 2030. By doing this, the influence of the inputs that are most likely to change in the future are combined and the impact of time on the results is analysed.

For the costs of scenarios, the following parameters are adjusted as these significantly change between the previously made analysis and 2030:

- Energy installation cost
- Power installation cost
- Lifetime
- Efficiency

The following table shows the additional input data taken into account for 2030 (International Renewable Energy Agency, 2017).

	Lithium-ion		**Redox flow**		**CAES**		**PHS**		
	2016	**2030**	**2016**	**2030**	**2016**	**2030**	**2016**	**2030**	
Energy installation cost	420	167,3	346,5	118,8	52,5	44,2	21	21	$/kWh
Power installation cost	105	51	105	51	945	693	840	840	$/kW
Efficiency	93,1	94,8	68,6	76,5	60,0	68,0	80,0	80,0	%
Lifetime	12	18,4	12	19,2	50	50	60	60	years

Figure 41: The input data for 2030 for the sensitivity analysis

When the future impact of the cost of storage is taken into account the following graph is the result. This shows that the cost of the portfolio with Lithium-ion and Redox flow does decrease largely towards 2030, however for CAES the cost decreases slightly and for PHS there is an no expected difference in the cost. It should be noted that in this analysis the cost of generation is kept unaltered as the impact of the cost of storage examined.

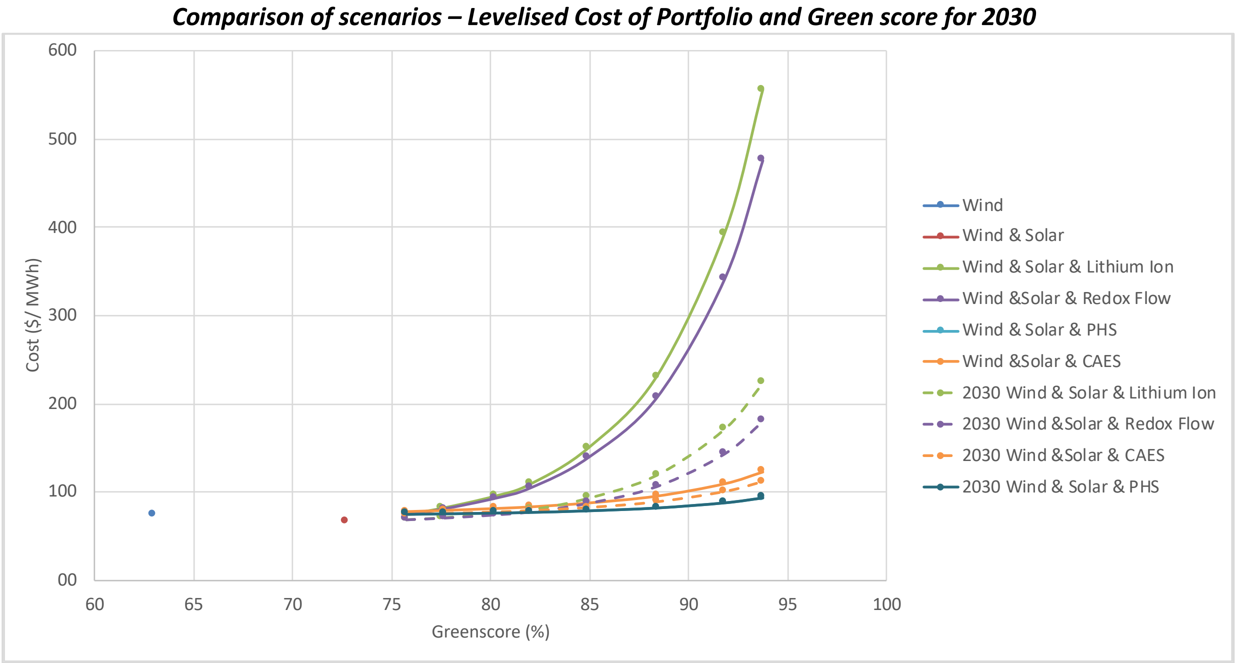


Figure 42: A graph depicting the results of the analysis of the influence of time on the LCOP and the green score.

To better illustrate the implications for the costs that are closer to the current portfolio cost a detailed version of Figure 42 is given in Figure 43.

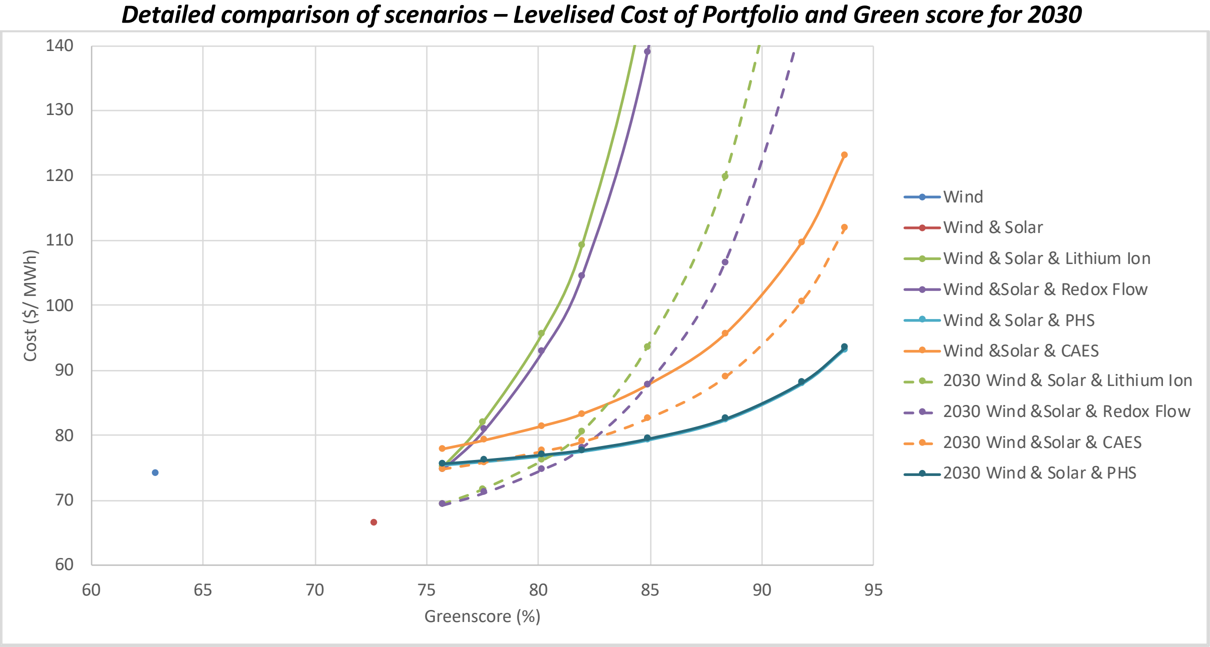


Figure 43: A detailed graph depicting the results of the analysis of the influence of time on the LCOP and the green score

Firstly, the detailed graph in Figure 43 shows that the cost of increasing the green score generally decrease for all technologies towards 2030. This is the case for all storage technologies excluding PHS. This can be explained by the fact that there is limited technological innovation in PHS, while the other storage technologies are still being further developed.

Secondly, it shows that the initial cost for the first increase of green score (the starting point of the curve) drops substantially for Redox flow and Lithium-ion in 2030. The does not drop as much for CAES and does not change for PHS.

Thirdly, between a green score of 80% and 85% the curves of Lithium-ion 2030 and Redox flow 2030 cross the CAES line, indicating that up to the intersecting point Lithium-ion and Redox flow have a lower LCOP, after this point, the cost of CAES is lower. Therefore, either the desired LCOP or green score should be based on this point.

6. Discussion

In this chapter the results of chapter 5 are discussed and the analysis that was performed on the influence of technologies in a portfolio on the green score and LCOP. In this chapter, the data input used in the research, , the methodology used, the results compared to other research and the implications of the results are discussed.

Data sources

For the data for electricity generation for the model Bloomberg New Energy Outlook, (2018a) is used, this data is indicative of costs in the market. An important consideration is the additional costs associated with the production and actual integration of the renewable energy technologies into the system. It should be noted that the LCOE does not include contractual terms on price, duration or price inflators. Subsidies are not incorporated in the LCOE. Which would in reality make the cost of generation lower. The costs correspond to some of the recent binning prices for offshore wind in the Netherlands (Velthuijsen et al., 2018)

For the data used for the costs of EES, data from the International Renewable Energy Agency (2017) has been used. After an extensive amount of literature research, it has been selected as it is comprehensive, detailed data, having been compiled from a large range of sources. However, as developments are quick in the battery market these values should be used with caution. Although in this report the use of the most accurate data available has been strived for, the cost of the technology can differ due to these rapid developments and the different implementation possibilities. The costs that are used in the model are from 2016. From the data the next possible date was 2020. As the report from which the data is sourced was published in 2018, the data of 2016 was chosen as this was not a prediction but is based on the actual costs at that time. The cost of storage in actuality is likely to be on the low side of the data due to the fact that it would be implemented commercially on a large scale, by energy suppliers that have high negotiating power. Although for wind and solar PV production, specific data is used, the costs of storage are not specifically for the Netherlands.

Temporal influence

The model used is limited in the fact that it makes use of data of a single year. This year starts in the winter (January) and ends in the winter (see Appendix for graphs). The required energy capacity of electricity for a year is equal to the electricity offtake in the given year. However, as the model starts halfway through the winter (and there is more wind available in the winter), this is not enough to provide and be stored for the entire summer. This problem could be solved by modelling a two-year period. The first year is only used to estimate the depth of discharge of the storage device used. This improvement is recommended for future development of the current model.

Technologies

The technologies used in this model give a good indication of the effect of different technologies on the hourly match and on the cost of the system with the LCOP. However, if one of these technologies is selected as a potential option to implement, the impact of the exact implementation characteristics on the cost of the analysed storage technologies need to be verified. The assumed costs of production are unsubsidised, which means the cost of production in the LCOP is higher than in reality.

The amount of solar PV used in the different scenarios is 30%, this is a large amount of energy generated from solar PV. For the case of SKU Radboud university, the total yearly offtake is nearly 100 GWh. The total yearly production of a solar PV park in Ameland is 26 GWh. If 30% of the offtake of SKU Radboud University came from solar PV this would be more than this solar park generates. It indicates the importance of the addition of solar PV.

This research finds that PHS has the lowest LCOP for the highest green score, followed by CAES and then Redox Flow and Lithium-ion, of which the cost of the last two is expected to fall more rapidly. The order of these results are corroborated by Navigant (2018). Air and water CAES and PHS represent low cost energy storage media compared with batteries which requires mining refining and manufacture (R. E. Hester, 2018). It is critical to note that although PHS and CAES have the lowest costs these face challenges surrounding geographic limitations and extensive development timelines and must be relatively large scale to achieve these price points.

The low cost of PHS shows the positive impact of large-scale storage on the green score. The drawback of pumped hydro is that the feasibility of implementation highly depends on geographic location. Large scale PHS is not locatable in the Netherlands, it is however possible in Scandinavia, Belgium and Germany. Also, the origins of energy used to pump water into the basin should, of course, be fossil free.

In this research CAES comes out to be a favourable option for storage. Although it gives indication of the cost, fuel costs and therefore the cost of gas for CAES is not taken into consideration in this study. Taking this cost into consideration would increase the accuracy of the estimated costs. As an indication of these costs, according to Gu et al., (2013) the requirements of gas is 4.0 MMBTU/ MWh for CAES and the cost are 4.25$/MWh. Making the costs for additional gas 17$/MWh from storage. This will result in higher costs for the CAES scenario than depicted in this study. The opinion of the LSE consumer on the CAES scenario is not further explored in this study which would be important to understand how realistic actual implementation of the CAES scenario is and therefore recommended for future research. In an effort to disengage the CAES from gas the use of biofuel in CAES is proposed by some and could also be further investigated (Kaldellis & Zafirakis, 2007). However Adiabatic CAES would be an option without using additional gas. The technical characteristics of CAES and A CAES and the power based CAPEX and the energy based CAPEX are largely comparable (Huang et al., 2017). However, the technology is less developed than diabatic CAES, and data was not available on the technology. When using Adiabatic CAES, the costs would be higher. However, the technology is less developed than diabatic CAES, and data was not available on the technology. According to (R. E. Hester, 2018), the LCOS of Adiabatic CAES and CAES are similar. The estimated costs of heat storage for Adiabatic CAES are in the region of 25% of the total CAPEX.

It is important to recognise that CAES is in actuality probably more theoretical than would be required for implementation by the companies involved in this research. It has been taken into account and gives good insight into the benefit of such a large-scale storage technology. However only a small number of the installations have been built. Although these few installations have a significantly large energy capacity, an assumption has been made in the costs being comparable to these existing technologies. This is done as there is not a large amount of data available due to the lack of installations but also due to the fact that the it makes use of common and mature technologies (Cárdenas et al., 2017).

Due to the fact that the costs of Lithium-ion batteries are decreasing so fast the she costs of lithium-ion used in this thesis are likely to be on the high side. According to Bloomberg these are currently stated as being 176$/kWh in 2018 (BloombergNEF, 2019). The current lowest costs are already approaching the 2030 costs analysed in this research. (as can be seen in the appendix in EES Energy installation and Power installation costs).

It is possible that when a large number of Dutch companies have the desire to improve their green score and optimise the technologies in their portfolio problems arise. Such as the limited availability of some types of renewable energy (e.g. tidal, solar, wind) or the limited availability of storage solutions. (e.g. Caverns for CAES, basins for PHS).

A number of storage technologies were selected for use in the model, which were seen as initial potential technologies for Hourly Matching as mentioned in Chapter 4.4.2. However, it would be interesting to conduct further research on additional technologies and possible forms of flexibility in the model. Furthermore, it would be interesting to add other forms of storage that have not been taken into account in this research. For the application of electrical energy storage hydrogen is not seen as optimal in this research for a number of reasons, however, if the hydrogen infrastructure is readily available in future scenarios it could possibly provide a form of flexibility and could be analysed in further research. Where currently mature technologies were selected, innovative technologies, such as Ecovat (Ecovat, 2018), and Liquid Air Energy Storage (ESA, 2018) would be interesting additions to the analysis. In addition to specific technologies that can be installed independently, incorporating flex potentially available from energy intensive processed in industry would be interesting. Other additions would be to look at "Stacked" Batteries, in which multiple revenue streams are obtainable from a single storage installation (Lazard, 2017b) and Hybrid energy storage systems (Bocklisch, 2016) which could provide opportunities to combine different storage technologies for which the insights from this research can give direction into the potential of different options. Furthermore, incorporating technologies specific to the type of company can be explored. An example of this would be to explore the influence of Electric Vehicles (EVs) as storage systems on the green score and the LCOP.

Comparison to other research

The results of this study show a combination of production technologies wind and solar PV in the portfolio can achieve a green score of 70% without increasing the LCOP. As explained in the introduction the goal of this research is to some extent comparable to research on optimal configurations of renewables on islands. The optimal renewable penetration as compared to the LCOP is consistent with results obtained in literature for island systems such as 40-80% (Gioutsos et al., 2018) or 70% (Fuchs Illoldi, 2017). It is also in line with previous research that suggests that electricity storage devices would be needed after a 50% penetration of RES for a 100% renewable energy system in a country (Child et al., 2017). Other research done by Denholm & Hand (2011) conducted in a US grid where different mixes of wind, solar PV and concentrating solar power are used up to 80% of the electric demand can be achieved. For penetration levels up to 80% of the system's electricity demand, requires a combination of load shifting and storage equal to about one day of average demand. In this research, with storage of one day a green score of 85% can be achieved.

Increasing the renewable penetration in the island studies require the addition of storage systems. The research done by Gioutsos, shows an exponentially increase of LCOS when renewable and storage penetration is pushed over the 40-80% level. This is reinforced by this thesis and is due to the added cost of storage as with the island studies. It is notable that in the island research even by adding storage, the renewable and storage penetration cannot be taken over the 90% levels, hence that study uses diesel generators to supply the last 10% of needed electricity. This study, however, shows that for LSE consumers a green score of 90% can be realised through the addition of storage. The reason why this is not possible in the island studies could lay in the fact that the island grids are very small, or that the cost of storage on islands are higher than what we envisage in this study.

System Complexity

The administration of tracking renewable energy sources is currently done using GO's. However, for storage of RES there is no system currently in place. Therefore, the options for tracking the storage of RES is a relevant topic that should be further explored. Although this research shows the implications of different technologies on the green score and portfolio cost, it would not be possible to track the origins of these technologies immediately, which could in turn play a role in large-scale consumers making a selection for specific technologies.

The results show that a 100% green score is not possible with the current selection of technologies but does give insight into the possibilities of increasing the green score for the lowest LCOP. The addition of energy from solar production provides an improvement for no additional costs. A green score up to 90% only seems feasible with the addition of PHS or CAES, for an acceptable LCOP. It shows that although the perfect solution is not in a combination of the used production and storage technologies, the combination of the green score and the LCOP do provide valuable insight into sustainability impacts of the portfolio of a company.

7. Conclusion and recommendations

7.1 Conclusion

The objective of this thesis was to identify how large-scale electricity consumers can procure towards 100% hourly matched renewable electricity. For this, the literature was reviewed regarding electricity production and storage technologies. To assess the implications of technologies on the portfolio, a green score is used and to assess the costs a Levelised Cost of Portfolio (LCOP) is introduced. The following can be concluded from this thesis.

The model developed can be used to analyse and optimise the green score and the LCOP for a specific case study. It gives insight into the hourly match of an electricity portfolio of a large-scale commercial electricity consumer and their demand. This model can be elaborated on for future case studies.

Various technologies were analysed and the influence of Variable Renewable Energy Sources (VRES) and storage on the green score of a portfolio explored. Due to its low price and high availability in the Netherlands, wind energy remains a base for the portfolio, and the addition of solar PV helps in balancing the production due to its more predictable and daily profile. Other forms of electricity production are more complex regarding social acceptance (biomass, nuclear energy) or availability (tidal energy).

