Green hydrogen for residential heating and agricultural mobility in rural areas

J.A.M van der Weijden

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GREEN HYDROGEN FOR RESIDENTIAL HEATING AND AGRICULTURAL MOBILITY IN RURAL AREAS

- Socio-technical analysis of a hydrogen based energy system in Oudeschip -

by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday August 25, 2020 at 15:00 AM.

Student number:	4738608	
Project duration:	December 1, 2019 – June 10, 2020	
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Preface

This is it, the capstone of my study time which started in Groningen and ended in Delft. I graduated during Covid-19, which proved to give me some personal challenges, but we got through it! I would like to thank a few people, who made this all possible.

First of all, there are a few people who helped me a lot professionally. I would like to start with Zofia. You were capable of giving me guidance when I did not think that I needed it. This was not only regarding my thesis, but also with other stuff I was dealing with. You helped me to gain a zoomed out perspective of problems almost every time we met. Ad, thank you for providing me with this project. I could not have chosen something that suited my interest more. Furthermore, you provided me with the connections to gain insight in the workings of such a hydrogen project, in combination with the freedom to contact these people by myself. Martijn, thank you for the personal touch. In the beginning you mentioned that I had enough people surrounding me to comment on the content of what I was doing, you were 'merely' there to get me through this whole graduation phase. Thank you for giving me the feeling that there was someone watching my back. Theo, we did not meet as often since I had the possibility to meet with Els to talk about the PtX model, but your extensive feedback helped me a lot and I enjoyed the few relaxed talks that we had one-to-one. Last but not least, Els. I am so thankful for the time that you put into helping me out, even when you might not have had that time at all. I don't think you realize how stuck I was at some times, when you effortlessly helped me gain traction again. Thank you for letting me work with/on your model.

There were also some people there to guide me through this process from a personal perspective. Mom, you gave me someone to talk to, let me vent my irritations if something was not working, giving me a PEP talk. Dad, your interest in what I am doing is limitless. Whenever you read or hear about something related to what I am doing, you call me or send it to me. You even went to Hamburg with me to visit a hydrogen conference. If you are reading this, just know that my parents are awesome. Goof, my little brother. Without you, this whole thesis report would not be possible, since my laptop broke down, and I used yours to do my research and write my entire thesis. I am taking you out for dinner to repay you. Isabelle, you gave me distraction and a balcony to relax on, which was extremely valuable during coronatimes! Of course, I also need to thank you for reviewing parts of my thesis. Daan, I think we helped each other through the hardest part of Covid-19 with games and insightfull, high level, conversations. I am glad that I did not move back to my parents, but stayed with you at the Henegouwerlaan.

Lastly, all my other friends whom I met throughout my study time. It was the best of times, it was the worst of times. A lot of you helped me through this process with reversed psychology to motivate me to finish: 'You are never going to stop studying, right?'

J.A.M. van der Weijden
Woerden, August 2020

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Executive Summary

The government of the Netherlands is picking up the pace in the energy transition, of which the Climate Agreement is the embodiment. However, the increased installation of wind parks is facing congestion challenges, the increase of wind generation is resulting in an increase of curtailment. Next to that, it is not always possible to electrify residential heat demand and the same goes for heavy duty vehicles. Furthermore, the seasonality in consumption of agricultural mobility and household heat demand increases the burden on energy storage. These are the barriers which occur together in the energy transition in rural areas of the Netherlands. Solutions to these issues are not only dependent on existing and innovative technology, but also on the existing infrastructure, distribution channels, as well as interests of local parties and human behaviour.

Oudeschip is such a rural village with approximately 180 homes next to the Eemshaven in the province of Groningen, in which the issues described above come together in a small isolated setting. Of these households, some are crop growing farms with tractors driving on diesel. All of the homes are connected to the electricity and natural gas grid and the houses are heated using a natural gas boiler. To facilitate the energy transition and increase the share of renewables in the energy mix, a new wind-park is built at 650 meters from the village. The park consists of 21 turbines. Furthermore, since Oudeschip is on top of the gas field of Slochteren, the houses are sinking and cracking due to the natural gas extraction. Since these residents face a direct consequence of the extraction of natural gas, they are eager to replace their fossil fuel consumption with a renewable alternative, preferably by making use of the locally generated wind-power. To ensure the sustainability of modern societies, hydrogen has emerged as a promising energy carrier to balance out the intermittency of renewable energy sources, especially since its capability of seasonal energy storage. Since Oudeschip embodies the problems occurring in the energy transition in rural areas, it is used as a case study. To structure the research, the following research question is used:

How can the agricultural mobility and residential heat demand of Oudeschip be fulfilled by wind generation with a combination of electricity and hydrogen as energy carriers?

A literature research points out that an integrated approach, to investigate synergies between sectors in rural areas, is missing. The research combines different sources of (renewable) energy to supply heat and power to households, but it is unclear how the single use of wind power can be combined with residential heat demand and the demand of agricultural mobility in rural areas like Oudeschip, by making use of both electricity and hydrogen as energy carriers. This research proposes to view these problems together as a complex socio-technical environment, and solve them with an integrated approach.

Desk research points out that the main option for Oudeschip is to utilize hydrogen as an energy carrier, next to electricity. The homes in and around Oudeschip can use a hydrogen boiler for heating, the farmers can convert their diesel tractors to hydrogen-diesel hybrids, and the electricity from the wind turbines which would otherwise be curtailed, can be used to produce hydrogen. The main components of the future energy system of Oudeschip are: two wind turbines, an electrolyser, hydrogen boilers, a hydrogen fueling station with two dispensers at 350 bar and 700 bar, one or two tube trailers, hydrogen-diesel hybrid tractors and a natural gas grid which is converted to transport hydrogen.

The household heating demand has a seasonal pattern with its maximum in the winter and a minimum in summer. There is a continuous demand for tap water over the entire year. For the agricultural mobility

demand, there are two peaks during the sowing and harvesting times in spring and autumn. Over summer the demand is relatively stable and in winter there is no demand at all.