Furthermore, the impact of storage technologies in the portfolio were explored. Different storage technologies have been selected that have a large energy storage capacity, have an acceptable efficiency, can provide storage for hours, are socially accepted and are technologically mature. The Electrical Energy Storage (EES) technologies that were analysed in the portfolio of the case study are Compressed Air Energy Storage (CAES), Pumped Hydro Storage (PHS), Redox flow and Lithium-ion. The importance of large-scale storage is apparent.

The model shows that the addition of solar PV to electricity generated from wind gives a substantial improvement to the green score, it does so without increasing the cost of the portfolio. The green score increases from 62% to 72 % where the LCOP decreases from 74$/MWh to 67$/MWh, due to a lower cost of solar PV. With the addition of energy storage, a green score of over 80% can be achieved. The analysis shows that with a LCOP of 100 $/MWh a green score of just over 80% is possible with Lithium-ion and Redox flow storage. With CAES a green score of 90% can be reached and with PHS a green score of 93% is possible for 95$/MWh.

The results of the model show that storage for up to around 6 hours gives the strongest increase in green score. For the case study, the combination of wind, solar PV and PHS storage gives the highest green score for the lowest increase in cost of the portfolio. For the combination of solar PV, wind and PHS, with a LCOP increase of 10% a green score is possible of 85%.

A sensitivity analysis is conducted in which the impact of changes of the cost of storage in the LCOP towards 2030 are also analysed. While the cost of PHS is not expected to change, the cost of CAES is expected to decrease slightly, however the cost of Lithium-ion and Redox flow show a relatively large decrease. As the cost of Lithium-ion and Redox flow drops the results indicate that up to around 83% green score can be reached with these technologies and an LCOP which is lower than for CAES and PHS. However, if a higher green score is desired CAES and PHS remain with a lower LCOP.

The large-scale commercial electricity consumer described in the case study cannot procure 100% hourly matched renewable energy with the selected production and storage technologies for a feasible LCOP, however a strong increase in the green score is possible.

7.2 Recommendations

Based on the results and the conclusions of this report two types of recommendations are given. Firstly, managerial recommendations are given based on the outcomes of this research. Secondly, recommendations for further research are given.

Recommendations for LSE consumers and energy suppliers

First, following from this research recommendations can be given for LSE consumers to start to increase their hourly match. The step that should naturally be taken by any electricity consumers before moving towards hourly matching is to improve system efficiency and procure 100% renewable electricity annually. In the current situation, this is often from electricity generated from wind, with a green score of approximately 62%. The next step is to optimise this portfolio; by adding solar PV the green score in this research increases to around 72%. This step can be achieved relatively easily, as it requires replacing guarantees of origin of Dutch wind for Dutch Solar PV (and potentially solar PV placed on location). Furthermore, the options for optimising the production portfolio can be further examined. From this research it appears that, to substantially improve the green score, large scale energy storage is required. In this, portfolios with storage such as CAES and PHS have lower LCOPs than those with Redox flow and Lithium-ion. After adapting the generation portfolio, and possibilities of implementing storage further research can be conducted in options regarding demand response to increase the hourly match. As companies at this point have insights into impact of actions on the green score, they can further improve the green score. Due to the steep increase of the LCOP towards a 100% green score, the options of offsetting of carbon emissions can be explored to close the final gap.

Recommendations for further research

Research into possibilities of influencing the demand side

In the model, the demand has been kept fixed, however influencing the demand (to reach towards a 100% green score) should be further explored. Research into demand response is suggested, in addition to optimising the portfolio. By initially optimising the portfolio of a large-scale consumer, the need for adjusting the demand can become clearer and more focused on the moments that this is especially required.

One of the limitations of this study is that it is conducted for a single demand profile. Although this profile shows a clear commercial pattern, the research could be optimised by repeating and verified it for multiple demand profiles, and thereby also improving the impact on a national level by regarding all companies that have the potential to improve their green score.

Extension of the methodology by adding other technologies

Further research is recommended into reaching a green score of 100%. In this report the influence of different technologies on the green score and the accompanying LCOP was analysed, however although it gives clear results on the impact of different technologies, with this methodology a 100% green score was not achieved for an acceptable LCOP. A further analysis using back-casting could for example be conducted (Vergragt & Quist, 2011) in which the desire for various 100% green score scenarios in 2030 is used as a starting point and the required pathway towards this portfolio is developed. In this case it would be interesting to expand the technologies and flex possibilities used in the model and aim to find a combination that does achieve a 100% green score for a feasible cost for the LSE consumer.

The addition of baseload technologies to increase green score is a subject for further research. In this study, the main focus was on VRES production technologies in combination with an Electrical Energy Storage that fits the application to also investigate the dynamics in the current electricity market. However, the impact of the addition of baseload production to the portfolio to increase the hourly match without greatly increasing the LCOP would be worth further investigation. It would be of interest to review the implications for the green score, costs, acceptance, and environmental impact when using, for example, biomass (although its origins must not lead to controversy), wave energy, or nuclear energy.

Defining and addressing implementation barriers

Furthermore, research should be conducted on the organisational side of implementing an Hourly Matching system. The current concept of Hourly Matching is a product or service that can be offered by Eneco, however, the impact of such a system is enhanced if it is well accepted by a large range of stakeholders. Therefore, research into the collaboration between different organisations in setting up a novel Hourly Matching system is advised.

Further research could also be conducted into the drivers of large-scale electricity consumers in the energy transition (Hayes & Parker, 2018) and how they can optimise their role, making use of their potential to influence the energy transition. Furthermore, implementation of different storage technologies analysed in this thesis entails the question of the placement and ownership of EES. Further research should be conducted into the opportunities for different business models regarding Electrical Energy Storage. This can be done centralised, can be facilitated by an energy supplier for an energy consumer, but can also be handled by the electricity consumer themselves.

8. References

Ahmad, S., & Tahar, R. M. (2014). Selection of renewable energy sources for sustainable development of electricity generation system using analytic hierarchy process: A case of Malaysia. *Renewable Energy*, *63*, 458–466. https://doi.org/10.1016/j.renene.2013.10.001

Akinyele, D. O., & Rayudu, R. K. (2014). Review of energy storage technologies for sustainable power networks. *Sustainable Energy Technologies and Assessments*, *8*, 74–91. https://doi.org/10.1016/j.seta.2014.07.004

Aneke, M., & Wang, M. (2016). Energy storage technologies and real life applications – A state of the art review. *Applied Energy*, *179*, 350–377. https://doi.org/10.1016/j.apenergy.2016.06.097

APX group. (2019). EPEX SPOT Power NL Day Ahead. Retrieved February 7, 2019, from https://www.apxgroup.com/market-results/apx-power-nl/dashboard/

Archer, C. L., & Jacobson, M. Z. (2003). Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements. *Journal of Geophysical Research: Atmospheres*, *108*(D9), n/a-n/a. https://doi.org/10.1029/2002JD002076

Archer, C. L., & Jacobson, M. Z. (2007). Supplying baseload power and reducing transmission requirements by interconnecting wind farms. *Journal of Applied Meteorology and Climatology*, *46*(11), 1701–1717. https://doi.org/10.1175/2007JAMC1538.1

Argyrou, M. C., Christodoulides, P., & Kalogirou, S. A. (2018). Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications. *Renewable and Sustainable Energy Reviews*, *94*(November 2017), 804–821. https://doi.org/10.1016/j.rser.2018.06.044

Association of issuing bodies. (2017). *The value of Guarantees of Origin: empowering consumers in the energy transition - YouTube*. Retrieved from https://www.youtube.com/watch?v=7aJVFYIytbo

Beaudin, M., Zareipour, H., Schellenberglabe, A., & Rosehart, W. (2010). Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy for Sustainable Development*, *14*(4), 302–314. https://doi.org/10.1016/j.esd.2010.09.007

Beekhuis, R. (2018). *Interview*.

Belderbos, A., Delarue, E., Kessels, K., & D'haeseleer, W. (2016). *The Levelized Cost of Storage critically analyzed and its intricacies clearly explained KULeuven Energy Institute TME Branch*. Retrieved from http://www.mech.kuleuven.be/tme/research/

Belderbos, A., Virag, A., D'haeseleer, W., & Delarue, E. (2017). Considerations on the need for electricity storage requirements: Power versus energy. *Energy Conversion and Management*, *143*(August), 137–149. https://doi.org/10.1016/j.enconman.2017.03.074

Bessette, D. L., & Arvai, J. L. (2018). Engaging attribute tradeoffs in clean energy portfolio development. *Energy Policy*, *115*(January), 221–229. https://doi.org/10.1016/j.enpol.2018.01.021

Better biomass. (2015). Better Biomass NTA 8080 Certificatie | QS Certification. Retrieved May 4, 2019, from https://www.qsbv.com/nl/29/nta-8080-certificering

Beushausen, F. M. H. (2016). How to determine meaningful, comparable costs of energy storage. Retrieved from https://www.apricum-group.com/how-to-determine-meaningful-comparable-costs-of-energy-storage/

BLIX Consultancy BV & partners. (2018). *Study into Levelized Cost of Energy*.

Bloomberg New Energy Outlook. (2018a). *1H 2018 LCOE Update - Global*. 2019.

Bloomberg New Energy Outlook. (2018b). Netherlands country profile. Retrieved October 11, 2018, from Power market structure website: https://www.bnef.com/core/country-profiles/nld?tab=Tableaus

BloombergNEF. (2019). A Behind the Scenes Take on Lithium-ion Battery Prices | Bloomberg NEF. Retrieved May 7, 2019, from https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

Bluerise. (n.d.). Markets | Bluerise. Retrieved February 21, 2019, from http://www.bluerise.nl/markets/

Bocklisch, T. (2016). Hybrid energy storage approach for renewable energy applications. *Journal of Energy Storage*, *8*, 311–319. https://doi.org/10.1016/j.est.2016.01.004

Brinkman, M. (2017). *Corporate power purchase agreements in Dutch electricity market*. Retrieved from www.stek.com.

Brook, B. W., & Bradshaw, C. J. A. (2015). Key role for nuclear energy in global biodiversity conservation. *Conservation Biology*, *29*(3), 702–712. https://doi.org/10.1111/cobi.12433

Buth, M. C. (2018). *Blockchain technology for peer-to-peer trading in the Dutch electricity system : from hype to reality*.

Cárdenas, B., Pimm, A. J., Kantharaj, B., Simpson, M. C., Garvey, J. A., & Garvey, S. D. (2017). Lowering the cost of large-scale energy storage: High temperature adiabatic compressed air energy storage. *Propulsion and Power Research*, *67*, 126–133. https://doi.org/10.1016/j.jppr.2017.06.001

Castellanos, J. A. F., Coll-Mayor, D., & Notholt, J. A. (2017). Cryptocurrency as guarantees of origin: Simulating a green certificate market with the Ethereum Blockchain. *2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE)*, 367–372. https://doi.org/10.1109/SEGE.2017.8052827

CBS. (2018a). Energie - Cijfers - Economie | Trends in Nederland 2018 - CBS. Retrieved February 7, 2019, from https://longreads.cbs.nl/trends18/economie/cijfers/energie/

CBS. (2018b). Share of renewable energy at 6.6 percent. Retrieved February 20, 2019, from https://www.cbs.nl/en-gb/news/2018/22/share-of-renewable-energy-at-6-6-percent

CE Delft. (2016). *Ontwikkeling prijzen garanties van oorsprong*. 1–2.

CertiQ. (2018). Electricity. Retrieved March 1, 2019, from http://www.certiq.nl/en/energy-source/electricity/

Child, M., Breyer, C., Bogdanov, D., & Fell, H. J. (2017). The role of storage technologies for the transition to a 100% renewable energy system in Ukraine. *Energy Procedia*, *135*, 410–423. https://doi.org/10.1016/j.egypro.2017.09.513

Clean Tecnica. (2019). Solar Power In The Netherlands Grows 50% In 2018 — With More To Come. Retrieved from https://cleantechnica.com/2019/01/08/solar-power-in-the-netherlands-grows-50-in-2018-with-more-to-come/

Comello, S. (2018). *Economic Analysis of Battery Storage Systems : A Levelized Cost Approach Abstract :* (July). Retrieved from http://content.ebscohost.com/ContentServer.asp?T=P&P=AN&K=130999551&S=R&D=bth&EbscoContent=dGJyMNLr40SeprA4zdnyOLCmr1Cep7dSr6q4SraWxWXS&ContentCustomer=dGJyMPGsr1CyqbNNuePfgeyx43zx

Connolly, D., Lund, H., & Mathiesen, B. V. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renewable and Sustainable Energy Reviews*, *60*, 1634–1653. https://doi.org/10.1016/j.rser.2016.02.025

Davids, M., Dijkstra, S., van Kletersteeg, J., & Reumkens, D. (2015). *How large energy consumers can power the Energy Transition Translating Demand into Additional Renewable Power Generation 2 3*. Retrieved from http://climex.com/wp-content/uploads/2016/01/Climex-Report-How-large-energy-consumers-can-power-the-Energy-Transition.pdf

De Vos, K., Petoussis, A. G., Driesen, J., & Belmans, R. (2013). Revision of reserve requirements following wind power integration in island power systems. *Renewable Energy*, *50*, 268–279. https://doi.org/10.1016/j.renene.2012.06.048

Delta 21. (2018). Delta 21. Retrieved December 5, 2018, from 2018 website: https://www.delta21.nl/

Demirtas, O. (2013). Evaluating the Best Renewable Energy Technology for Sustainable Energy Planning. *International Journal of Energy Economics an Policy*, *3*, 23–33.

Denholm, P., & Hand, M. (2011). Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. *Energy Policy*, *39*(3), 1817–1830. https://doi.org/10.1016/j.enpol.2011.01.019

Dingenen, S., Reid, E., Gürdenli, L., & Graff, P. (2018). *Corporate PPAs An international perspective*. Retrieved from https://www.twobirds.com/~/media/articles/international-corporate-ppas-brochure.pdf?la=en

Donker, J., Huygen, A. E. H., Westerga, R., & Weterings, R. (2015). *Naar een toekonstbestendig energiesysteem: flexibiliteit met waarde*. Retrieved from http://dare.uva.nl

Dornburg, V., Faaij, A., Verweij, P., Langeveld, H., Van De Ven, G., Wester, F., … Van Egmond, S. (2008). *Biomass Assessment Assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy Main report the Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change (WAB)*. Retrieved from www.mnp.nl

ECN. (2016). *The demand for flexibility of the power system in the Netherlands , 2015-2050*. (April).

ECN. (2017a). *Demand and supply of flexibility in the power system of the Netherlands, 2015-2050 Summary report of the FLEXNET project*. (November 2017), 1–69. Retrieved from https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-E--17-053%0Ahttps://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-E--17-063

ECN. (2017b). *Energy Outlook 2017*. 21. Retrieved from https://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2017/bp-energy-outlook-2017.pdf

Ecovat. (2018). Home of Ecovat | Seasonal Thermal Energy Storage. Retrieved November 28, 2018, from https://www.ecovat.eu/

Eneco. (2015). Biomassa -NTA8080 & Better Biomass. Retrieved May 4, 2019, from https://www.eneco.nl/over-ons/projecten/bio-golden-raand/biomassa/

EnecoGroup. (2018a). *Internal workshop Hourly Matching.*

EnecoGroup. (2018b). Mission: everyone's sustainable energy | Eneco Group. Retrieved April 3, 2019, from https://www.enecogroup.com/who-we-are/mission-and-strategy/mission/

Energieopwek. (2019). Energieopwek.nl - Inzicht in de actuele (near-realtime) opwekking van duurzame energie in Nederland. Retrieved January 26, 2019, from http://energieopwek.nl/

Energy Information Administration, U. (2019). *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019*. Retrieved from http://www.eia.gov/outlooks/aeo/assumptions/

Energy Storage Association. (2018). Hydrogen Energy Storage | Energy Storage Association. Retrieved May 8, 2019, from http://energystorage.org/energy-storage/technologies/hydrogen-energy-storage

Environmental Graphiti. (2017). Global Carbon Emissions by Source — Environmental Graphiti. Retrieved April

6, 2019, from http://www.environmentalgraphiti.org/global-carbon-emissions-by-source

ESA. (2018). Energy Storage Association. Retrieved from http://energystorage.org/energy-storage/technologies/liquid-air-energy-storage-laes

Frei, F., Sinsel, S. R., Hanafy, A., & Hoppmann, J. (2018). Leaders or laggards? The evolution of electric utilities' business portfolios during the energy transition. *Energy Policy*, *120*(April), 655–665. https://doi.org/10.1016/j.enpol.2018.04.043

Fuchs Illoldi, J. (2017). *Optimal Configurations of Hybrid Renewable Energy Systems for Islands ' Energy Transition*.

Gioutsos, D. M. (2016). *Masters Thesis: Determination of Cost-Optimal Electricity System Configurations for the Transition to Sustainable Energy Systems on Islands*.

Gioutsos, D. M., Blok, K., van Velzen, L., & Moorman, S. (2018). Cost-optimal electricity systems with increasing renewable energy penetration for islands across the globe. *Applied Energy*, *226*, 437–449. https://doi.org/10.1016/J.APENERGY.2018.05.108

Global WInd Energy Council. (2017). *GWEC Global Wind 2017 REport: A snapshot of Top wind markets in 2017: offshore wind* (Vol. 106). https://doi.org/10.1021/jp0213102

Goiri, Í., Haque, M. E., Le, K., Beauchea, R., Nguyen, T. D., Guitart, J., … Bianchini, R. (2015). Matching renewable energy supply and demand in green datacenters. *Ad Hoc Networks*, *25*(PB), 520–534. https://doi.org/10.1016/j.adhoc.2014.11.012

Google. (2018). *Moving toward 24x7 Carbon-Free Energy at Google Data Centers : Progress and Insights Introduction*.

Gu, Y., McCalley, J., Ni, M., & Bo, R. (2013). Economic modeling of compressed air energy storage. *Energies*, *6*(4), 2221–2241. https://doi.org/10.3390/en6042221

Gulagi, A., Bogdanov, D., & Breyer, C. (2017). The Demand for Storage Technologies in Energy Transition Pathways Towards 100% Renewable Energy for India. *Energy Procedia*, *135*, 37–50. https://doi.org/10.1016/j.egypro.2017.09.485

Guney, M. S., & Tepe, Y. (2017). Classification and assessment of energy storage systems. *Renewable and Sustainable Energy Reviews*, *75*(October 2016), 1187–1197. https://doi.org/10.1016/j.rser.2016.11.102

Hamwi, M., & Lizarralde, I. (2017). A Review of Business Models towards Service-Oriented Electricity Systems. *Procedia CIRP*, *64*, 109–114. https://doi.org/10.1016/j.procir.2017.03.032

Harrison, K. (2018). *Corporate PPA volumes*. Retrieved from http://resource-platform.eu/files/knowledge/reports/BNEF-RESource-CorporatePPAs-Q32018.pdf

Hayes, M., & Parker, V. (2018). New drivers of the renewable energy transition Part1. *KPMG International-Global Energy Institute*, (June 2017), 1–4.

Hijgenaar, S. (2017). *Electric vehicles: the driving power for energy transition*. Retrieved from http://repository.tudelft.nl/.

Holland Trade and Invest. (2018). Renewable Energy from Tidal Currentsle. Retrieved January 14, 2019, from Clean Energy Transitions website: https://www.hollandtradeandinvest.com/dutch-solutions/clean-energy/tidal-turbines-oosterschelde-renewable-energy-from-tidal-currents

Hölsgens, R. (2019). Resource dependence and energy risks in the Netherlands since the mid-nineteenth century. *Energy Policy*, *125*, 45–54. https://doi.org/10.1016/J.ENPOL.2018.10.020

Huang, Y., Chen, H. S., Zhang, X. J., Keatley, P., Huang, M. J., Vorushylo, I., … Hewitt, N. J. (2017). Techno-economic Modelling of Large Scale Compressed Air Energy Storage Systems. *Energy Procedia*, *105*, 4034–4039. https://doi.org/10.1016/J.EGYPRO.2017.03.851

International Renewable Energy Agency. (2017). *ELECTRICITY STORAGE AND RENEWABLES: COSTS AND MARKETS TO 2030*. Retrieved from www.irena.org

ISEA. (2012). Technology Overview on Electricity Storage - Overview on the potential and on the deployment perceptives of electric storage technologies. *Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University*, (June), 1–66. https://doi.org/10.13140/RG.2.1.5191.5925

Jülch, V. (2016). *Comparison of electricity storage options using levelized cost of storage (LCOS) method*. https://doi.org/10.1016/j.apenergy.2016.08.165

Kaldellis, J. K., & Zafirakis, D. (2007). Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency. *Energy*, *32*, 2295–2305. https://doi.org/10.1016/j.energy.2007.07.009

Kaya, T., & Kahraman, C. (2010). Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul. *EGY*, *35*, 2517–2527. https://doi.org/10.1016/j.energy.2010.02.051

Krabbe, O., Linthorst, G., Blok, K., Crijns-Graus, W., Van Vuuren, D. P., Höhne, N., … Pineda, A. C. (2015). *Aligning corporate greenhouse-gas emissions targets with climate goals*. https://doi.org/10.1038/NCLIMATE2770

Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., & Bansal, R. C. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and Sustainable*

Energy Reviews, *69*(June 2016), 596–609. https://doi.org/10.1016/j.rser.2016.11.191

Lagaaij, J. A. C., & Verbong, G. P. J. (1999). Different Visions of Power The Introduction of Nuclear Power in the Netherlands 1955?1970. *Centaurus*, *41*(1–2), 37–63. https://doi.org/10.1111/j.1600-0498.1999.tb00274.x

Lai, C. S., & McCulloch, M. D. (2017). Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Applied Energy*, *190*, 191–203. https://doi.org/10.1016/J.APENERGY.2016.12.153

Lazard. (2017a). *Lazard's Levelized Cost of Energy 11*. (November), 0–21. Retrieved from https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf

Lazard. (2017b). *Levelized Cost of Storage 2017*. (November). https://doi.org/10.1016/j.ahj.2015.12.004

Liu, C., Chau, K. T., Chenxi Diao, Zhong, J., Zhang, X., Shuang Gao, & Diyun Wu. (2010). A new DC micro-grid system using renewable energy and electric vehicles for smart energy delivery. *2010 IEEE Vehicle Power and Propulsion Conference*, 1–6. https://doi.org/10.1109/VPPC.2010.5728991

Loock, M. (2012). Going beyond best technology and lowest price: On renewable energy investors' preference for service-driven business models. *Energy Policy*, *40*(1), 21–27. https://doi.org/10.1016/j.enpol.2010.06.059

Lovins, A. B., & Lovins, L. H. (1982). Electric utilities. Key to capitalizing the energy transition. *Technological Forecasting and Social Change*, *22*(2), 153–166. https://doi.org/10.1016/0040-1625(82)90020-8

Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, *137*, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081

Magagna, D., & Uihlein, A. (2015). Ocean energy development in Europe: Current status and future perspectives. *International Journal of Marine Energy*, *11*, 84–104. https://doi.org/10.1016/j.ijome.2015.05.001

Mahlia, T. M. I., Saktisahdan, T. J., Jannifar, A., Hasan, M. H., & Matseelar, H. S. C. (2014). A review of available methods and development on energy storage; Technology update. *Renewable and Sustainable Energy Reviews*, *33*, 532–545. https://doi.org/10.1016/j.rser.2014.01.068

Mandelli, S., Brivio, C., Leonardi, M., Colombo, E., Molinas, M., Park, E., & Merlo, M. (2016). The role of electrical energy storage in sub-Saharan Africa. *Journal of Energy Storage*, *8*, 287–299. https://doi.org/10.1016/j.est.2015.11.006

Mardani, A., Zavadskas, E. K., Khalifah, Z., Zakuan, N., Jusoh, A., Nor, K. M., & Khoshnoudi, M. (2017). A review of multi-criteria decision-making applications to solve energy management problems: Two decades from 1995 to 2015. *Renewable and Sustainable Energy Reviews*, *71*(December 2016), 216–256. https://doi.org/10.1016/j.rser.2016.12.053

Milieucentraal. (2018). Is jouw stroom groen? - MilieuCentraal. Retrieved March 1, 2019, from https://www.milieucentraal.nl/klimaat-en-aarde/energiebronnen/groene-stroom/

Morshed, F. A. (2019). Network Operator: No Pain, No Gain The electricity distribution network – Part 1. In *ABN AMRO Energy monitor* (Vol. 17). https://doi.org/10.1016/0160-4120(91)90153-h

Mulder, M. (2018). Energy Transition and the Electricity Market: An Exploration of an Electrifying Relationship. In *Ssrn*. https://doi.org/10.2139/ssrn.2940974

Navigant. (2018). *Long Duration Energy Storage*.

Orellano, M., Neubert, G., Gzara, L., & Le-Dain, M. A. (2017). Business Model Configuration for PSS: An Explorative Study. *Procedia CIRP*, *64*, 97–102. https://doi.org/10.1016/j.procir.2017.03.008

Poullikkas, A. (2013). *Journal of Power Technologies 93 (2) (2013) 78-89 Optimization analysis for pumped energy storage systems in small isolated power systems $*. Retrieved from http://www.papers.itc.pw.edu.pl/index.php/JPT/article/viewFile/382/527

Qi, Z., & Koenig, G. M. (2017). Review Article: Flow battery systems with solid electroactive materials. *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena*, *35*(4), 040801. https://doi.org/10.1116/1.4983210

R. E. Hester, R. M. H. (2018). Energy Storage Options and Their Environmental Impact - Google Books. Retrieved May 7, 2019, from https://books.google.nl/books?id=2m10DwAAQBAJ&pg=PA71&lpg=PA71&dq=comparison+aCAES+dCAES+cost+of+CO2+gas&source=bl&ots=36MvWZaNOI&sig=ACfU3U1ItycoqUebJC3VlV_xpNnE70M-7A&hl=en&sa=X&ved=2ahUKEwjKqr2nhoniAhVJZVAKHfhoBbYQ6AEwC3oECAgQAQ#v=onepage&q=comparison%25

RE-source. (2018). *Corporations seek removal of barriers to renewable energy procurement in support of Europe ' s climate and energy goals*.

Richter, M. (2012). Utilities' business models for renewable energy: A review. *Renewable and Sustainable Energy Reviews*, *16*(5), 2483–2493. https://doi.org/10.1016/j.rser.2012.01.072

Richter, M. (2013). Business model innovation for sustainable energy: German utilities and renewable energy. *Energy Policy*, *62*, 1226–1237. https://doi.org/10.1016/j.enpol.2013.05.038

Roelofsen, O., De Pee, A., & Speelman, E. (2018). *Accelerating the energy transition: cost or opportunity? A* *thought starter for the Netherlands*. Retrieved from http://www.nvde.nl/wp-content/uploads/2016/09/Accelerating-the-energy-transition-McKinsey.pdf

Romare, M., & Dahllöf, L. (2017). The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries. In *IVL Swedish Environmental Research Institute*. https://doi.org/978-91-88319-60-9

Ros, J., Koelemeijer, R., Elzenga, H., Jeroen, P., Hekkenberg, M., & Bosch, P. (2011). *Exploration of pathways towards a clean economy by 2050: How to realise a climate-neutral Netherlands*. Retrieved from https://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2011-exploration-of-pathways-towards-a-clean-economy-by-2050.pdf

Schill, W. P. (2014). Residual load, renewable surplus generation and storage requirements in Germany. *Energy Policy*, *73*, 65–79. https://doi.org/10.1016/j.enpol.2014.05.032

Schmidt, O., Melchior, S., Hawkes, A., & Staffell, I. (2018). Projecting the future levelized cost of electricity storage technologies. *Joule*, *[submitted*(1), 81–100. https://doi.org/10.1016/J.JOULE.2018.12.008

Sensfuss, F., & Pfluger, B. (2014). *Optimized pathways towards ambitious climate protection in the European electricity system (EU Long-term scenarios 2050 II)*. (September).

Sgobbi, A., Simões, S. G., Magagna, D., & Nijs, W. (2016). Assessing the impacts of technology improvements on the deployment of marine energy in Europe with an energy system perspective. *Renewable Energy*, *89*, 515–525. https://doi.org/10.1016/J.RENENE.2015.11.076

Slingerland, S., Rothengatter, N., Veen, R. van der, Bolscher, H., & Rademaekers, K. (2015). *The Balance of Power – Flexibility Options for the Dutch Electricity Market*. 1–90. Retrieved from http://trinomics.eu/wp-content/uploads/2015/05/The-Balance-of-Power-—-Flexibility-Options-for-the-Dutch-Electricity-Market-final-report.pdf

Sonnemans, E., & Buiting, T. (2018). *Interview with Radboud university*.

Sousa, J. L., Martins, A. G., & Jorge, H. (2013). Dealing with the paradox of energy efficiency promotion by electric utilities. *Energy*, *57*, 251–258. https://doi.org/10.1016/j.energy.2013.02.040

Staffell, I., & Rustomji, M. (2016). Maximising the value of electricity storage. *Journal of Energy Storage*, *8*, 212–225. https://doi.org/10.1016/j.est.2016.08.010

Steinke, F., Wolfrum, P., & Hoffmann, C. (2013). Grid vs. storage in a 100% renewable Europe. *Renewable Energy*, *50*, 826–832. https://doi.org/10.1016/j.renene.2012.07.044

Sternberg, A., & Bardow, A. (2015). Power-to-What? – Environmental assessment of energy storage systems. *Energy Environ. Sci.*, *8*(2), 389–400. https://doi.org/10.1039/C4EE03051F

Suman, S. (2018). Hybrid nuclear-renewable energy systems: A review. *Journal of Cleaner Production*, *181*, 166–177. https://doi.org/10.1016/J.JCLEPRO.2018.01.262

Tennet. (2019a). Balancing responsibility - TenneT. Retrieved May 4, 2019, from https://www.tennet.eu/electricity-market/dutch-market/balancing-responsibility/

Tennet. (2019b). Netherlands Load - TenneT. Retrieved February 23, 2019, from https://www.tennet.eu/electricity-market/data-dashboard/load/

TenneT. (2019). TenneT: na succesvolle pilots door met Blockchain. Retrieved April 1, 2019, from https://www.tennet.eu/nl/nieuws/nieuws/tennet-na-succesvolle-pilots-door-met-blockchain-1/

the climate group. (2019). Moving to truly global impact | The Climate Group. Retrieved February 20, 2019, from https://www.theclimategroup.org/news/moving-truly-global-impact

Tocardo. (2018). Tidal Power Plant in Dutch Delta Works. Retrieved November 15, 2018, from https://www.tocardo.com/Project/oosterschelde/

Track My Electricity. (2019). Retrieved from http://www.trackmyelectricity.com/learn-more/certificate-system/

Tsiropoulos I, Tarvydas D, & Lebedeva N. (2018). *Li-ion batteries for mobility and stationary storage applications Scenarios for costs and market growth*. https://doi.org/10.2760/87175

Velthuijsen, W. J., Jeroen, V. H., Helmer, D., Jean, P., & Muller, N. (2018). *Unlocking Europe's offshore wind potential. Moving towards a subsidy free industry*. (April). Retrieved from https://www.pwc.nl/nl/assets/documents/pwc-unlocking-europes-offshore-wind-potential.pdf

Verbong, G. (2001). Een kwestie van lange adem: de geschiedenis van duurzame energie in Nederland - Google Books. Retrieved May 3, 2019, from https://books.google.nl/books?hl=en&lr=&id=zibzmAwNhgAC&oi=fnd&pg=PT12&ots=OgkJVCRx_n&sig=g8vlI97-7qj5nbSoKnxx2bumXVk&redir_esc=y#v=onepage&q&f=false

Vergragt, P. J., & Quist, J. (2011). Backcasting for sustainability: Introduction to the special issue. *Technological Forecasting and Social Change*, *78*(5), 747–755. https://doi.org/10.1016/j.techfore.2011.03.010

Wen, Z. guo, Di, J. han, Yu, X. wei, & Zhang, X. (2017). Analyses of CO2mitigation roadmap in China's power industry: Using a Backcasting Model. *Applied Energy*, *205*(August), 644–653. https://doi.org/10.1016/j.apenergy.2017.08.026

Wise. (2018). Wat is sjoemelstroom? | Wise Nederland. Retrieved May 5, 2019, from https://wisenederland.nl/groene-stroom/wat-sjoemelstroom

Wise Nederland. (2017). Sjoemelstroom komt niet meer uit Noorwegen | Wise Nederland. Retrieved February 25, 2019, from https://wisenederland.nl/groene-stroom/sjoemelstroom-komt-niet-meer-uit-noorwegen

Wise Nederland. (2018). Prijzen GvO’s | Wise Nederland. Retrieved February 28, 2019, from https://wisenederland.nl/groene-stroom/prijslijst-garanties-van-oorsprong

World Bank, & Ecofys. (2017). *State and Trends of Carbon Pricing 2017*. https://doi.org/10.1596/978-1-4648-1218-7

Zakeri, B., & Syri, S. (2015). Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews*, *42*, 569–596. https://doi.org/10.1016/J.RSER.2014.10.011

Zhang, C., Wei, Y. L., Cao, P. F., & Lin, M. C. (2018). Energy storage system: Current studies on batteries and power condition system. *Renewable and Sustainable Energy Reviews*, *82*(July 2017), 3091–3106. https://doi.org/10.1016/j.rser.2017.10.030

Zondag met Lubach. (2018). *Groene stroom - Zondag met Lubach (S08) - YouTube* (p. Season 9-Episode 3). Retrieved from https://www.youtube.com/watch?v=xW-VLPyxqAM

Appendix A - Developments in interconnection capacity

One of the options to increase the amount of RES in the Dutch energy grid and a solution to problem of limited control over the supply of electricity from wind and solar PV would be to increase the border grid capacity to neighbouring countries. In these countries, the installed RES capacity will also significant increase up to 2030. (Slingerland et al., 2015). By doing this, excess VRES can be sold to neighbouring countries when there too much is produced, and at moment when there is too little RES, electricity can be imported from neighbouring countries. At this scale it could be possible to balance supply and demand patterns and to some level use pumped storage as a balance strategy (Ros et al., 2011). There are several plans, when looking at the timeframe up to 2030, for new cross-border transmission lines between the Netherlands and surrounding countries.

Table 10 shows the current amount of VRES in neighbouring countries

Table 10: Intermittent renewable production of the total indigenous production + policy plans for RES-E in countries with direct interconnection to the Netherlands (as far as specified)

Country	Wind	Solar	RES-E policy goals
Netherlands	2013: 5,6%	2013: 0,5%	
Germany	2014: 9%	2014: 6,8%	55 -60% % RES in electricity (2030) 35% RES in electricity (2020)
Belgium	2012: 2,8%	2012: 2,1%	
United Kingdom	2013: 6,6%	2013: 0,01%	
Denmark	2013: 32,7%	2012: 0,1%	50% wind in electricity (2020)
Norway	2012: 1,1%	2012: 0%	

The interconnections that are foreseen up to 2030 are to Denmark in 2019, the COBRA cable which is planned to have a 700 MW capacity, and the second connector to Norway, the NorNed2 with a capacity of 700MW which is expected to become operational after 2022.

Although these increase grid capacities to neighbouring countries can be seen as a way of redistributing possible excess energy VRES, problems due to large percentages of RES in other countries can also be imported. However, in the countries with much higher RES, such as Denmark and Germany, flexibility problems have remained limited. (Slingerland et al., 2015). Another limit to a pan-European electricity is that is requires the collaboration of multiple European countries (Ros et al., 2011).

Appendix B - Load calculation

Comparison to the Dutch load profile

To verify the relevance of the load profile it is compared to the Dutch load profile. The correlation with the larger energy system can be indicated by showing the load profile of the Netherlands as shown in Figure 44. The decreasing load in the middle of the day is known as the duck curve and is caused by a demand drop due to solar energy production peaking at midday.