The investment costs, levelized costs of hydrogen and payback time greatly depend on the capacity of the electrolyser. In order to find an appropriate capacity for this component, the wind generation and demand for household heating and agricultural mobility needs to be simulated for an entire year. To do this, the PtX model is altered and used. The PtX model was developed for a neighbourhood where locally produced renewable energy is partly converted and stored in the form of heat and hydrogen. Next to that, rain water is collected, stored, purified and used in this model. This simulation model creates an energy balance and presents the associated costs. A design of experiments, with varying sizes of the electrolyser and hydrogen storage, allows the comparison of different energy system configurations.

The simulations show that a 2 MWelectrolyser is large enough to cover the local hydrogen demand and shaves a significant volume of wind generation, especially during peak generation. A 2 MW Alkaline electrolyser reduces congestion on the electricity grid and, together with two tube trailers, results in a Levelized Cost of Hydrogen (LCOH) of 2,19 €/kg. The choice of two tube trailers makes sure that there is significant buffer for windless periods during the year, and allows for a single tube trailer to be driven away when it is full, while the other remains as a buffer.

A stakeholder analysis shows the interest in and power over the continuation of the project, the most important stakeholders are: Enexis, the Theo Pouw Group, the Energie Cooperatie Oudeschip, H2Oudeschip, the local farmers and the province of Groningen. The province of Groningen should be involved and kept satisfied, while Enexis, the Theo Pouw Groep, the Energie Cooperatie Oudeschip, H2Oudeschip and local farmers should collaborate and be managed closely in order for the proposed future energy system of Oudeschip to emerge.

This research shows that an integrated approach to tackle problems in the decarbonization of rural areas allows the resolve of problems which would occur when a single sector would be investigated. Looking at the energy system of the specific context in Oudeschip shows that by combining the peaks in house-hold heat demand and agricultural mobility, a smoother demand curve over the entire year is obtained.Furthermore, peak wind generation which might be curtailed under normal circumstances, can still be generated, which relieves the burden on the electricity grid.

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Acronyms

AC Alternating Current. 14–16

CAPEX Capital Expenditure. 5, 59, 60
COP Coefficient of Performance. 13

DC Direct Current. 14, 16, 39

FCEV Fuel Cell Electric Vehicle. 8, 13, 17, 18, 23, 24, 31, 40, 46, 55, 58, 59

HHV Higher Heating Value. 13, 15, 16, 28, 30, 31

LCOH Levelized Cost of Hydrogen. 30, 32, 33, 38–40, 43, 44, 46, 48, 52, 53, 56, 60
LHV Lower Heating Value. 15, 16

OPEX Operational Expenditure. 5, 59

PEM Polymer Electrolyte Membrane. 15, 38, 50–53
PtX Power-to-X. 6, 7, 32, 35–38, 56, 57, 62

RES Renewable Energy Sources. 8, 9

TCoS Total Cost of Stakeholder. 38

Chapter 1

Introduction

Climate change is increasingly important in public discourse. In 2015, 197 countries signed the Paris Agreement, which states that these countries aim to hold the increase in global average temperature to well below 2 degrees Celsius compared to pre-industrial levels (United Nations / Framework Convention on Climate Change, 2015). The Netherlands have been slow in reducing the emissions of greenhouse gasses. However, the national government aims to correct that situation with the climate agreement, which goal is to reduce greenhouse gas emissions by 49% in 2030 versus 1990 through a large-scale transformation of the built environment, mobility, industry, agriculture & land use and electricity sector (Government of The Netherlands, 2019). The next paragraphs will zoom in to the reduction of emissions in electricity generation, heating in the built environment, and agricultural mobility.

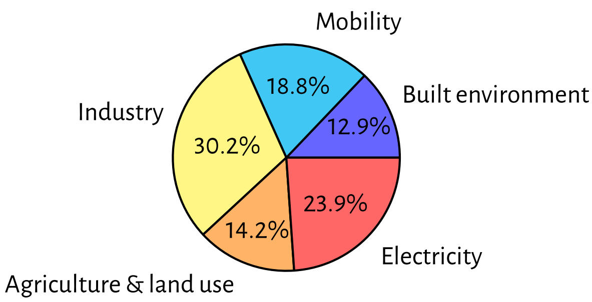


Figure 1.1: Greenhouse gas emissions of the Netherlands in 2018 by source (CBS, 2019)

1.1 Problem statement

Each of the sectors described before have their own issues with the transition to an emission free future. This section elaborates on specific issues in the decarbonization of the built environment, electricity and agricultural sector, namely the expansion of wind generation, residential heating and agricultural mobility, since these three topics come together in the rural areas of the Netherlands.

Expansion of wind generation

The electricity sector of the Netherlands has seen a large upsurge of renewable electricity over the past. Currently, the share of renewable electricity is 18% (CBS, 2020b). The goal is to have 70% of the electricity from renewable sources by 2030 (Government of The Netherlands, 2019). However, the growth of onshore wind has been declining for two reasons. Firstly, the capacity limits of the electricity grid, which is not ready for a growing decentralized energy system with intermittent resources. Currently, the capacity of the electricity grid can not grow as fast as wind- and solar parks are built (Middel, 2019). Secondly, a shift in the societal attitude of local communities in rural areas, where the wind turbines are being installed close to households (Evers, Nabielek & Tennekes, 2019). The residents are not favourable towards these wind turbines and are fighting the building permits of new parks.

Residential heating

The biggest CO_2 emissions by energy source in the Netherlands are from natural gas, namely 43% (IEA, 2018). Of this natural gas use, 34,5% can be contributed to residential consumption (IEA, 2019b). However, the national gas extraction in Groningen is planned to stop in 2022 (NOS, 2019), and by 2050, all homes should be heated by some other means than natural gas (Reijnen, 2019).

Phasing out natural gas in the residential sector is facing challenges since virtually all of the 7 million homes and 1 million buildings in the Netherlands are heated by burning natural gas. These homes and buildings are planned to be better insulated, heated using renewable energies and in which clean electricity is used (and generated). Depending on the characteristics of a district, the optimal solution to achieve this differs (Government of The Netherlands, 2019). The main solutions are a local heat network, electrical heating with heat pumps, solar water heating or burning green gas. For each district, a meticulous process will have to be completed to determine the best solution, if houses can no longer be heated with traditional central-heating boilers on natural gas.

There are many factors influencing the applicability of different solutions like: density of the population, presence of high-rise buildings, age of the buildings, presence of a reusable gas grid, wishes of the residents, etc. In a densely developed area with many high-rise buildings or homes built before 1995, district heating might be the most suitable solution. If the area contains new homes, then all-electric solutions may be better. In the Netherlands, homes installed after 1992 are generally well isolated and can easily transition to heat pumps. For districts where the natural gas network will remain in place beyond 2030, green gas or hydrogen can be an option (Government of The Netherlands, 2019). The choice of heating solution impacts the capital- and operational costs greatly.

Agricultural mobility

The agricultural sector in the Netherlands is under pressure to decarbonize. Most of the emissions in the agricultural sector is methane from livestock farming, followed by CO_2 from burning fossil fuels and nitrogen for fertilization, as shown in figure 1.2. The largest greenhouse gas emissions in this sector is from CH_4, which comes from cattle breeding. As will be discussed later, the considered case in this research is situated in a rural area of the Netherlands, which consists mainly of crop growing farms instead of cattle breeding farms. Therefore, their main emissions are N_2O, which originates from the fertilization, and CO_2, which mainly originates from the agricultural mobility. The CO_2 is emitted when burning fossil fuels. This is either natural gas to heat greenhouses, or diesel to power heavy machinery like tractors. Agricultural mobility with its heavy machinery and high intensity of use, has little options to decarbonize. The considerations are discussed in section 3.4.4.

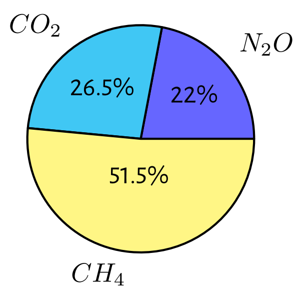


Figure 1.2: Emissions in agriculture in CO_2 equivalents (Moerkerken & Smit, 2016)

1.2 Introduction to the village of Oudeschip

The reason why the last section zoomed in to the expansion of wind generation, residential heating and agricultural mobility is the village of Oudeschip. Oudeschip is a rural village with approximately 180 homes next to the Eemshaven in the province of Groningen, in which the issues described above come together in a small isolated setting. Of these households, some are crop growing farms with tractors driving on diesel. All of the homes are connected to the electricity and natural gas grid and the houses are heated using a natural gas boiler.

To facilitate the energy transition and increase the share of renewables in the energy mix, a new wind-park is built at 650 meters from the village. The park consists of 21 turbines, the installed capacity will sum up to approximately 100 MW (Topwind, n.d.). To compensate the 180 households within a 1,5 kilometer radius around the wind turbines in the Eemshaven for their loss of view, the local residents came to an agreement with the developers of the wind park that they are to receive 10% of the revenues from the wind park.

Furthermore, since Oudeschip is on top of the gas field of Slochteren, the houses are sinking and cracking due to the extraction of natural gas. Because these residents face a direct consequence of the extraction of natural gas, they are eager to replace their fossil fuel use with a renewable alternative, preferably by making use of the locally generated wind-power. The system considered in this study is a grid-connected microgrid with wind generation and already existing infrastructure in a village in a rural area of the Netherlands. The contextual information of Oudeschip will be elaborated on in section 3.1.

As will be further explained in section 3.2, hydrogen is proposed as an energy carrier to transition Oudeschip to a renewable energy system. To ensure the sustainability of modern societies, hydrogen is seen as a promising energy carrier to balance out the intermittency of renewable energy sources, especially since its capability of seasonal energy storage. A new hydrogen economy paradigm, based on hydrogen as energy carrier, has emerged: the hydrogen economy (da Silva Veras, Mozer, da Costa Rubim Messeder dos Santos & da Silva César, 2017). The Northern Netherlands are the first region to receive a subsidy for the so-called Hydrogen Valley. This is a subsidy, approved by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) of the European commission, of 20 million euros with a public-private co-financing of 70 million euros (FuelCellsWorks, 2019). The intention of the Hydrogen Valley is a fully functioning green hydrogen chain in the Northern Netherlands. Furthermore, Gasunie Transport Services (GTS) is developing a hydrogen backbone in the Netherlands, especially in the northern Netherlands, which will have a capacity ranging from 10 to 15 GW which can be available from 2026 (GTS, 2020). The outline of this backbone is shown in figure 1.3 and figure 1.4. The part in the northern Netherlands might be available as of 2023.

Figure 1.3: HyWay 27 hydrogen backbone in the Netherlands (The Dutch Ministry of Economic Affairs and Climate Policy, 2020)

Figure 1.4: Hydrogen backbone in Groningen (GTS, 2020)

Figure 1.4 shows that the backbone in Groningen starts in the Eemshaven, and consists of large scale storage in a salt cavern in Zuidwending. Groningen Seaports is the port authority for the port of Delfzijl, Eemshaven and the adjoining industrial sites. A large part of the Eemshaven has been earmarked for the development of energy-related industry with large energy providers such as ENGIE, NorNed, Vattenfall, Tennet, and RWE/Essent. Recently, Groningen Seaports, Shell Nederland and Gasunie announced Europe's largest green hydrogen project (Groningen Seaports, 2020), and Groningen Seaports announced that it will build a 4km long hydrogen pipeline from Delfzijl to the Eemshaven (Groningen Seaports, 2018). Hydrogen is a hot topic in the area, which is why the inhabitants of Oudeschip are considering hydrogen as an energy carrier, and two inhabitants founded H2Oudeschip in order to facilitate the synergy between electricity and hydrogen for the local residents. This will be discussed further in section 3.1.

The problems in Oudeschip are complex, which requires problem solving from multiple dimensions. By looking at these issues in an integrated manner, a more favourable solution might occur than by solving the mentioned issues separately. This research is performed to advise the stakeholders involved in the wind generation, household heating and agricultural mobility in and around Oudeschip on a course of action in the energy transition. The next section touches upon current literature about the integrated approach in solving energy transition issues like those described above.

1.3 Integrated energy system

The load and generation have to be balanced at all times, which means that future power systems need to be able to cope with the increased variability in both supply and demand. There are several ways to do this, including flexible generation (backup dispatchable power plants), demand response, energy storage, and increased interconnection. Integrated designs, combining several sectors, have the potential to balance out the intermittency problems. Various studies have been conducted on the socio-technical design and economics of integrated energy systems like the research by Farahani et al.(2019) and Park Lee, Chappin, Lukszo and Herder(2015).