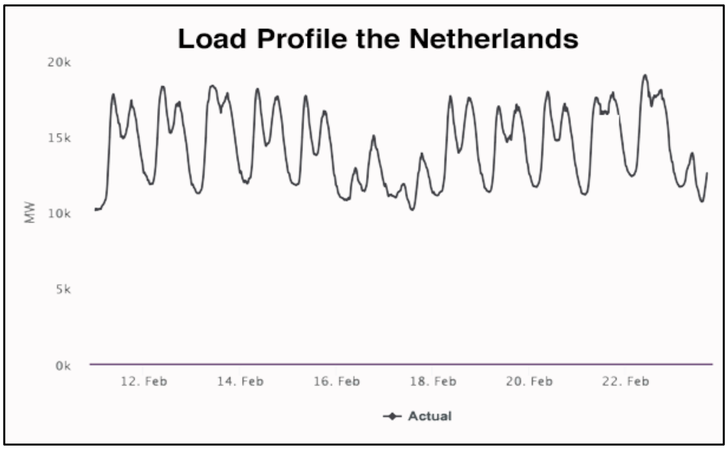


Figure 44:The load profile of the Netherlands (Tennet, 2019b)

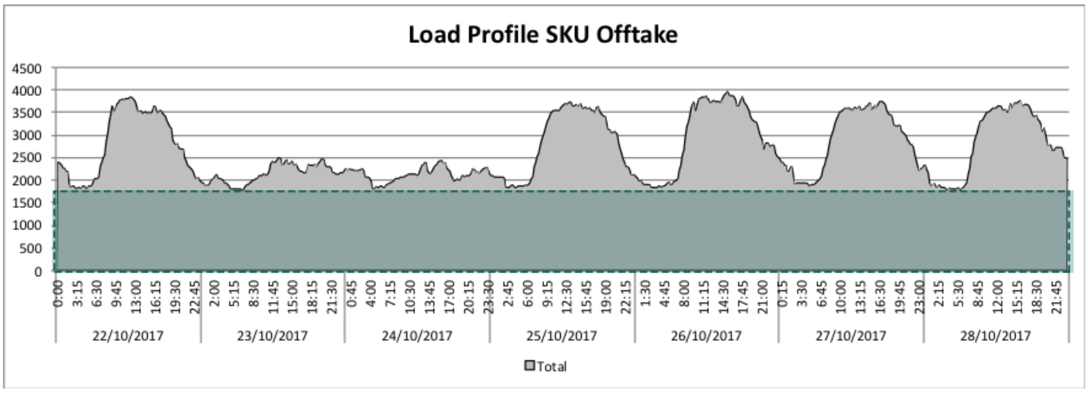
Calculation baseload of load profile

To calculate the total energy capacity of the load profile that is baseload

Lowest offtake = 1780 kWh/15 minutes

Offtake per year = 1780 kWh *4 *8760 = 62371 MWh

Baseload offtake per year (MWh)/ Offtake per (year MWh) = 62371/ 96310 =65%



Appendix C - Technologies Analysis

Literature on storage

	Luo et Al. (2015)	Argyrou et Al. (2018)	IRENA (2017)	Description	Modelling	Further Info
PHS	🟢	🟢	🟢	🟢	🟢	
CAES	🟢	🟢	🟢	🟢	🟢	
FES	🟢	🟢	🟢	🟢	🔴	Short term storage doesn't match initial criteria for Hourly Matching
LAES	🟢	🟢	🔴	🔴	🔴	Thermal Energy Storage
Li-Ion (Batteries)	🟢	🟢	🟢 NCA & NMC & Titanite	🟢	🟢	Industry standard and literature available on price projections
LA (Batteries)	🟢	🟢	🟢 VRLA & Flooded LA	🟢	🔴	Li-ion batteries analysed instead as comparable characteristics, li-ion are currently cheapest and industry standard.
NaNiCl			🟢	🟢	🔴	Li-ion batteries analysed instead as comparable characteristics, li-ion are currently cheapest and industry standard.
NAs (Batteries)	🟢	🟢	🟢	🟢	🔴	Li-ion batteries analysed instead as comparable characteristics, li-ion are currently cheapest and industry standard.
VRB (Flow Batteries)	🟢	🟢	🟢	🟢	🟢	Decoupling of power and energy is beneficial at large scale
ZnBr (Flow Batteries)			🟢	🔴	🔴	VRB is analysed instead, comparable characteristics
SMES	🟢	🟢	🔴	🟢	🔴	Short term storage doesn't match initial criteria for Hourly Matching
Superconductor	🟢	🟢	🔴	🟢	🔴	Short term storage doesn't match initial criteria for Hourly Matching
Hydrogen	🔴	🔴	🔴	🟢	🔴	Much more expensive & inefficient than other forms of storage

Summary of Advantages and Disadvantages of technologies

The following table shows the general advantages and disadvantages of different production technologies.

Renewable Technology	Advantages	Disadvantages
Wind	* Emits no CO_2 across its life cycle. *Has no fuel costs.	* Impacts the landscape and emits noise. * Is dependent on wind in given location. * Has high investment costs. * Little is known of Impacts on ecosystems. * Energy produced is intermittent and difficult to predict
(Onshore)	*Maintenance is easier	
(Offshore)	*Generation is more stable than onshore *Large scale implementation and large capacity planned in coming years	
Solar PV	* Volumes of Solar PV will continue to grow, as costs decrease, there is high public support and low CO_2 emissions. * When combined with energy storage and smart software solutions, solar energy has potential to becomes a reliable source of electricity * The sun is an unlimited resource. * Easy to install, little operation and maintenance work is required. * Long lifetime of more than 25 years.	* Is intermittent as electricity production is depends on sunlight. * Expensive but Solar PV cost has decreased significantly. * Sunlight depends on location and season. * Forecasts can be incorrect (but better than wind). * Not dispatchable.
Hydro	* Almost no emissions that impact climate or the environment. * large-scale and stable electricity generation. * Balancing power. * No fuel costs. * Have a long lifetime	* Have large impact on the environment * High investment for new hydro
Biomass & waste	* CO_2 emissions are reduced compared to fossil fuels. * Can be carbon neutral.	* Larger volumes are difficult to secure. * More expensive than using energy sources such as coal, gas or nuclear power. * Origin of biomass questionable
High temperature Geothermal	[Not taken into account in research due to heating purposes]	
Low temperature geothermal	[Not taken into account in research due to heating purposes]	
Nuclear	* Large-scale of baseload electricity *Limited external impacts	* Negative public opinion * The Netherlands is densely populated, making it difficult to implement *Extremely expensive
Tidal	*Could function as baseload *Has no fuel costs *The Netherlands has large coastline	*Technology is not developed yet *Environmental impact is unknown

Increasing wind and solar in the Netherlands

Figure 45 shows the planned offshore parks. The red areas show the current wind parks (1,118 MWh) (Global Wind Energy Council, 2017) and the other areas show planned wind parks, an additional 7,000 MW, (BLIX Consultancy BV & partners, 2018)

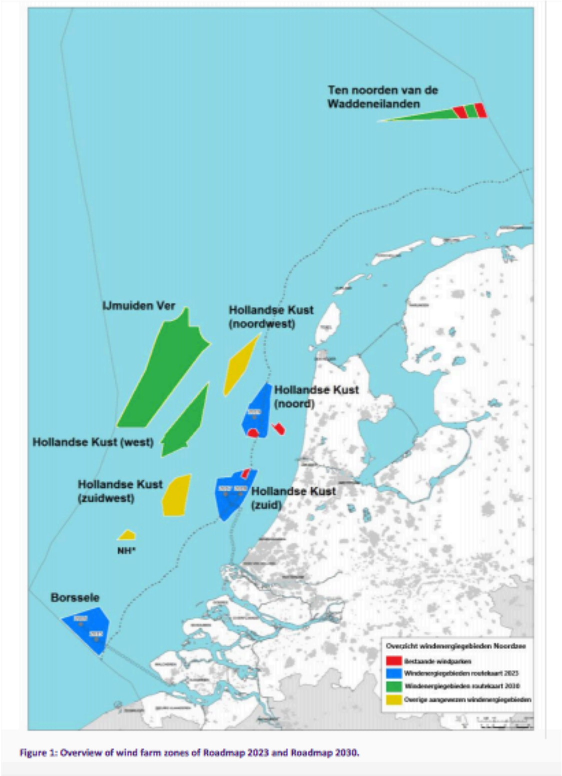
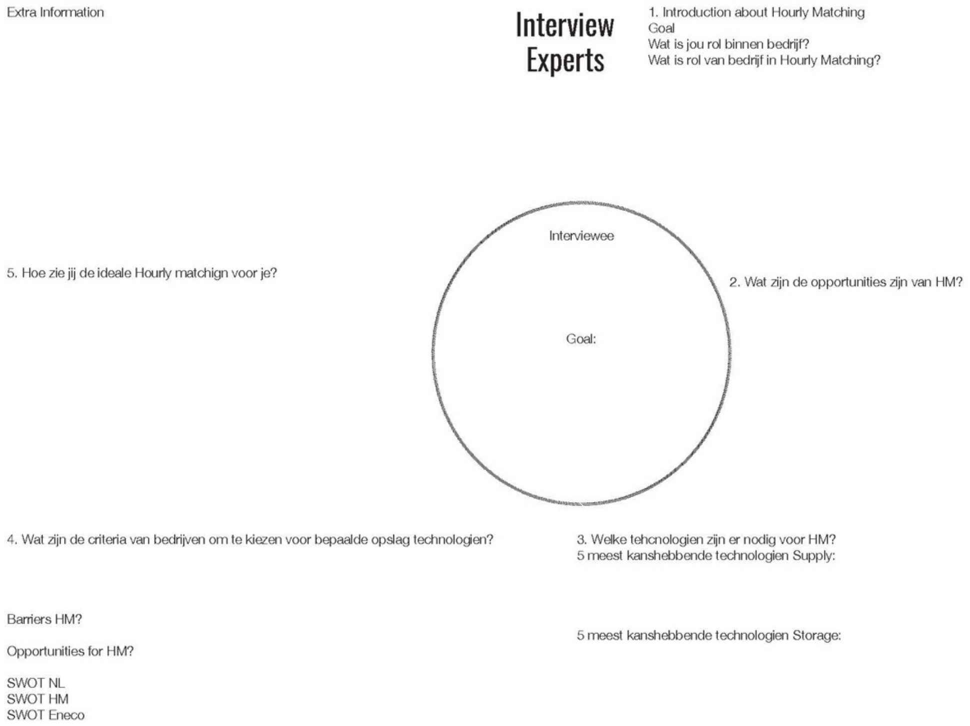


Figure 45: Overview of wind farm zones of Roadmap 2023 and Roadmap 2030 in the North Sea

Appendix D - Interviews

Interview guides

The following interview guides were used for the interviews.



Extra Information

Interview Experts

1. Introduction about Hourly Matching
Goal
Wat is jou rol binnen bedrijf?
Wat is rol van bedrijf in Hourly Matching?

Interviewee

Goal:

5. Hoe zie jij de ideale Hourly matchign voor je?

2. Wat zijn de opportunities zijn van HM?

4. Wat zijn de criteria van bedrijven om te kiezen voor bepaalde opslag technologien?

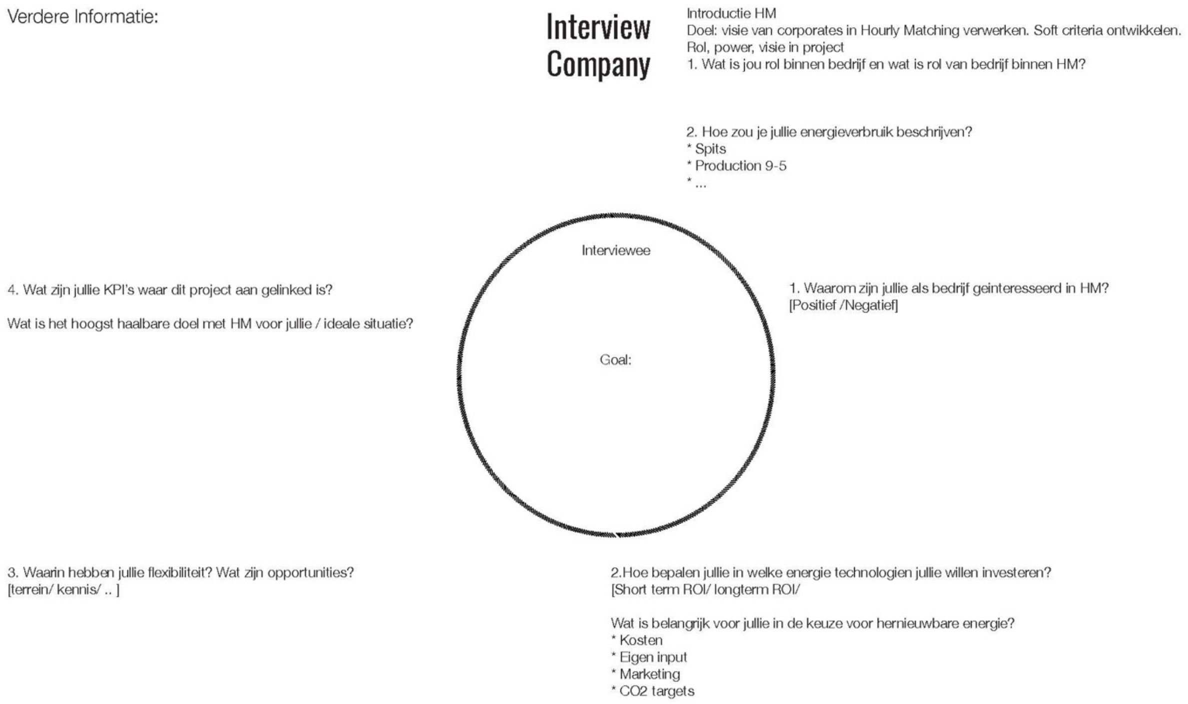
3. Welke tehcnologien zijn er nodig voor HM?
5 meest kanshebbende technologien Supply:

Barriers HM?

Opportunities for HM?

SWOT NL
SWOT HM
SWOT Eneco

5 meest kanshebbende technologien Storage:



Verdere Informatie:

Interview Company

Introductie HM
Doel: visie van corporates in Hourly Matching verwerken. Soft criteria ontwikkelen.
Rol, power, visie in project
1. Wat is jou rol binnen bedrijf en wat is rol van bedrijf binnen HM?

2. Hoe zou je jullie energieverbruik beschrijven?
* Spits
* Production 9-5
* ...

Interviewee

Goal:

4. Wat zijn jullie KPI's waar dit project aan gelinked is?

Wat is het hoogst haalbare doel met HM voor jullie / ideale situatie?

1. Waarom zijn jullie als bedrijf geinteresseerd in HM?
[Positief /Negatief]

3. Waarin hebben jullie flexibiliteit? Wat zijn opportunities?
[terrein/ kennis/ ..]

2.Hoe bepalen jullie in welke energie technologien jullie willen investeren?
[Short term ROI/ longterm ROI/

Wat is belangrijk voor jullie in de keuze voor hernieuwbare energie?
* Kosten
* Eigen input
* Marketing
* CO2 targets

Summary of interview with TNO

Interview with Richard Beekhuis
The fully transcribed interviews have been summarised below.

- **Rol:** Business Developer bij TNO - opzetten van samenwerkingsprojecten en dat zijn eigen ik altijd innovatieve projecten
- **Rol van TNO In Hourly Matching:** Zijn bezig geweest met een consortium met certificering en administratie van gelabelde energie. Genoemde eigenschappen
    - Locatie
    - Bron
    - Kleinere spelers interessant maken op de markt
    - Labelen zou nog steeds samen kunnen met GVO's - geldt als extra officiële certificering (voorbeeld van een gecertificeerde garage om een auto te kopen vs. een verkoper op marktplaats)
- **Definitie van Hourly Matching:** Een eerste product. Als je zegt ik heb een handelsplaats zoals en Square of een dergelijke Markt is daar verwachten we ook niet dat iedere eindgebruiker daar zijn eigen dienst bij elkaar gaat zoeken maar dat haar partijen op zijn tijd zeggen Nou wij maak er gebruik van dat aanbod Wat is op de markt om een heel gericht aanbod te maken naar onze eindklant enzo dat doordat die Markt al die attributen kent
  Als een energiedienst leverancier die op een dergelijk generieke marktplaats eigenlijk een Middel heeft waarbij je je Enerzijds een soort standaardproduct aanbiedt maar waarbij de invulling maat gesneden is. Zo zie ik hem. En dat is een prachtig voorbeeld van zo'n Markt.
- **Opportunities HM**
    - Groen + GVO's niet meer goed genoeg bij de RVB/
    - Ik zie daar gewoon een grote rol voor veel meer grote bedrijven ook in het kader van het klimaatakkoord en maatschappelijk verantwoord ondernemen eigenlijk zeggen van joh voor deze manier van energie afnemen betalen we misschien wel een klein beetje meer of nog steeds een goede prijs, maar wat we in ieder geval stimuleren is dat dat we de ontwikkeling en de juiste inzet van duurzame installaties
    - Ik dan zie is dat dat veel bedrijven zeker in de industrie die merken gewoon dat het maatschappelijk draagvlak als het ware en voor een deel van hun concurrentiepositie zie toch echt wel iets te maken heeft met het feit dat zij laten zien dat ze ook voor een betere wereld zijn.
    - Het is wel echt ondersteuning nog alleen je blijft nog wel even van je primaire proces af en kijkt naar het secundaire proces.
    - Is momenteel lastig voor bedrijven: "dat maakt het voor die bedrijven erg lastig. Enerzijds zelfopgelegde Kis om te verduurzamen, dat moet je ergens doen daar ontkom je ook niet aan, Nou daar kan je dus invulling aan geven. Anderzijds wordt er externe ook van alles opgelegd en biedt het ook op deze manier mogelijkheden om verantwoord met energie om te gaan. Aan en hoef je nou gelijk verduurzaamd of een hele slag maakt dat is iets anders wat. "
    - … naar die flexibiliteit te zoeken en ook al echt een bijdrage te leveren zonder dat je de hele boel ondersteboven hoeft te gooien.
    - *Over proactive compliance* Ja misschien dat dat ik denk dat je ook wel, en natuurlijk wat ik al zei het ingrijpen op wat ik het primaire bedrijfsproces is natuurlijk een enorme stap. En dat is er eentje die moet je volgens mij overal wel goed doen en daar zullen ook de beleidslijnen vanuit de overheid heel helder op moeten zijn dat zijn ze nu nog niet.
    - Maar ook bijvoorbeeld door collectieven beter te ondersteunen
    - Zonder dat je zelf de boel omgooit ga je door je inkoopmacht eigenlijk en leg je in principe de leverancier zulke randvoorwaarden op dat je eigenlijk al duur samen energie krijgt dan anders vanwege die voorwaarden.

Technologieën :

- Hydro: RB: Als je gaat kijken naar Nederland dan denk ik dat pumped Hydro dat zie ik niet zitten.
  MS: Nee ja daarvan is het dus of je kan een contract afsluiten met het buitenland en dat je het uit Frankrijk of Duitsland gaat doen.
  MS: Of je zou in Nederland met valmeren gaan werken of met cavernes ondergrond. En dat je het kleinschalig gemaakt dan hele grote dammen bouwen Maar dat zou ook nog een optie zijn

RB: Ja dat is een optie inderdaad.

- Compressed Air: Kijk compressed Air dat is eentje die is Ontzettend lastig want er zitten wel heel veel energie in alleen het rendement daarvan van is gewoon heel erg laag dat schiet echt niet op en daarnaast heb je bij Compressed Air. Want het is mechanisch het comprimeert dus een heel groot verlies zit in de warmte kant. Dus bij het comprimeren decomprimeren, Dat is een heel lastig ding dat moet je je onder druk zetten en dat in gasvelden en, en nou het kan bijna niet uit. Rendementen zijn ontzettend laag en je moet altijd een bepaalde druk hebben (41:39). Het is lastig je ziet ook dat de projecten die over compressed air gingen ook alweer worden gestopt want dan doen ze in die cavernes. Onder andere volgens mij Gasunie is daarmee bezig en die hebben gezegd Laten we er geen samengedrukte lucht in stoppen maar gewoon energetisch interessante moleculen instoppen
  - Compressed Air is, nou als alle andere dingen niet kunnen dan is dat veilig laat maar zeggen. Dan moet je alleen kijken waar kan je zoveel lucht in kwijt Dat kan. Van en in een zoutcaverne haal je eigenlijk te weinig echt om daar echt veel energie in te stoppen dan moet je echt naar gasvelden kijken en dan moet je daar stikstof instoppen en geen lucht.
- Waterstof:
  RB: ... ja En dan zie je dat het naar waterstof gaat, zet dat is sowieso wel een ding waar veel in gaat zitten...
- Flow batterij: we zien dat flow batterij en belangrijke linkje, Daar komt steeds meer aandacht voor en het kan in grote volumes. Het is natuurlijk wel groot dus het is nog niet… It.is denk ik wel een belangrijke. En als je gaat kijken naar energieopslag en je haalt er een paar uit.
- SMES en supercapacitors zijn natuurlijk ook erg korte termijn.
- De elektrochemische kant dan heb je Flow batterijen
- Lithium- Ion: En je ziet natuurlijk nu wel dat er wat Lithium-ion wordt gedaan aan of dat nou heel groot word ik verwacht het niet ...niet voor de volumes die we nodig hebben. bij Storage moet je fit for purpose hebben. Dus welke purpose heb je en welke vit heb je nodig en je moet niet gaan proberen een systeem voor een hele korte termijn die waarschijnlijk duur is in vermogen en capaciteit, voor hele grote seizoen opslag te gaan gebruiken dat wil je niet. Daar heb je wat anders voor nodig.

Algemeen

- Ik denk dat een grote route Dat zie je steeds meer gaat naar hetgeen dat we goed kunnen opslaan in grote volumes en dat is molecule. Dus is eigenlijk het grootste deel zal waarschijnlijk gaan naar Chemical waarbij y afhankelijk van het type moleculen dat je maakt het in grote vaten of in de ondergrond. Waar we hebben heel veel ruimte hebben energie kunnen opslaan. Aan We hadden het natuurlijk net wel over draagvlak Dat is een puntje. Aan de andere kant We leven al miljoenen jaren met een enorm Bel gas onder ons dat ging altijd prima. Stoppen we daar wat anders in misschien iets dat ongevaarlijk is dan zijn we in één keer erop tegen dus dat is natuurlijk wel een dingetje je.
- Sowieso zo een energieopslag is sowieso ontzettend duur je doet er niks zinnigs mee. E vanuit TNO kijken we dus bijvoorbeeld wat Hoe kun je nou de assets die we al hebben beter inzetten en kijken naar flexibiliteit ervan van daar zit vaak ook een soort opslag in. Namelijk het in de tijd kunnen schuiven En die heb je al. Al en die gebruik je voor een ander bedrijf doel. Dus als je daar In de tijd wat kan spelen Dan kun je daarvoor een hele hoop opslagcapaciteit die je anders extern zou moeten neerzetten met geen andere functie dan alleen opslag zijn kun je voorkomen.

Productie:

- Biomassa & gas: RB: Wat je natuurlijk sowieso ziet is de hele route naar biomassa en biogas dat is natuurlijk een ding en afhankelijk van welke profetieën aanhoort is het heel veel heel weinig. De wind profeten gaan voor alles weer en de biomassa profeten gaan voor alles biomassa ieder zo zijn eigen geloof.
- Nucleair: ik denk dat de discussie over Nucleair er nog wel een tijdje zal blijven. Ik word er niet meer gelukkig van Maar ja ja het is er eentje je die nu opkomt.
- Als je gaat kijken naar wat de moeite is om zeg maar zon en wind voor elkaar te krijgen.

MS: Wat zijn criteria van bedrijven om te kiezen voor bepaalde opslag technologieën?

RB: Op dit moment zie je natuurlijk dat bedrijven pure bedrijfseconomisch kijken open, gewoon een optimalisatie van een bedrijfsproces. Bijvoorbeeld in de centrale in Amsterdam am1 in Diemen waren enorm watervat komt te staan, aan Ze willen op die manier gewoon de piek productie voorkomen en daarmee hun installatie efficiënter laten draaien en zorgen dat ze hun buffer opvullen, en zorgen dat ze een buffer hebben tussen Enerzijds en productiemiddel en anderzijds een afname.

MS: Zie jij verder nog barrières voor Hourly Matching?

- Waarde voor bedrijven: “de grote vraag is natuurlijk wat hebben bedrijven ervoor over en lopen ze tegen een meerprijs op en wat vinden ze van die meerprijs”
- Opschaalbaarheid ”...en kan Eneco voldoende groene Energie inzetten en voldoen aan het profiel als ze een aantal grote spelers hebben? op die manier is er geen barrière maar kan het zijn dat op het moment dat er een aantal grote spelers zegt dit willen wij de belofte van Hourly matching maar zeer beperkt ingevuld kan worden omdat een Eneco met de energie die ze hebben gecontracteerd het maar gelimiteerd kunnen invullen maar een barrière is het eigenlijk niet Het is alleen gaan we dit als product inzetten Dan moet je dat serieus doen dan moet je daar een aantal kenmerken en garantie door kunnen geven dat moet je als Eneco gewoon weloverwogen kunnen doen want als je een keer introduceert dan zit je er ook aan vast

Summary of interview SKU Radboud

- **Rol:** Coordinator energiebeleid binnen de Radboud Universiteit en UMC
- **Rol van SKU In Hourly Matching:** Kijken hoe wij ons vraagprofiel kunnen aanpassen zodat het matcht met het aanbod Profile van duurzaam; een beter beeld krijgen over wat onze inbreng kan zijn. Zeg maar simpel als wij wij meer buffers moeten maken of dat wij zelf batterijen moeten kopen of dat we we wind moeten ruilen voor zon dat dat ons meer gaat kosten .

- **Definitie van Hourly Matching:** Afstemmen van de vraag van elektriciteit aan het aanbod van duurzame elektriciteit, en dan wat betreft het profiel dat het matcht want de totale vraag dat hij wel gedekt met de overeenkomst. En nu gaan we kijken hoe kunnen we het qua profiel beter er op elkaar laten passen

- **Opportunities HM**
  - Er moet iets gebeuren en dat gaat zorgen dat profielen goed gaan matchen. Je ziet bijvoorbeeld in die lijst van WISE, dat suggereert dat je als huishouden 100% groene stroom in kan kopen. Dat kan eignelijk helemaal niet want je profiel als huishouden matcht niet. Dus er komt altijd grijze stroom bij en dat realiseren wij ons ook en daarom willen we die andere stap ook nog gaan maken
  - Je gaat toch voor 10 jaar maar met een bedrijf in zee en dan wil je niet met een stelletje cowboys, snelle jongens die wat parken neerzetten. Heel wezenlijk we willen ook wel een bedrijf die echt een hart voor duurzaamheid heeft of daar meer mee bezig is.
  - Het is een beetje van twee kanten hoor als ze zien dat je met goede dingen bezig bent laten ze dat makkelijker, meer universiteiten zijn goed bezig hoor
  - Ideaal is dat we 100% kunnen met je dus dat dat wat we in gaan kopen open en dat is wel 100% groen en maar dan op verbruiks niveau per jaar zeg maar, maar dat dat ook op het moment precies past. want dan kunnen we zeggen het verbruik op de universiteit daar hoeven geen fossiele centrales vooraan te gaan. Dat zou ideaal zijn.

Ambities:

- 2040 energieneutraal 2030 energieneutraal weet je wel. Dat soort redelijk vage algemene credo, zonder dat ze weten wat het energieverbruik is roepen ze dat al.
- Geen KPI’s maar je krijgt natuurlijk wel bij een aanbesteding. Deze was dus voor 10 jaar en dat kost ook wat want we gaan ons vastleggen aan GVO’s, dan heb je in ieder geval het verhaal dat er ambities zijn uitgesproken. Dus dit is een van die stappen en zo krijg je terugkoppeling erbij. Zo zit terugkoppeling naar de eerder genoemde ambities er wel in. Dus dan is het op zich wel handig als een ambitie hebben.
- Bij de RU hebben we nu een beleid vastgesteld in dat we 2% in absolute zin willen besparen per jaar en energie in primair verbruik. De kosten die komen uit het energiebudget dat werkt redelijk en ik denk dat we dit jaar ook die doelstellingen halen. Maar er is behoefte aan een grotere ambitie

Financiering:

- Het valt mij op bij de universiteit dat we niet zo heel strak in de budgetten zitten. Als we beginnen met we moeten het energiebudget verruimen en dan kunnen we er meer mee gaan doen, dan dat stuit je op heel veel bezwaren bij heel veel financiële mensen, die juist de tarieven voor de gebruikers willen verlagen omdat dan geen goed idee vinden. Maar dan komt er een andere oplossing van we gaan gewoon een investeringsvoorstel doen. En als het bestuur daar akkoord mee eens is dan schuift dat. Heel veel energie investeringen verdienen zichzelf natuurlijk terug ook.

  - Verlichting
  - Isolatie

Zie jij verder nog barrières voor Hourly Matching?

- Het kwartje is nog niet gevallen bij een hoop mensen, Ja wij zijn er toch wel wat meer de voorlopers in het gebied van energie
- Jaren geleden dachten studenten, ok maar als je maar GVO's koopt dan is het goed. Je kunt niet zeggen we gaan zo ineens van fossiel af. Dit is de uitdaging.

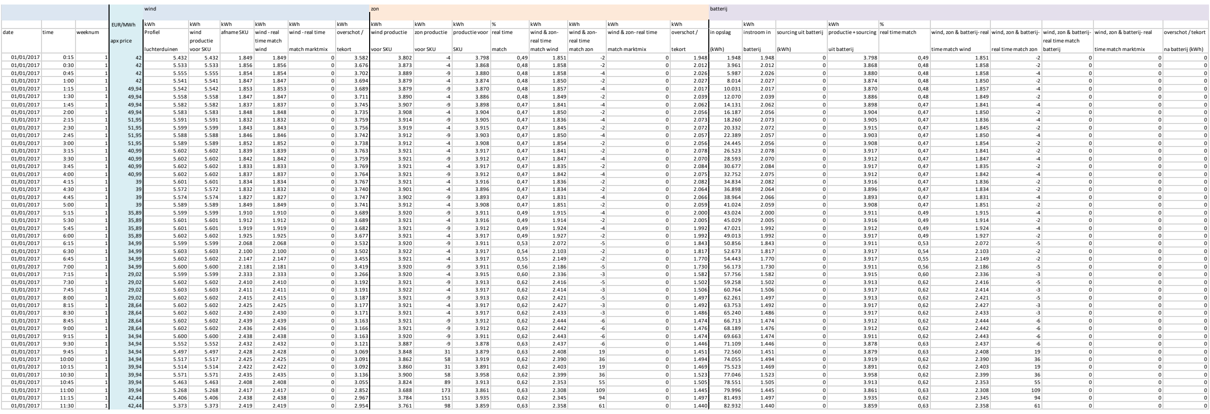
Round Table meeting with companies interested in a pilot project

During this research a round table was organised by Eneco with all the involved companies. The main conclusions from this day are given below:

- Different companies have different options for improving their greenscore.
- The initial greenscore of all companies is around 62% with just wind energy.
- Production of electricity from gas instead of marketmix electricity generation is not acceptable for multiple companies. For this use they state it can be difficult to comunicate even though the CO2 emissions would be lower and it could help make a statement against coal fired power plants in the Netherlands.
- The importance of being able to communicate the strategy for the companies. Both the possibility of internal and external communication are essential. As the current portfolio is given the name 100% green it would be complex to have to explain that within 100% green , gas is a good option to add (regarding CO2 emissions compared to market mix).

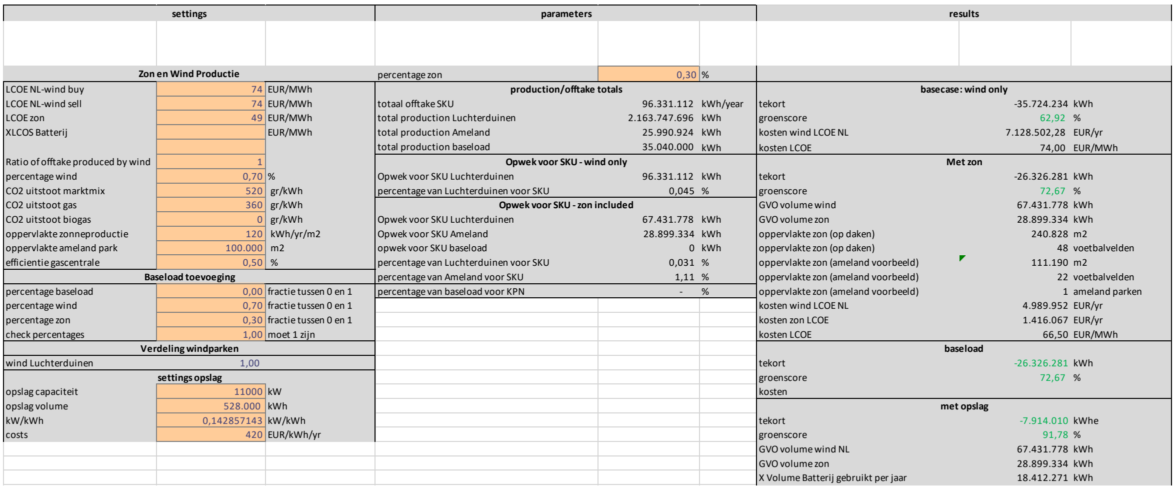
Appendix E - Model Input

The most important dashboards of the model are given to illustrate the build-up of the model used in this research.