Several cases show how synergies between hydrogen and electricity networks can solve the problem of congestion in the power network and fast variation in the generation profile, without curtailment in the RES generation (Alavi, Park Lee, van de Wouw, De Schutter & Lukszo, 2017). On a system level, hydrogen is cheaper for the transport and storage of energy. When comparing the BBL pipeline and BritNed electricity cable between the Netherlands and Britain, both constructions cost 500 million euros, but the capacity of the electricity cable is 1 GW, while the pipeline has a capacity of 15 GW. Per year, the electricity cable can transport 8 TWh, while the gas pipeline can transport 120 TWh (van Wijk, 2020). The utilization of the natural gas grid for the transport of hydrogen can significantly reduce the investment in the expansion of the electricity grid. Furthermore, the storage of gas is favourable over storage of electricity in batteries over longer periods of time, while batteries are favourable for short term energy storage. McPherson, Johnson and Strubegger show that hydrogen storage costs are around 830 $/kW while the cost of lithium-ion batteries range from 1200 to 4000 $/kW.

Since the energy transition around Oudeschip is considered a socio-technical system, an integrated approach, as described by Alavi et al.; Farahani et al.; Park Lee et al. (2017; 2019; 2015), to investigate synergies between both the social fields of studies as well as the technical domain, is needed to analyse the energy system of Oudeschip.

1.4 Research Questions

The solutions for the energy transition in rural areas differ per region, since it is not only dependent on existing and innovative technology, but also on the existing infrastructure, geology, distribution channels, as well as interests of local parties and human behaviour. Therefore, it is key that the case of Oudeschip is analysed as a complex socio-technical environment. The master Complex Systems Engineering and Management explores innovations in complex socio-technical environments. As a multi-disciplinary scholar in the energy domain, I am educated to identify dilemmas arising during the design process and can structure this complex problem from a multi-actor and socio-technical systems perspective.

Each of the options to decarbonize the energy system results in a different way of dealing with the gap between supply and demand of energy. The components in each of these systems differ in technical and economic properties, as well as the implications for stakeholders. A techno-economic assessment, as well as a stakeholder analysis, shed light on each of these aspects and are to be combined in order to perform a comprehensive analysis of a future energy system of Oudeschip. There needs to be an understanding of the different technological options for using the electricity of the wind turbines, as well as the different options for heating these rural residential buildings, and the decarbonization of agricultural mobility. Lastly, the involved companies and local residents need to all agree on a certain proposed design for the district before it can be implemented. These subjects show a variety of disciplines working together in a sociotechnical landscape in order to research the connection between wind-power generation and the demand for agricultural mobility and residential heating.

The research question in this thesis is as follows:

How can the agricultural mobility and residential heat demand of Oudeschip be fulfilled by wind generation with a combination of electricity and hydrogen as energy carriers?

This main research question is structured by division into the following sub-questions:

1. What would a decarbonized energy system in Oudeschip look like?
2. What are the major components in the new energy system of Oudeschip, their technical and economic parameters, and reasonable sizes for those components?
3. What is the energy profile of Oudeschip including generation and demand?
4. Which stakeholders are involved in the new energy system of Oudeschip and what are their incentives?
5. What are the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for stakeholders in the new energy system?

The main research question is the dot on the horizon for this research, which is reached by answering the sub-questions. The manner in which this research is approached is elaborated in the next section.

1.5 Research approach

The objective of this research is to provide H2Oudeschip with insights into the required components for a new energy system in Oudeschip with hydrogen as energy carriers, and the required capacity of these components. Furthermore, the research will provide insight into the consequences for involved stakeholders.

This research will have the form of an exploratory research with a modelling approach, to compare options for using wind power to fulfil mobility and heat demand. As is depicted in figure 1.5, the research starts with a more extensive literature review about integrated energy systems. After that, expert interviews in combination with literature research is performed to create a new energy system for Oudeschip with hydrogen and electricity as energy carriers, and form the supply and demand profile for this energy system. Next to these technical aspects, a stakeholder analysis gives an overview of the stakeholder landscape.

When the system components and energy profile of the future energy system of Oudeschip is known, the method of analysis is through simulations, since simulations can provide insight into the possible operation of such a system, without real-life consequences, within an acceptable time frame (Holtz, 2011). A quantitative modelling approach is appropriate, since the quantitative analysis of the gap between the wind generation, agricultural mobility and residential heat demand determines the capacity of the components in the system like the storage facilities. In turn, the capacity of these storage facilities influences the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) of the new energy system. Several simulations are run according to a 'Design of Experiments', which are described in section 5.6.

The village of Oudeschip is used as a case study in the model, but the approach is replicable for the analysis of other energy systems with hydrogen as energy carriers in rural areas. The simulations will result in an energy balance and allows the costs of different configurations of the new energy system to be compared.

The tool used for these simulations is an existing simulation model called Power-to-X (PtX), which is altered for this specific situation. The PtX model was developed for a neighbourhood where locally produced renewable energy is partly converted and stored in the form of heat and hydrogen. Next to that, rain water is collected, stored, purified and used in this model. This simulation model creates an energy balance and delivers the associated costs. This model and the alterations are further described in chapter 5. The research flow diagram of this thesis is shown in Figure 1.5

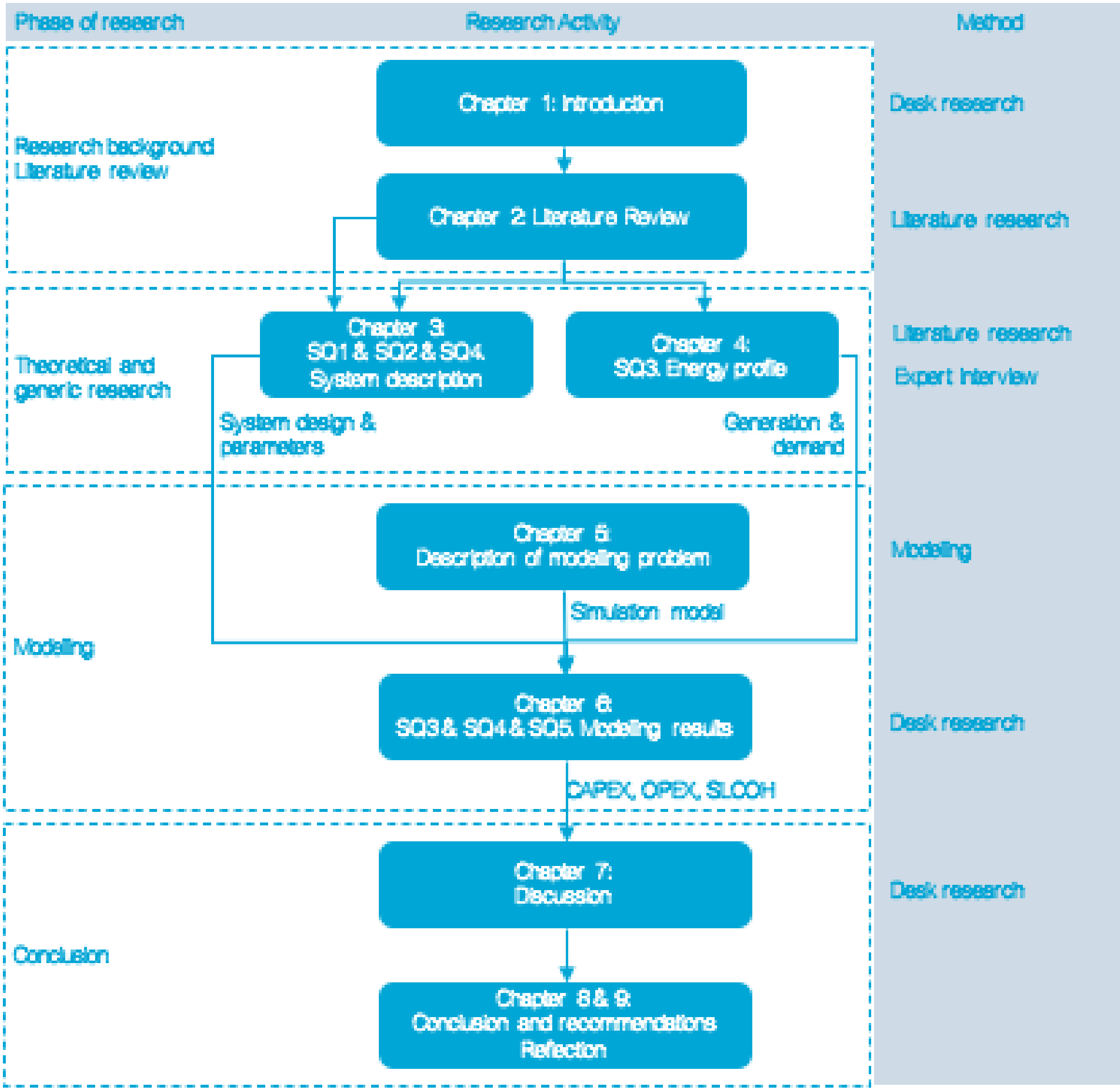


Figure 1.5: Research flow diagram

1.6 Report outline

As shown in Figure 1.5, the next chapter provides a literature review about integrated energy systems. After that, chapter 3 describes the context information about the Oudeschip case which form the requirements for the new energy system. After that, the new energy system and the technical and economic parameters of the system components are described. The chapter finishes with a stakeholder analysis. Chapter 4 elaborates on the supply pattern of wind generation, as well as the demand pattern of household heating and mobility. The technical and economic parameters discussed in 3 in combination with the supply and demand patterns described in section 4 form the input for the simulation model. Chapter 5 elaborates on the PtX simulation model, after which the simulation results are presented in Chapter 6. This thesis report ends with the discussion and conclusion in Chapter 7 and 8 respectively.

Chapter 2

Literature about Integrated Energy Systems

As mentioned in section 1.3, an integrated approach helps to solve the barriers in the energy transition of Oudeschip, since it is considered a socio-technical system. This integrated approach includes both the social and technical aspects of the energy system, as well as different sectors, as demonstrated by Alavi et al.(2017), Farahani et al.(2019) and Park Lee et al.(2015). This chapter provides insight into current literature around this topic. The literature is reviewed to find overlap with the Oudeschip case, with a focus of integrating renewable energy supply with energy demand from residential heating and agricultural mobility, in combination with electricity and hydrogen as energy carriers.

Alavi et al.(2017), Farahani et al.(2019) and Park Lee et al.(2015) demonstrate an integrated approach to solve issues in socio-technical environments, but the energy systems considered look into the Car as a Power Plant concept, where hydrogen is used as a supplement to the electricity system. The focus in these papers lies with the Fuel Cell Electric Vehicle (FCEV) car, not with the fulfillment of energy demand in rural areas by combining different sectors.

Jones and Powell (2015) and Khalid, Aydin, Dincer and Rosen (2016) investigate the integration of Renewable Energy Sources (RES) in an energy system including the storage of electricity, heat and/or hydrogen. The supply side is investigated, but heat demand and/or mobility is not incorporated. Other research by Heinen and O'Malley (2015), Kontu, Rinne, Olkkonen, Lahdelma and Salminen (2015), Sichilalu, Tazvinga and Xia (2016) and Wang et al. (2019) consider renewable heating options on the consumption side, but rely on either natural gas or the electricity grid to supply this energy.

Furthermore, Alahäivälä, Ekström, Jokisalo and Lehtonen (2017) and Xydis and Mihet-Popa (2017) utilize wind-power to fulfill residential heat and power demand, as is the objective in Oudeschip. However, they only consider the use of surplus wind and use this as ramping power.

Li, Fang, Zeng and Chen (2016) and McKenna, Merkel and Fichtner (2017) completely fulfill residential heating demand solely with RES. However, since this research is performed for urban areas, the heat is supplied by combined heat and power, which is not an option for rural areas.