				wind						zon								batterij									
			EUR/MWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	%	kWh	kWh	kWh	kWh		kWh		kWh	%					
date	time	weeknum	apx price	Profiel luchterduinen	wind productie voor SKU	afname SKU	wind - real time match wind	wind - real time match marktmix	overschot / tekort	wind productie voor SKU	zon productie voor SKU	productie voor SKU	real time match	wind & zon- real time match wind	wind & zon- real time match zon	wind & zon- real time match marktmix	overschot / tekort	in opslag (kWh)	instroom in batterij	sourcing uit batterij (kWh)	productie + sourcing uit batterij	real time match	wind, zon & batterij- real time match wind	wind, zon & batterij- real time match zon	wind, zon & batterij- real time match batterij	wind, zon & batterij- real time match marktmix	overschot / tekort na batterij (kWh)
01/01/2017	0:15	1	42	5.432	5.432	1.849	1.849	0	3.582	3.802	-4	3.798	0,49	1.851	-2	0	1.948	1.948	1.948	0	3.798	0,49	1.851	-2	0	0	0
01/01/2017	0:30	1	42	5.533	5.533	1.856	1.856	0	3.676	3.873	-4	3.868	0,48	1.858	-2	0	2.012	3.961	2.012	0	3.868	0,48	1.858	-2	0	0	0
01/01/2017	0:45	1	42	5.555	5.555	1.854	1.854	0	3.702	3.889	-9	3.880	0,48	1.858	-4	0	2.026	5.987	2.026	0	3.880	0,48	1.858	-4	0	0	0
01/01/2017	1:00	1	42	5.541	5.541	1.847	1.847	0	3.694	3.879	-4	3.874	0,48	1.850	-2	0	2.027	8.014	2.027	0	3.874	0,48	1.850	-2	0	0	0
01/01/2017	1:15	1	49,94	5.542	5.542	1.853	1.853	0	3.689	3.879	-9	3.870	0,48	1.857	-4	0	2.017	10.031	2.017	0	3.870	0,48	1.857	-4	0	0	0
01/01/2017	1:30	1	49,94	5.558	5.558	1.847	1.847	0	3.711	3.890	-4	3.886	0,48	1.849	-2	0	2.039	12.070	2.039	0	3.886	0,48	1.849	-2	0	0	0
01/01/2017	1:45	1	49,94	5.582	5.582	1.837	1.837	0	3.745	3.907	-9	3.898	0,47	1.841	-4	0	2.062	14.131	2.062	0	3.898	0,47	1.841	-4	0	0	0
01/01/2017	2:00	1	49,94	5.583	5.583	1.848	1.848	0	3.735	3.908	-4	3.904	0,47	1.850	-2	0	2.056	16.187	2.056	0	3.904	0,47	1.850	-2	0	0	0
01/01/2017	2:15	1	51,95	5.591	5.591	1.832	1.832	0	3.759	3.914	-9	3.905	0,47	1.836	-4	0	2.073	18.260	2.073	0	3.905	0,47	1.836	-4	0	0	0
01/01/2017	2:30	1	51,95	5.599	5.599	1.843	1.843	0	3.756	3.919	-4	3.915	0,47	1.845	-2	0	2.072	20.332	2.072	0	3.915	0,47	1.845	-2	0	0	0
01/01/2017	2:45	1	51,95	5.588	5.588	1.846	1.846	0	3.742	3.912	-9	3.903	0,47	1.850	-4	0	2.057	22.389	2.057	0	3.903	0,47	1.850	-4	0	0	0
01/01/2017	3:00	1	51,95	5.589	5.589	1.852	1.852	0	3.738	3.912	-4	3.908	0,47	1.854	-2	0	2.056	24.445	2.056	0	3.908	0,47	1.854	-2	0	0	0
01/01/2017	3:15	1	40,99	5.602	5.602	1.839	1.839	0	3.763	3.921	-4	3.917	0,47	1.841	-2	0	2.078	26.523	2.078	0	3.917	0,47	1.841	-2	0	0	0
01/01/2017	3:30	1	40,99	5.602	5.602	1.842	1.842	0	3.759	3.921	-9	3.912	0,47	1.847	-4	0	2.070	28.593	2.070	0	3.912	0,47	1.847	-4	0	0	0
01/01/2017	3:45	1	40,99	5.602	5.602	1.833	1.833	0	3.769	3.921	-4	3.917	0,47	1.835	-2	0	2.084	30.677	2.084	0	3.917	0,47	1.835	-2	0	0	0
01/01/2017	4:00	1	40,99	5.602	5.602	1.837	1.837	0	3.764	3.921	-9	3.912	0,47	1.842	-4	0	2.075	32.752	2.075	0	3.912	0,47	1.842	-4	0	0	0
01/01/2017	4:15	1	39	5.601	5.601	1.834	1.834	0	3.767	3.921	-4	3.916	0,47	1.836	-2	0	2.082	34.834	2.082	0	3.916	0,47	1.836	-2	0	0	0
01/01/2017	4:30	1	39	5.572	5.572	1.832	1.832	0	3.740	3.901	-4	3.896	0,47	1.834	-2	0	2.064	36.898	2.064	0	3.896	0,47	1.834	-2	0	0	0
01/01/2017	4:45	1	39	5.574	5.574	1.827	1.827	0	3.747	3.902	-9	3.893	0,47	1.831	-4	0	2.066	38.964	2.066	0	3.893	0,47	1.831	-4	0	0	0
01/01/2017	5:00	1	39	5.589	5.589	1.849	1.849	0	3.741	3.912	-4	3.908	0,47	1.851	-2	0	2.059	41.024	2.059	0	3.908	0,47	1.851	-2	0	0	0
01/01/2017	5:15	1	35,89	5.599	5.599	1.910	1.910	0	3.689	3.920	-9	3.911	0,49	1.915	-4	0	2.000	43.024	2.000	0	3.911	0,49	1.915	-4	0	0	0
01/01/2017	5:30	1	35,89	5.601	5.601	1.912	1.912	0	3.689	3.921	-4	3.916	0,49	1.914	-2	0	2.005	45.029	2.005	0	3.916	0,49	1.914	-2	0	0	0
01/01/2017	5:45	1	35,89	5.601	5.601	1.919	1.919	0	3.682	3.921	-9	3.912	0,49	1.924	-4	0	1.992	47.021	1.992	0	3.912	0,49	1.924	-4	0	0	0
01/01/2017	6:00	1	35,89	5.602	5.602	1.925	1.925	0	3.677	3.921	-4	3.917	0,49	1.927	-2	0	1.992	49.013	1.992	0	3.917	0,49	1.927	-2	0	0	0
01/01/2017	6:15	1	34,99	5.599	5.599	2.068	2.068	0	3.532	3.920	-9	3.911	0,53	2.072	-5	0	1.843	50.856	1.843	0	3.911	0,53	2.072	-5	0	0	0
01/01/2017	6:30	1	34,99	5.603	5.603	2.100	2.100	0	3.502	3.922	-4	3.917	0,54	2.103	-2	0	1.817	52.673	1.817	0	3.917	0,54	2.103	-2	0	0	0
01/01/2017	6:45	1	34,99	5.602	5.602	2.147	2.147	0	3.455	3.921	-4	3.917	0,55	2.149	-2	0	1.770	54.443	1.770	0	3.917	0,55	2.149	-2	0	0	0
01/01/2017	7:00	1	34,99	5.600	5.600	2.181	2.181	0	3.419	3.920	-9	3.911	0,56	2.186	-5	0	1.730	56.173	1.730	0	3.911	0,56	2.186	-5	0	0	0
01/01/2017	7:15	1	29,02	5.599	5.599	2.333	2.333	0	3.266	3.920	-4	3.915	0,60	2.336	-3	0	1.582	57.756	1.582	0	3.915	0,60	2.336	-3	0	0	0
01/01/2017	7:30	1	29,02	5.602	5.602	2.410	2.410	0	3.192	3.921	-9	3.913	0,62	2.416	-5	0	1.502	59.258	1.502	0	3.913	0,62	2.416	-5	0	0	0
01/01/2017	7:45	1	29,02	5.603	5.603	2.411	2.411	0	3.191	3.922	-4	3.917	0,62	2.414	-3	0	1.506	60.764	1.506	0	3.917	0,62	2.414	-3	0	0	0
01/01/2017	8:00	1	29,02	5.602	5.602	2.415	2.415	0	3.187	3.921	-9	3.913	0,62	2.421	-5	0	1.497	62.261	1.497	0	3.913	0,62	2.421	-5	0	0	0
01/01/2017	8:15	1	28,64	5.602	5.602	2.425	2.425	0	3.177	3.921	-4	3.917	0,62	2.427	-3	0	1.492	63.753	1.492	0	3.917	0,62	2.427	-3	0	0	0
01/01/2017	8:30	1	28,64	5.602	5.602	2.430	2.430	0	3.171	3.921	-4	3.917	0,62	2.433	-3	0	1.486	65.240	1.486	0	3.917	0,62	2.433	-3	0	0	0
01/01/2017	8:45	1	28,64	5.602	5.602	2.439	2.439	0	3.163	3.921	-9	3.912	0,62	2.444	-6	0	1.474	66.713	1.474	0	3.912	0,62	2.444	-6	0	0	0
01/01/2017	9:00	1	28,64	5.602	5.602	2.436	2.436	0	3.166	3.921	-9	3.912	0,62	2.442	-6	0	1.476	68.189	1.476	0	3.912	0,62	2.442	-6	0	0	0
01/01/2017	9:15	1	34,94	5.600	5.600	2.438	2.438	0	3.163	3.920	-9	3.911	0,62	2.443	-6	0	1.474	69.663	1.474	0	3.911	0,62	2.443	-6	0	0	0
01/01/2017	9:30	1	34,94	5.552	5.552	2.432	2.432	0	3.121	3.887	-9	3.878	0,63	2.437	-6	0	1.446	71.109	1.446	0	3.878	0,63	2.437	-6	0	0	0
01/01/2017	9:45	1	34,94	5.497	5.497	2.428	2.428	0	3.069	3.848	31	3.879	0,63	2.408	19	0	1.451	72.560	1.451	0	3.879	0,63	2.408	19	0	0	0
01/01/2017	10:00	1	34,94	5.517	5.517	2.425	2.425	0	3.091	3.862	58	3.919	0,62	2.390	36	0	1.494	74.055	1.494	0	3.919	0,62	2.390	36	0	0	0
01/01/2017	10:15	1	39,94	5.514	5.514	2.422	2.422	0	3.092	3.860	31	3.891	0,62	2.403	19	0	1.469	75.523	1.469	0	3.891	0,62	2.403	19	0	0	0
01/01/2017	10:30	1	39,94	5.571	5.571	2.435	2.435	0	3.136	3.900	58	3.958	0,62	2.399	36	0	1.523	77.046	1.523	0	3.958	0,62	2.399	36	0	0	0
01/01/2017	10:45	1	39,94	5.463	5.463	2.408	2.408	0	3.055	3.824	89	3.913	0,62	2.353	55	0	1.505	78.551	1.505	0	3.913	0,62	2.353	55	0	0	0
01/01/2017	11:00	1	39,94	5.268	5.268	2.417	2.417	0	2.852	3.688	173	3.861	0,63	2.308	109	0	1.445	79.996	1.445	0	3.861	0,63	2.308	109	0	0	0
01/01/2017	11:15	1	42,44	5.406	5.406	2.438	2.438	0	2.967	3.784	151	3.935	0,62	2.345	94	0	1.497	81.493	1.497	0	3.935	0,62	2.345	94	0	0	0
01/01/2017	11:30	1	42,44	5.373	5.373	2.419	2.419	0	2.954	3.761	98	3.859	0,63	2.358	61	0	1.440	82.932	1.440	0	3.859	0,63	2.358	61	0	0	0

Figure 46: An indication of the data used for combinations of technologies.

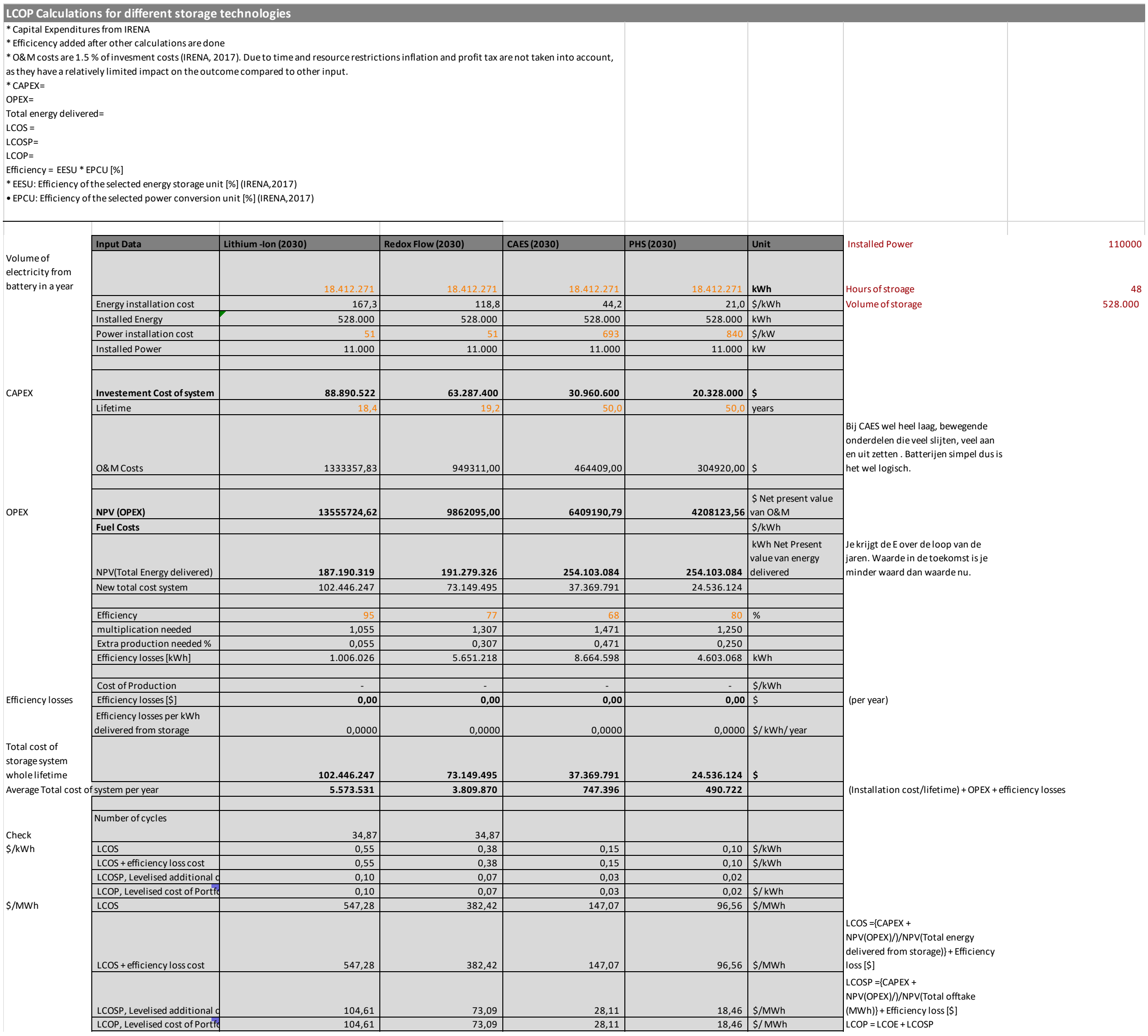


settings		
Zon en Wind Productie		
LCOE NL-wind buy	74	EUR/MWh
LCOE NL-wind sell	74	EUR/MWh
LCOE zon	49	EUR/MWh
XLCOS Batterij		EUR/MWh
Ratio of offtake produced by wind	1	
percentage wind	0,70	%
CO2 uitstoot marktmix	520	gr/kWh
CO2 uitstoot gas	360	gr/kWh
CO2 uitstoot biogas	0	gr/kWh
oppervlakte zonneproductie	120	kWh/yr/m2
oppervlakte ameland park	100.000	m2
efficientie gascentrale	0,50	%
Baseload toevoeging		
percentage baseload	0,00	fractie tussen 0 en 1
percentage wind	0,70	fractie tussen 0 en 1
percentage zon	0,30	fractie tussen 0 en 1
check percentages	1,00	moet 1 zijn
Verdeling windparken		
wind Luchterduinen	1,00	
settings opslag		
opslag capaciteit	11000	kW
opslag volume	528.000	kWh
kW/kWh	0,142857143	kW/kWh
costs	420	EUR/kWh/yr

parameters		
percentage zon	0,30	%
production/offtake totals		
totaal offtake SKU	96.331.112	kWh/year
total production Luchterduinen	2.163.747.696	kWh
total production Ameland	25.990.924	kWh
total production baseload	35.040.000	kWh
Opwek voor SKU - wind only		
Opwek voor SKU Luchterduinen	96.331.112	kWh
percentage van Luchterduinen voor SKU	0,045	%
Opwek voor SKU - zon included		
Opwek voor SKU Luchterduinen	67.431.778	kWh
Opwek voor SKU Ameland	28.899.334	kWh
opwek voor SKU baseload	0	kWh
percentage van Luchterduinen voor SKU	0,031	%
percentage van Ameland voor SKU	1,11	%
percentage van baseload voor KPN	-	%

results		
basecase: wind only		
tekort	-35.724.234	kWh
groenscore	62,92	%
kosten wind LCOE NL	7.128.502,28	EUR/yr
kosten LCOE	74,00	EUR/MWh
Met zon		
tekort	-26.326.281	kWh
groenscore	72,67	%
GVO volume wind	67.431.778	kWh
GVO volume zon	28.899.334	kWh
oppervlakte zon (op daken)	240.828	m2
oppervlakte zon (op daken)	48	voetbalvelden
oppervlakte zon (ameland voorbeeld)	111.190	m2
oppervlakte zon (ameland voorbeeld)	22	voetbalvelden
oppervlakte zon (ameland voorbeeld)	1	ameland parken
kosten wind LCOE NL	4.989.952	EUR/yr
kosten zon LCOE	1.416.067	EUR/yr
kosten LCOE	66,50	EUR/MWh
baseload		
tekort	-26.326.281	kWh
groenscore	72,67	%
kosten		
met opslag		
tekort	-7.914.010	kWhe
groenscore	91,78	%
GVO volume wind NL	67.431.778	kWh
GVO volume zon	28.899.334	kWh
X Volume Batterij gebruikt per jaar	18.412.271	kWh

Figure 47: The dashboard used to adapt parameters in the model regarding the green score

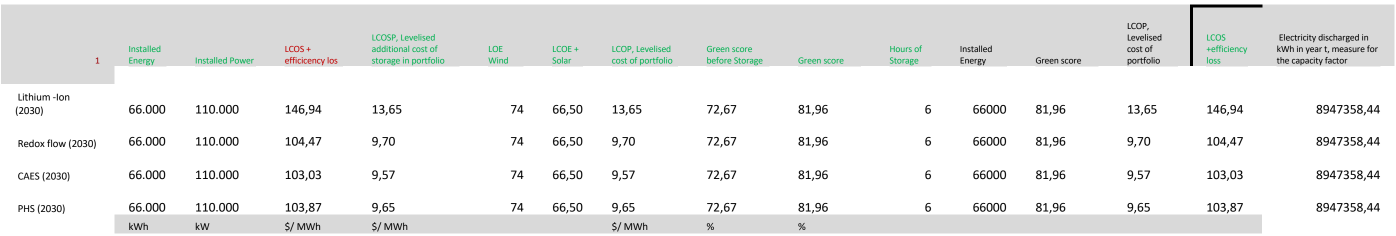


LCOP Calculations for different storage technologies

* Capital Expenditures from IRENA
* Efficicency added after other calculations are done
* O&M costs are 1.5 % of invesment costs (IRENA, 2017). Due to time and resource restrictions inflation and profit tax are not taken into account, as they have a relatively limited impact on the outcome compared to other input.
* CAPEX=
OPEX=
Total energy delivered=
LCOS =
LCOSP=
LCOP=
Efficiency = EESU * EPCU [%]
* EESU: Efficiency of the selected energy storage unit [%] (IRENA,2017)
• EPCU: Efficiency of the selected power conversion unit [%] (IRENA,2017)