Franco and Fantozzi (2016) and Milan, Bojesen and Nielsen (2012) also focus on the fulfilment of residential heating demand with renewable electricity, but their research is scaled on a single building. McKenna et al. (2017) mention that self-sufficiency at a single building scale is not viable from an economic perspective. However, when combining several buildings into a self-sufficient neighbourhood or district, the associated marginal cost become lower. This is mainly due to the shared investment in storage capacity, a proportionally large specific investment which is crucial for self-sufficiency.

Research by Sorgulu and Dincer (2018) shows that the heating, cooling and electricity demands of a 100 household neighbourhood can be fulfilled by a combination of wind turbines, solar collectors and by making use of hydrogen storage. However, only the technical applicability is researched, there is no economic analysis and comparison to other renewable systems. Similarly, Hughes (2010) research the use of RES by implementing resistance heating in combination with electric thermal storage. There is no comparison made to other types of heating systems.

Hacatoglu, Dincer and Rosen (2016) compare a traditional gas-turbine plant with regeneration, district heating and a refrigeration cycle to a wind-hydrogen system with an air-source heat pump. These are not compared from a pure cost perspective, but from a sustainability perspective, which has an economic factor incorporated. The results show that a traditional gas system performs slightly better than a hydrogen system when using a sustainability assessment. It can be argued that this is mainly because costs are already taken into account, which is obvious since the gas-system pollutes more than the hydrogen system. The weighing of the sustainability-indicators is crucial for the outcomes. For instance, with a high CO_2 price the natural gas system would become more expensive.

The research mentioned above combine different sources of (renewable) energy to supply heat and power to households, but it is unclear how the single use of wind power can be combined with residential heat demand and the demand of agricultural mobility in rural areas, by making use of both electricity and hydrogen as energy carriers. Furthermore, the social aspect of these energy systems is not considered.

The next chapter will describe both the technical, as well as the social components of the future energy system of Oudeschip, to get to the integrated approach described in this chapter.

Chapter 3

Description of New Energy System in Oudeschip

This chapter begins by giving an overview of the Oudeschip case, which shape the requirements of the new energy system of Oudeschip in section 3.2. Section 3.3 shows the new energy system of Oudeschip with a combination of hydrogen and electricity as energy carriers, section 3.4 describes each of the components of the new energy system. Lastly, section 3.5 sheds light on the social aspect of the energy transition around Oudeschip by outlining the key stakeholders in the proposed energy system, and presents a stakeholder analysis.

3.1 Context of situation in Oudeschip

As mentioned in Chapter 1, Oudeschip is a rural village in the north of the Netherlands, next to the Eemshaven seaport. There are currently approximately 90 wind turbines installed around the Eemshaven, another 60 are planned to be built. Some of the new turbines are to replace older models, others are part of the planned expansion of the wind park. The currently installed wind turbines are shown in figure 3.1, together with the plans for the expansion of the wind parks.

The expansion of the wind park contributes to the goal of the Province of Groningen to have 855 MW of installed wind generation in 2020. Figure 3.2 shows the new turbines as blue and red dots, while all the houses within 1,5km from each of the turbines are shown as a yellow dot. The expansion of the Eemshaven wind generation has an effect on the local residents including a loss of view, shadow flicker, and a depreciation of the buildings. Therefore, the Energie Cooperatie Oudeschip is founded, in which the local residents of Oudeschip, Eemshaven, Nieuwstad, Vierhuizen, Polen, Nooitgedacht, Koningsoord, Heuvelderij and Valom can join to receive compensation for the negative impact on their livelihood. There is an agreement between the developers of the wind park, Waddenwind B.V. and Innogy, and the Energie Cooperatie Oudeschip, which states that the Energie Cooperatie Oudeschip will receive 10% of the revenues from the new Oostpolder wind park. The Oostpolder wind park is shown as a yellow plane in figure 3.1, the new wind turbines of this park are presented as blue dots in figure 3.2.

Figure 3.1: Wind parks around the Eemshaven (Provincie Groningen, 2017)

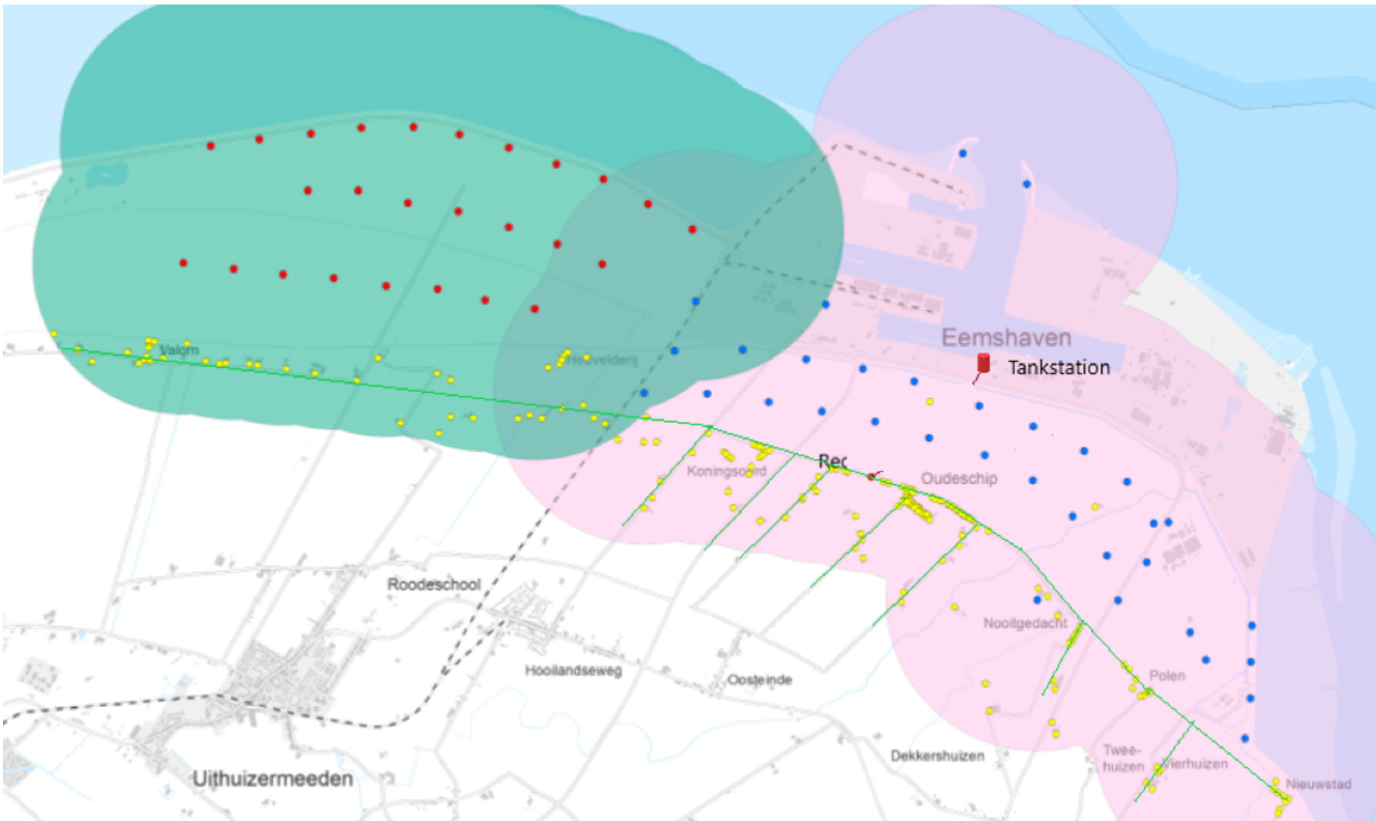


Figure 3.2: New turbines at the Eemshaven and affected households

Next to the expansion of the wind generation in the province of Groningen, the extraction is of natural gas from the Slochteren gas field is decreasing. This decline is the direct result of the increase of the number and intensity of earthquakes in the area. Figure 3.3 shows the ground acceleration for the area above the gas field of Slochteren. The area around the Eemshaven is in yellow, which means that the number and intensity of earthquakes is relatively low.

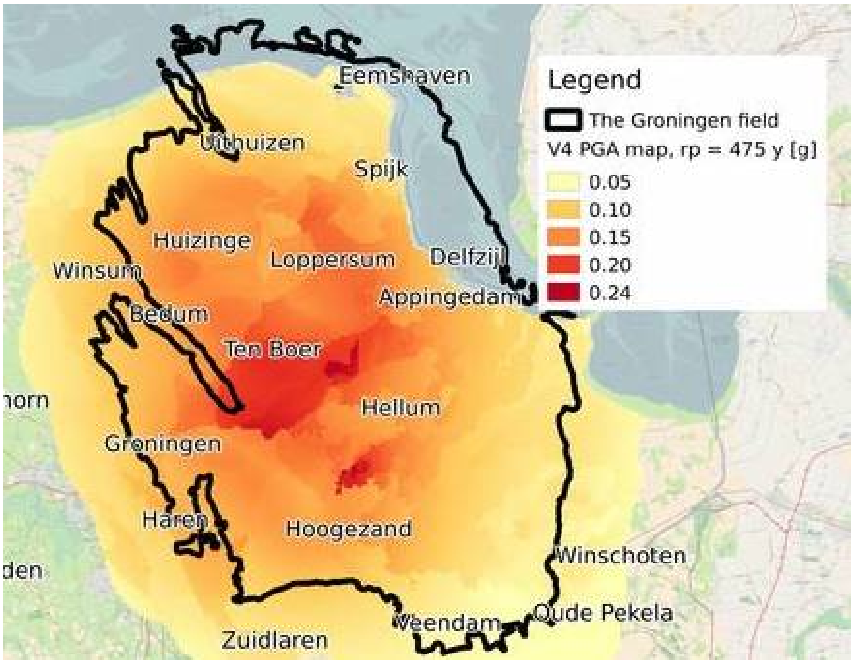


Figure 3.3: Earth quake hazard area Groningen (Koninklijk Nederlands Meteorologisch Instituut, 2017)

In order to compensate the households on top of the Slochteren field for the damage due to extraction induced earthquakes, the affected households around Oudeschip are renovated by a company named Borg. During this renovation the houses are thermally and acoustically isolated, which results in a better energy label. However, since Oudeschip is not in the heavily hit area shown in figure 3.3, the renovations in Oudeschip are not on the top of the priority list and it could therefore take a few years before these renovations start.

The area around Oudeschip includes 15 crop growing farms with tractors driving on diesel, therefore, methane emissions and greenhouses do not play a major role in agriculture in the Oudeschip area. However, after fertilization, the use of diesel in the tractors is a hard to abate source of emissions.

All of the 180 homes in Oudeschip are connected to the electricity and natural gas grid and the houses are heated using a natural gas boiler. Since these residents face a direct consequence of the extraction of natural gas and have some extra money to spend due to the wind park expansion, they are eager to invest in the replacement of their fossil fuel use with a renewable alternative, preferably by making use of the locally generated wind-power. Their options are discussed in the next section.

H2Oudeschip was founded by two inhabitants of Oudeschip to facilitate a hydrogen system for Oudeschip. They would secure the investment in an electrolyser and tube trailer and manage the operations of the hydrogen production and storage. H2Oudeschip is the problem owner in this research.

3.2 Requirements for a new energy system in Oudeschip

The three main options for residential heating are by using bio-gas, an all-electric system, or an energy system with hydrogen as an energy carrier (Nakata, Kubo & Lamont, 2005). Since the inhabitants of

Oudeschip want to utilize wind-power, bio-gas is not considered in this research.

If the homes are to be heated electrically with heat pumps, the natural gas grid will not be used anymore. As will be elaborated in section 4.2, the average energy consumption of a household in Oudeschip is 2.000 kWh of electricity and 1.200 m^3 of natural gas per year. Using the Higher Heating Value (HHV) value of natural gas from the Groningen gas field of 35,17 MJ/m^3, this is the same as 7.200 MJ and 42.204 MJ respectively. If an all-electric solution is chosen, the household heating would be fulfilled with a heat pump which has an average Coefficient of Performance (COP) of 3, but on a cold winter day this can go down to 2 (Warmtepompenadvies.be, n.d.). The electricity for the heat pump would be supplied through the electricity grid, which is designed for the electricity use of 2.000 kWh per household per year. On a cold winter day, this requires the electricity infrastructure to transport 4 times the volume of energy than for which is was designed. Henk van Krimpen from Enexis shared that the local electricity grid in Oudeschip has a reserve capacity of less than 50% (H. van Krimpen, personal communication, 5 June, 2020). Oudeschip is a rural area, which means that the houses are relatively far apart, which increases this investment per connection if the electricity grid is to be expanded. Moreover, it would leave the gas infrastructure without use. Since this would require a significant investment in the electricity grid from the utility provider, which can be avoided when a gaseous energy carrier like hydrogen is chosen, electric heating is not considered.