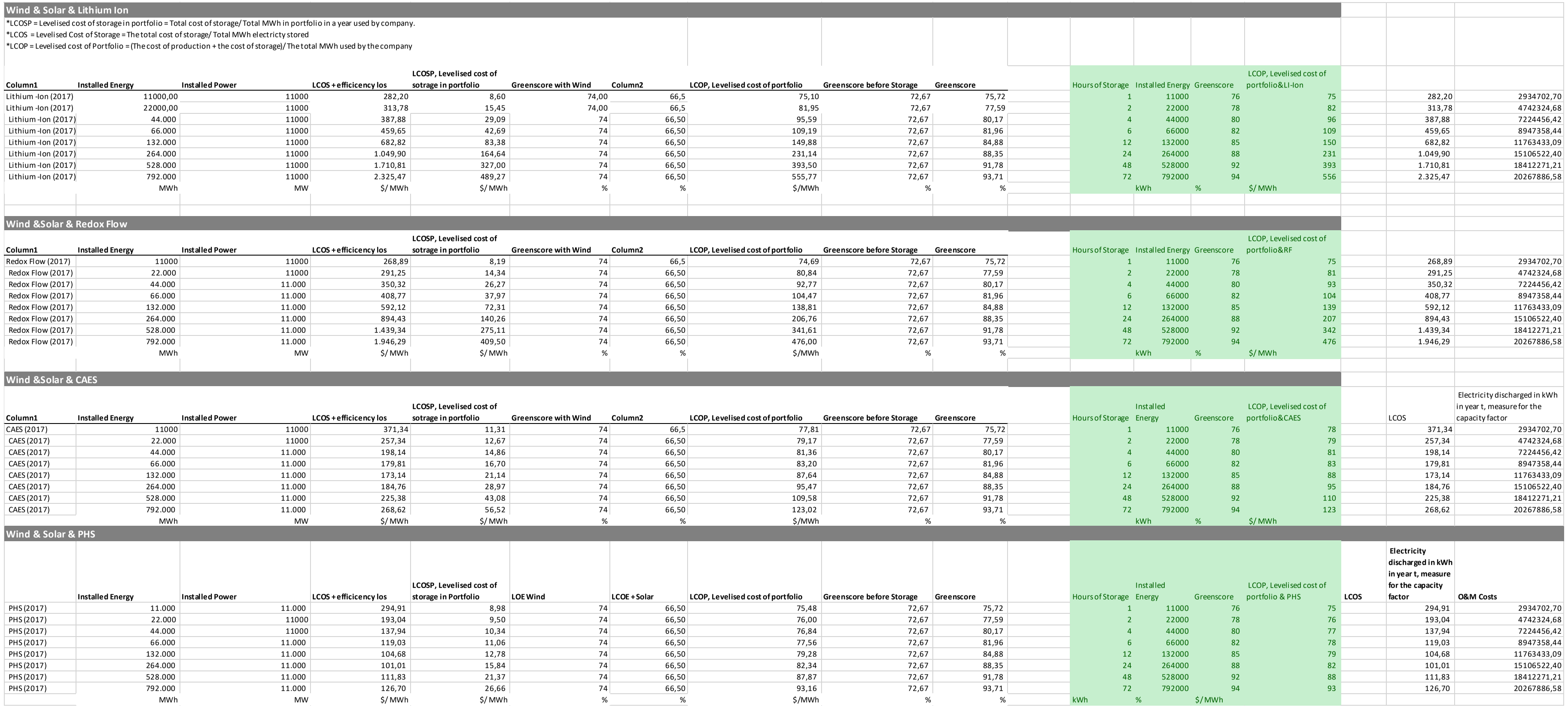
	Input Data	Lithium -Ion (2030)	Redox Flow (2030)	CAES (2030)	PHS (2030)	Unit		
							Installed Power	110000
Volume of electricity from battery in a year		18.412.271	18.412.271	18.412.271	18.412.271	**kWh**	Hours of stroage	48
	Energy installation cost	167,3	118,8	44,2	21,0	$/kWh	Volume of storage	528.000
	Installed Energy	528.000	528.000	528.000	528.000	kWh		
	Power installation cost	51	51	693	840	$/kW		
	Installed Power	11.000	11.000	11.000	11.000	kW		
CAPEX	**Investement Cost of system**	**88.890.522**	**63.287.400**	**30.960.600**	**20.328.000**	$		
	Lifetime	18,4	19,2	50,0	50,0	years		
	O&M Costs	1333357,83	949311,00	464409,00	304920,00	$	Bij CAES wel heel laag, bewegende onderdelen die veel slijten, veel aan en uit zetten . Batterijen simpel dus is het wel logisch.	
OPEX	**NPV (OPEX)**	**13555724,62**	**9862095,00**	**6409190,79**	**4208123,56**	$ Net present value van O&M		
	Fuel Costs					$/kWh		
	NPV(Total Energy delivered)	**187.190.319**	**191.279.326**	**254.103.084**	**254.103.084**	kWh Net Present value van energy delivered	Je krijgt de E over de loop van de jaren. Waarde in de toekomst is je minder waard dan waarde nu.	
	New total cost system	102.446.247	73.149.495	37.369.791	24.536.124			
	Efficiency	95	77	68	80	%		
	multiplication needed	1,055	1,307	1,471	1,250			
	Extra production needed %	0,055	0,307	0,471	0,250			
	Efficiency losses [kWh]	1.006.026	5.651.218	8.664.598	4.603.068	kWh		
	Cost of Production	-	-	-	-	$/kWh		
Efficiency losses	Efficiency losses [$]	**0,00**	**0,00**	**0,00**	**0,00**	$	(per year)	
	Efficiency losses per kWh delivered from storage	0,0000	0,0000	0,0000	0,0000	$/ kWh/ year		
Total cost of storage system whole lifetime		**102.446.247**	**73.149.495**	**37.369.791**	**24.536.124**	**$**		
Average Total cost of system per year		**5.573.531**	**3.809.870**	**747.396**	**490.722**		(Installation cost/lifetime) + OPEX + efficiency losses	
Check	Number of cycles	34,87	34,87					
$/kWh	LCOS	0,55	0,38	0,15	0,10	$/kWh		
	LCOS + efficiency loss cost	0,55	0,38	0,15	0,10	$/kWh		
	LCOSP, Levelised additional c	0,10	0,07	0,03	0,02			
	LCOP, Levelised cost of Portfo	0,10	0,07	0,03	0,02	$/ kWh		
$/MWh	LCOS	547,28	382,42	147,07	96,56	$/MWh		
	LCOS + efficiency loss cost	547,28	382,42	147,07	96,56	$/MWh	LCOS ={CAPEX + NPV(OPEX)/)/NPV(Total energy delivered from storage)} + Efficiency loss [$]	
	LCOSP, Levelised additional c	104,61	73,09	28,11	18,46	$/MWh	LCOSP ={CAPEX + NPV(OPEX)/)/NPV(Total offtake (MWh)} + Efficiency loss [$]	
	LCOP, Levelised cost of Portfo	104,61	73,09	28,11	18,46	$/ MWh	LCOP = LCOE + LCOSP	

Figure 48: The dashboard used to calculate the LCOP of portfolios with the addition of storage technologies



1	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised additional cost of storage in portfolio	LOE Wind	LCOE + Solar	LCOP, Levelised cost of portfolio	Green score before Storage	Green score	Hours of Storage	Installed Energy	Green score	LCOP, Levelised cost of portfolio	LCOS +efficiency loss	Electricity discharged in kWh in year t, measure for the capacity factor
Lithium -Ion (2030)	66.000	110.000	146,94	13,65	74	66,50	13,65	72,67	81,96	6	66000	81,96	13,65	146,94	8947358,44
Redox flow (2030)	66.000	110.000	104,47	9,70	74	66,50	9,70	72,67	81,96	6	66000	81,96	9,70	104,47	8947358,44
CAES (2030)	66.000	110.000	103,03	9,57	74	66,50	9,57	72,67	81,96	6	66000	81,96	9,57	103,03	8947358,44
PHS (2030)	66.000	110.000	103,87	9,65	74	66,50	9,65	72,67	81,96	6	66000	81,96	9,65	103,87	8947358,44
	kWh	kW	$/ MWh	$/ MWh			$/ MWh	%	%						

Figure 49: The output of the LCOP model



Wind & Solar & Lithium Ion

*LCOSP = Levelised cost of storage in portfolio = Total cost of storage/ Total MWh in portfolio in a year used by company.

*LCOS = Levelised Cost of Storage = The total cost of storage/ Total MWh electricty stored

*LCOP = Levelised cost of Portfolio = (The cost of production + the cost of storage)/ The total MWh used by the company

Column1	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of sotrage in portfolio	Greenscore with Wind	Column2	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio&LI-Ion			
Lithium -Ion (2017)	11000,00	11000	282,20	8,60	74,00	66,5	75,10	72,67	75,72		1	11000	76	75		282,20	2934702,70
Lithium -Ion (2017)	22000,00	11000	313,78	15,45	74,00	66,5	81,95	72,67	77,59		2	22000	78	82		313,78	4742324,68
Lithium -Ion (2017)	44.000	11000	387,88	29,09	74	66,50	95,59	72,67	80,17		4	44000	80	96		387,88	7224456,42
Lithium -Ion (2017)	66.000	11000	459,65	42,69	74	66,50	109,19	72,67	81,96		6	66000	82	109		459,65	8947358,44
Lithium -Ion (2017)	132.000	11000	682,82	83,38	74	66,50	149,88	72,67	84,88		12	132000	85	150		682,82	11763433,09
Lithium -Ion (2017)	264.000	11000	1.049,90	164,64	74	66,50	231,14	72,67	88,35		24	264000	88	231		1.049,90	15106522,40
Lithium -Ion (2017)	528.000	11000	1.710,81	327,00	74	66,50	393,50	72,67	91,78		48	528000	92	393		1.710,81	18412271,21
Lithium -Ion (2017)	792.000	11000	2.325,47	489,27	74	66,50	555,77	72,67	93,71		72	792000	94	556		2.325,47	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%			kWh	%	$/ MWh			

Wind &Solar & Redox Flow

Column1	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of sotrage in portfolio	Greenscore with Wind	Column2	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio&RF			
Redox Flow (2017)	11000	11000	268,89	8,19	74	66,5	74,69	72,67	75,72		1	11000	76	75		268,89	2934702,70
Redox Flow (2017)	22.000	11000	291,25	14,34	74	66,50	80,84	72,67	77,59		2	22000	78	81		291,25	4742324,68
Redox Flow (2017)	44.000	11.000	350,32	26,27	74	66,50	92,77	72,67	80,17		4	44000	80	93		350,32	7224456,42
Redox Flow (2017)	66.000	11.000	408,77	37,97	74	66,50	104,47	72,67	81,96		6	66000	82	104		408,77	8947358,44
Redox Flow (2017)	132.000	11.000	592,12	72,31	74	66,50	138,81	72,67	84,88		12	132000	85	139		592,12	11763433,09
Redox Flow (2017)	264.000	11.000	894,43	140,26	74	66,50	206,76	72,67	88,35		24	264000	88	207		894,43	15106522,40
Redox Flow (2017)	528.000	11.000	1.439,34	275,11	74	66,50	341,61	72,67	91,78		48	528000	92	342		1.439,34	18412271,21
Redox Flow (2017)	792.000	11.000	1.946,29	409,50	74	66,50	476,00	72,67	93,71		72	792000	94	476		1.946,29	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%			kWh	%	$/ MWh			

Wind &Solar & CAES

Column1	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of sotrage in portfolio	Greenscore with Wind	Column2	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio&CAES		LCOS	Electricity discharged in kWh in year t, measure for the capacity factor
CAES (2017)	11000	11000	371,34	11,31	74	66,5	77,81	72,67	75,72		1	11000	76	78		371,34	2934702,70
CAES (2017)	22.000	11000	257,34	12,67	74	66,50	79,17	72,67	77,59		2	22000	78	79		257,34	4742324,68
CAES (2017)	44.000	11.000	198,14	14,86	74	66,50	81,36	72,67	80,17		4	44000	80	81		198,14	7224456,42
CAES (2017)	66.000	11.000	179,81	16,70	74	66,50	83,20	72,67	81,96		6	66000	82	83		179,81	8947358,44
CAES (2017)	132.000	11.000	173,14	21,14	74	66,50	87,64	72,67	84,88		12	132000	85	88		173,14	11763433,09
CAES (2017)	264.000	11.000	184,76	28,97	74	66,50	95,47	72,67	88,35		24	264000	88	95		184,76	15106522,40
CAES (2017)	528.000	11.000	225,38	43,08	74	66,50	109,58	72,67	91,78		48	528000	92	110		225,38	18412271,21
CAES (2017)	792.000	11.000	268,62	56,52	74	66,50	123,02	72,67	93,71		72	792000	94	123		268,62	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%			kWh	%	$/ MWh			

Wind & Solar & PHS

	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of storage in Portfolio	LOE Wind	LCOE + Solar	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio & PHS	LCOS	Electricity discharged in kWh in year t, measure for the capacity factor	O&M Costs
PHS (2017)	11.000	11.000	294,91	8,98	74	66,50	75,48	72,67	75,72		1	11000	76	75		294,91	2934702,70
PHS (2017)	22.000	11000	193,04	9,50	74	66,50	76,00	72,67	77,59		2	22000	78	76		193,04	4742324,68
PHS (2017)	44.000	11000	137,94	10,34	74	66,50	76,84	72,67	80,17		4	44000	80	77		137,94	7224456,42
PHS (2017)	66.000	11.000	119,03	11,06	74	66,50	77,56	72,67	81,96		6	66000	82	78		119,03	8947358,44
PHS (2017)	132.000	11.000	104,68	12,78	74	66,50	79,28	72,67	84,88		12	132000	85	79		104,68	11763433,09
PHS (2017)	264.000	11.000	101,01	15,84	74	66,50	82,34	72,67	88,35		24	264000	88	82		101,01	15106522,40
PHS (2017)	528.000	11.000	111,83	21,37	74	66,50	87,87	72,67	91,78		48	528000	92	88		111,83	18412271,21
PHS (2017)	792.000	11.000	126,70	26,66	74	66,50	93,16	72,67	93,71		72	792000	94	93		126,70	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%		kWh	%	$/MWh				

Figure 50: The output of the model combined in multiple tables for 2017

Wind & Solar & Lithium Ion

*LCOSP = Levelised cost of storage in portfolio = Total cost of storage/ Total MWh in portfolio in a year used by company.
*LCOS = Levelised Cost of Storage = The total cost of storage/ Total MWh electricty stored
*LCOP = Levelised cost of Portfolio = (The cost of production + the cost of storage)/ The total MWh used by the company

Column1	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of sotrage in portfolio	Greenscore with Wind	Column2	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio&LI-Ion			
Lithium -Ion (2030)	11000	110000	96,20	2,93	74,00	66,50	69,43	72,67	75,72		1	11000	75,72	69,43		96,20	2934702,70
Lithium -Ion (2030)	22.000	110.000	104,91	5,16	74,00	66,50	71,66	72,67	77,59		2	22000	77,59	71,66		104,91	4742324,68
Lithium -Ion (2030)	44000	110000	127,87	9,59	74,00	66,50	76,09	72,67	80,17		4	44000	80,17	76,09		127,87	7224456,42
Lithium -Ion (2030)	66000	110000	150,58	13,99	74,00	66,50	80,49	72,67	81,96		6	66000	81,96	80,49		150,58	8947358,44
Lithium -Ion (2030)	132000	110000	221,81	27,09	74,00	66,50	93,59	72,67	84,88		12	132000	84,88	93,59		221,81	11763433,09
Lithium -Ion (2030)	264000	110000	339,24	53,20	74,00	66,50	119,70	72,67	88,35		24	264000	88,35	119,70		339,24	15106522,40
Lithium -Ion (2030)	528000	110000	550,92	105,30	74,00	66,50	171,80	72,67	91,78		48	528000	91,78	171,80		550,92	18412271,21
Lithium -Ion (2030)	792000	110000	747,84	157,35	74,00	66,50	223,85	72,67	93,71		48	792000	93,71	223,85		747,84	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%			kWh	%	$/ MWh			

Wind &Solar & Redox Flow

Column1	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of sotrage in portfolio	Greenscore with Wind	Column2	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio&RF			
Redox Flow (2030)	11000	110000	91,22	2,78	74,00	66,50	69,28	72,67	75,72		1	11000	75,72	69,28		91,22	2934702,70
Redox Flow (2030)	22.000	110.000	94,89	4,67	74,00	66,50	71,17	72,67	77,59		2	22000	77,59	71,17		94,89	4742324,68
Redox Flow (2030)	44000	110000	109,55	8,22	74,00	66,50	74,72	72,67	80,17		4	44000	80,17	74,72		109,55	7224456,42
Redox Flow (2030)	66000	110000	124,89	11,60	74,00	66,50	78,10	72,67	81,96		6	66000	81,96	78,10		124,89	8947358,44
Redox Flow (2030)	132000	110000	174,03	21,25	74,00	66,50	87,75	72,67	84,88		12	132000	84,88	87,75		174,03	11763433,09
Redox Flow (2030)	264000	110000	255,53	40,07	74,00	66,50	106,57	72,67	88,35		24	264000	88,35	106,57		255,53	15106522,40
Redox Flow (2030)	528000	110000	402,83	77,00	74,00	66,50	143,50	72,67	91,78		48	528000	91,78	143,50		402,83	18412271,21
Redox Flow (2030)	792000	110000	539,99	113,61	74,00	66,50	180,11	72,67	93,71		72	792000	93,71	180,11		539,99	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%			kWh	%	$/ MWh			

Wind &Solar & CAES

Column1	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of sotrage in portfolio	Greenscore with Wind	Column2	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio&CAES		LCOS	Electricity discharged in kWh in year t, measure for the capacity factor
CAES (2030)	11000	110000	272,96	8,32	74,00	66,50	74,82	72,67	75,72		1	11000	75,72	74,82		272,96	2934702,70
CAES (2030)	22.000	110.000	189,81	9,34	74,00	66,50	75,84	72,67	77,59		2	22000	77,59	75,84		189,81	4742324,68
CAES (2030)	44000	110000	147,12	11,03	74,00	66,50	77,53	72,67	80,17		4	44000	80,17	77,53		147,12	7224456,42
CAES (2030)	66000	110000	134,32	12,48	74,00	66,50	78,98	72,67	81,96		6	66000	81,96	78,98		134,32	8947358,44
CAES (2030)	132000	110000	131,35	16,04	74,00	66,50	82,54	72,67	84,88		12	132000	84,88	82,54		131,35	11763433,09
CAES (2030)	264000	110000	142,98	22,42	74,00	66,50	88,92	72,67	88,35		24	264000	88,35	88,92		142,98	15106522,40
CAES (2030)	528000	110000	178,36	34,09	74,00	66,50	100,59	72,67	91,78		48	528000	91,78	100,59		178,36	18412271,21
CAES (2030)	792000	110000	215,25	45,29	74,00	66,50	111,79	72,67	93,71		72	792000	93,71	111,79		215,25	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%			kWh	%	$/ MWh			

Wind & Solar & PHS

	Installed Energy	Installed Power	LCOS + efficicency los	LCOSP, Levelised cost of storage in Portfolio	LOE Wind	LCOE + Solar	LCOP, Levelised cost of portfolio	Greenscore before Storage	Greenscore		Hours of Storage	Installed Energy	Greenscore	LCOP, Levelised cost of portfolio & PHS	LCOS	Electricity discharged in kWh in year t, measure for the capacity factor	O&M Costs
PHS (2030)	11000	110000	298,88	9,11	74,00	66,50	75,61	72,67	75,72		1	11000	75,72	75,61		298,88	2934702,70
PHS (2030)	22.000	110.000	195,55	9,63	74,00	66,50	76,13	72,67	77,59		2	22000	77,59	76,13		195,55	4742324,68
PHS (2030)	44000	110000	139,67	10,47	74,00	66,50	76,97	72,67	80,17		4	44000	80,17	76,97		139,67	7224456,42
PHS (2030)	66000	110000	120,49	11,19	74,00	66,50	77,69	72,67	81,96		6	66000	81,96	77,69		120,49	8947358,44
PHS (2030)	132000	110000	105,93	12,94	74,00	66,50	79,44	72,67	84,88		12	132000	84,88	79,44		105,93	11763433,09
PHS (2030)	264000	110000	102,22	16,03	74,00	66,50	82,53	72,67	88,35		24	264000	88,35	82,53		102,22	15106522,40
PHS (2030)	528000	110000	113,18	21,63	74,00	66,50	88,13	72,67	91,78		48	528000	91,78	88,13		113,18	18412271,21
PHS (2030)	792000	110000	128,27	26,99	74,00	66,50	93,49	72,67	93,71		72	792000	93,71	93,49		128,27	20267886,58
	MWh	MW	$/ MWh	$/ MWh	%	%	$/MWh	%	%		kWh	%	$/ MWh				

Figure 51: The output of the model combined in multiple tables for 2030

EES Energy installation and Power installation costs

The following tables contain the EES Energy installaiton and Power installation costs. The costs indicated in bold are the reference costs used.

Energy Installation Costs

	2016			2020			2025			2030			
Column1	**best**	**worst**	**reference**	**best**	**worst**	**reference**	**best**	**worst**	**reference**	**best**	**worst**	**reference**	**unit**
Lithium- ion (NMC)	199,5	840,0	**420,0**	153,4	645,8	322,9	110,4	464,9	232,4	79,5	334,6	**167,3**	USD / kWh
Pumped Hydro	5,3	100,0	**21,0**	5,3	100,0	21,0	5,3	100,0	21,0	5,3	100,0	**21,0**	USD / kWh
CAES	2,0	84,0	**52,5**	1,8	77,0	48,1	1,7	73,1	45,7	1,7	70,7	**44,2**	USD / kWh
Flooded LA	105,0	472,5	**147,0**	86,2	388,1	120,7	67,4	303,4	94,4	52,7	237,2	**73,8**	USD / kWh
VRLA	105,0	472,5	**262,5**	86,2	388,1	215,6	67,4	303,4	168,6	52,7	237,2	**131,8**	USD / kWh
NaNiCl	315,0	488,0	**399,0**	243,2	376,8	308,0	176,0	272,7	222,9	127,4	197,3	**161,3**	USD / kWh
NaS	262,5	735,0	**367,5**	207,7	581,6	290,8	155,0	434,1	217,0	115,7	324,0	**162,0**	USD / kWh
Vanadium Flow	315,0	1050,0	**346,5**	232,0	773,4	255,2	158,3	527,7	174,2	108,0	360,1	**118,8**	USD / kWh
ZnBr Flow	525,0	1680,0	**900,0**	386,7	1237,4	662,9	263,9	844,4	452,3	180,1	576,2	**308,7**	USD / kWh
Flywheel	1500,0	6000,0	**3000,0**	1327,9	5311,8	2655,9	1140,3	4561,4	2280,7	979,3	3917,0	**1958,5**	USD / kWh
Power Installation Costs													
Vanadium flow	1050,0	1575,0	**1312,5**	851,1	1276,6	1063,8	654,5	981,8	818,2	503,4	755,1	**629,2**	USD / kW

Power Installation Costs

	2016			2020			2025			2030			
Column1	**best**	**worst**	**reference**	**best**	**worst**	**reference**	**best**	**worst**	**reference**	**best**	**worst**	**reference**	**unit**
Lithium- ion (NMC)	73,5	189,0	**105,0**	59,6	153,4	85,2	45,9	118,1	65,6	35,4	91,0	**50,6**	USD / kW
Pumped Hydro	525,0	2000,0	**840,0**	525,0	2000,0	840,0	525,0	2000,0	840,0	525,0	2000,0	**840,0**	USD / kW
CAES	400,0	1050,0	**945,0**	330,8	868,5	781,6	301,7	791,9	712,7	293,5	770,5	**693,4**	USD / kW
Flooded LA	73,5	189,0	**105,0**	59,6	153,4	85,2	45,9	118,1	65,6	35,4	91,0	**50,6**	USD / kW
VRLA	73,5	189,0	**105,0**	59,6	153,4	85,2	45,9	118,1	65,6	35,4	91,0	**50,6**	USD / kW
NaNiCl	73,5	189,0	**105,0**	59,6	153,4	85,2	45,9	118,1	65,6	35,4	91,0	**50,6**	USD / kW
NaS	73,5	189,0	**105,0**	59,6	153,4	85,2	45,9	118,1	65,6	35,4	91,0	**50,6**	USD / kW
Vanadium Flow	73,5	189,0	**105,0**	59,6	153,4	85,2	45,9	118,1	65,6	35,4	91,0	**50,6**	USD / kW
ZnBr Flow	73,5	189,0	**105,0**	59,6	153,4	85,2	45,9	118,1	65,6	35,4	91,0	**50,6**	USD / kW
Flywheel	315,0	1050,0	**300,0**	278,9	929,6	265,6	239,5	798,2	228,1	205,6	685,5	**195,9**	USD / kW

Energy Storage Efficiency

The following contain the efficiency of storage technology. First the energy round trip efficiency is shown, secondly the power conversion unit round trip efficiency and lastly the combined efficiency as storage round trip efficiency. The reference efficiency has been used.

$$\begin{aligned} &Storage\ round\ trip\ efficiency \\ &= Energy\ storage\ unit\ round\ trip\ efficiency \\ &* Power\ conversion\ unit\ round\ trip\ efficiency \end{aligned}$$

Energy storage Unit Round trip efficiency

	2016		
Column1	**best**	**worst**	**reference**
Lithium- ion (NMC)	98,0	81,0	**95,0**
Pumped Hydro	84,0	70,0	**80,0**
CAES	75,0	40,0	**60,0**
Flooded LA	92,0	75,0	**82,0**
VRLA	92,0	75,0	**80,0**
NaNiCl	92,0	80,0	**84,0**
NaS	90,0	70,0	**80,0**
Vanadium Flow	85,0	60,0	**70,0**
ZnBr Flow	85,0	60,0	**70,0**
Flywheel	99,0	70,0	**84,0**

Power conversion Unit Round trip efficiency

	2016		
Column1	**best**	**worst**	**reference**
Lithium- ion (NMC)	98,0	98,0	**98,0**
Pumped Hydro	100,0	100,0	**100,0**
CAES	100,0	100,0	**100,0**
Flooded LA	98,0	98,0	**98,0**
VRLA	98,0	98,0	**98,0**
NaNiCl	98,0	98,0	**98,0**
NaS	98,0	98,0	**98,0**
Vanadium Flow	98,0	98,0	**98,0**
ZnBr Flow	98,0	98,0	**98,0**
Flywheel	100,0	100,0	**100,0**

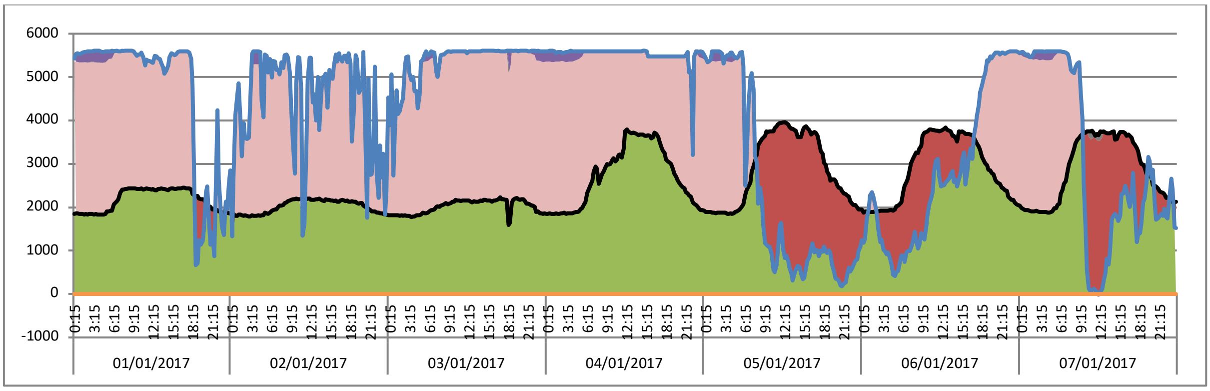
Storage Round trip efficiency

	2016		
Column1	**best**	**worst**	**reference**
Lithium- ion (NMC)	96,0	79,4	**93,1**
Pumped Hydro	84,0	70,0	**80,0**
CAES	75,0	40,0	**60,0**
Flooded LA	90,2	73,5	**80,4**
VRLA	90,2	73,5	**78,4**
NaNiCl	90,2	78,4	**82,3**
NaS	88,2	68,6	**78,4**
Vanadium Flow	83,3	58,8	**68,6**
ZnBr Flow	83,3	58,8	**68,6**
Flywheel	99,0	70,0	**84,0**

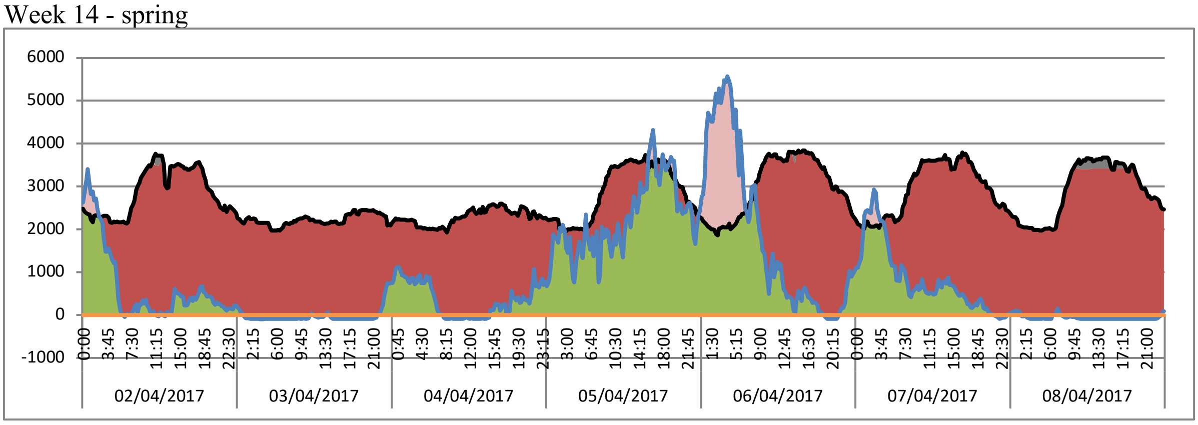
(International Renewable Energy Agency, 2017)

Appendix F - Model output

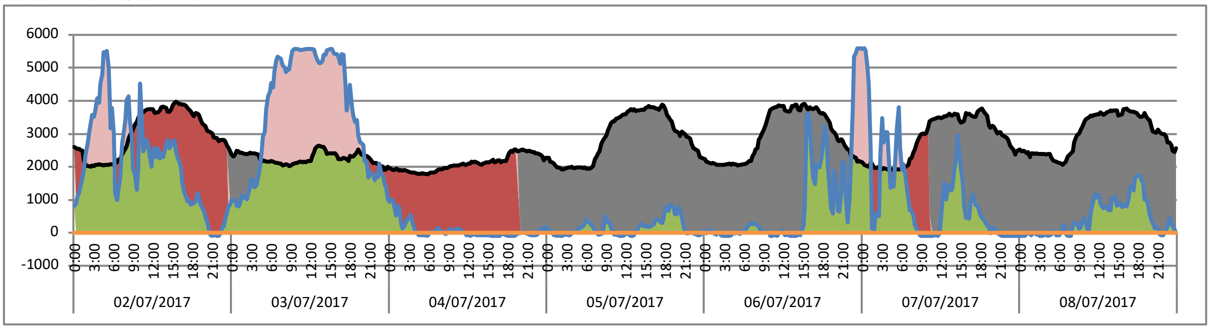
Week 1 – winter



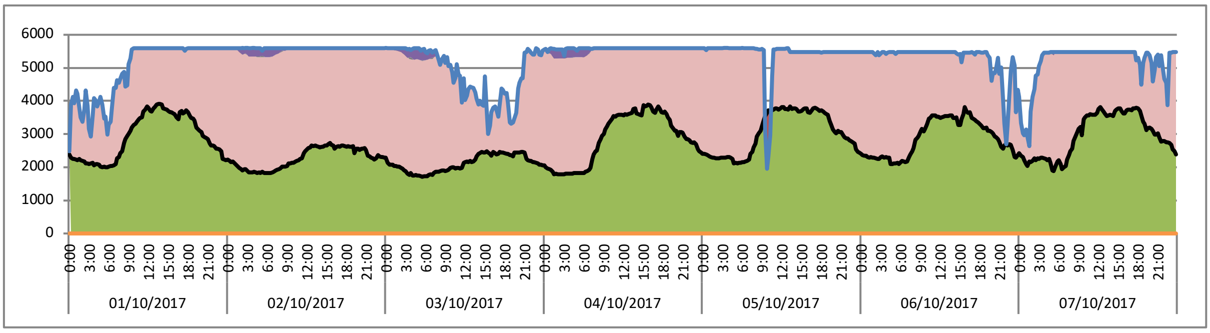
Week 14 - spring



Week 27 - Summer



Week 40 - Autumn



Green score possible per specific LCOP increase

The following green scores can be achieved for the LCOP increase percentages as stated in the results chapter.

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Table 11: The spcific green score possible for specific LCOP increases

LCOP Increase		PHS		CAES		Redox Flow		Lithium-ion	
		2017	**2030**	**2017**	**2030**	**2017**	**2030**	**2017**	**2030**
+/- 10%	80$/MWh	86%	86%	79%	83%	77%	83%	77%	82%
+/- 25%	90 $/MWh	92%	92%	86%	89%	79%	85%	79%	84%
+/- 35%	100 $/MWh	93+%	93+%	89%	92%	81%	87%	81%	86%

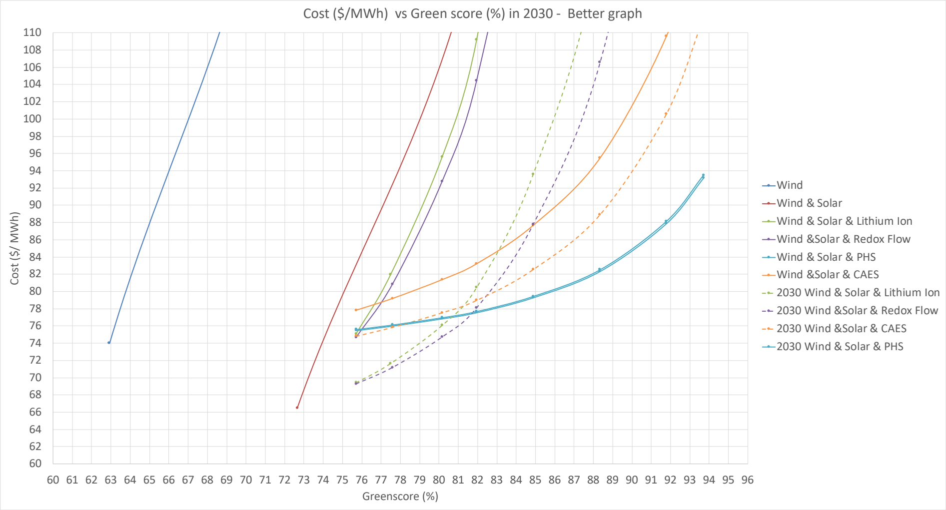

Figure 52: A further detailed graph used for the previous table