The remaining solution for residential heating is with hydrogen. A major advantage of hydrogen for heating is that it can make use of existing gas infrastructure, while other potential solutions would require major infrastructure investments (IEA, 2019a). Hydrogen heating technology is explained in section 3.4.3.

To decarbonize agricultural mobility, solutions span from all-electric to hydrogen. However, as discussed in section 3.4.4, this research narrows down to the option of a hydrogen-diesel hybrid.

The future energy system of Oudeschip should fulfil the following requirements:

1. The energy system of Oudeschip uses electricity and hydrogen as energy carriers
2. Oudeschip stores hydrogen in tube trailers
3. The energy system can be integrated into existing gas and electricity infrastructure
4. The energy system uses wind power as an energy source to fulfill the heat and mobility demand

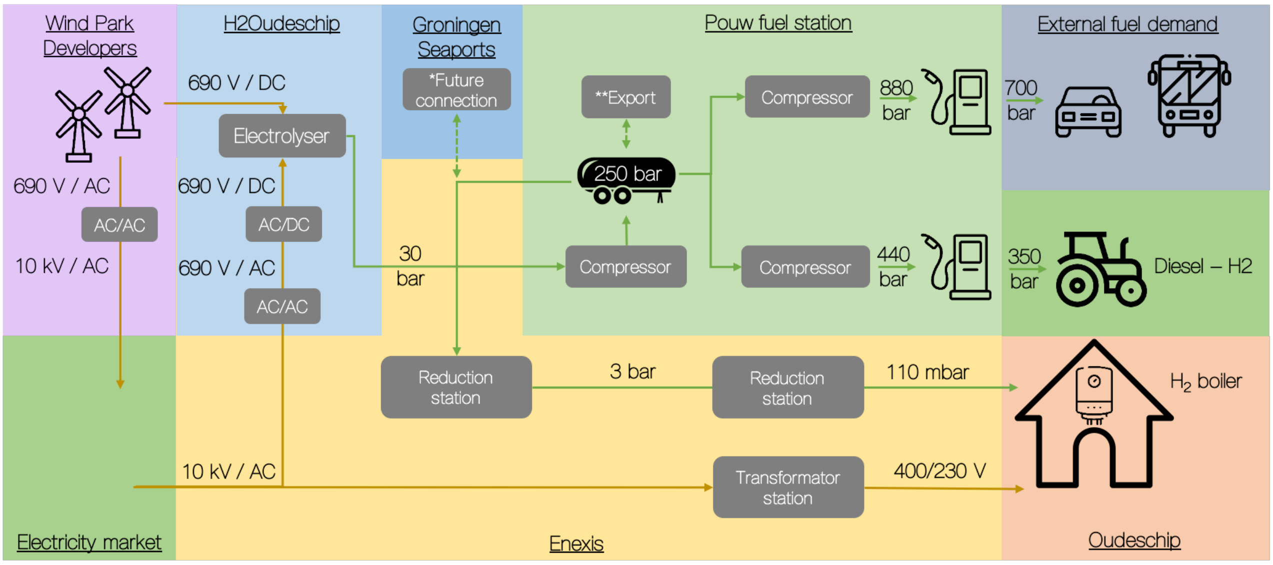
3.3 Hydrogen-electric energy system of Oudeschip

An energy system with hydrogen as an energy carrier utilizes electricity generated by the wind turbines to produce hydrogen. The wind turbines are owned and maintained by the developers of the Oostpolder wind park. This hydrogen is transported through the gas infrastructure, owned and maintained by Enexis. The hydrogen is stored in a tube trailer owned by H2Oudeschip on the property of a local fuel station, owned by the Theo Pouw Groep, who will be introduced further in section 3.4.6. The homes in Oudeschip use the hydrogen to heat their homes with a hydrogen boiler. Next to that, the household electricity demand is fulfilled by an electricity retailer, as is the case in the current energy system. The tractors of the local farms are converted into diesel-hydrogen hybrids, which can be filled with hydrogen at the fuel station. The fuel station can also sell the hydrogen to other FCEV vehicles like cars and busses. Lastly, if there is more hydrogen produced than used by the before-mentioned homes and vehicles, the tube trailer filled with hydrogen gas can be exported to be used for other purposes.

H2Oudeschip buys the electricity from the wind turbine developers and if needed from the electricity grid, owns and maintains the electrolyser and tube trailer, and sells the produced green hydrogen to the fuel station, households and external parties. It is assumed that the hydrogen is sold to the households directly, without a household heat provider as a middle man.

As mentioned before, Gasunie Transport Services is developing a hydrogen backbone which might be available in 2023. Moreover, Groningen Seaports is developing a hydrogen grid in the Eemshaven area (Groningen Seaports, 2018). A future scenario with a connection to this grid gives the opportunity for excess hydrogen gas to be sold through the hydrogen network of Groningen Seaports, as well as bought when there is a lack of hydrogen production. This would remove the need for a tube trailer and removes the costs of hydrogen compression to 250 bar.

The representation of this system is presented in figure 3.4, each coloured background represents a different stakeholder.



* Connection to hydrogen grid of Groningen Seaports, future scenario
** Export the tube trailer to external parties

Figure 3.4: Hydrogen-electric energy system of Oudeschip

In order to understand how this design came to be, certain aspects of the system components and their interactions need to be understood. Furthermore, the explanation of these components will be used as input for the simulations of the energy system of Oudeschip. The next section elaborates on the different components of the proposed new energy system of Oudeschip.

3.4 Description of components of the new energy system

Each of the components in the new energy system presented in the last section has its own technical and economic characteristics. These characteristics are key to the formation of the new energy system, and simulating the dynamics of the energy system. This section elaborates on these components.

3.4.1 Wind turbine

As mentioned in section 3.1, the Energie Cooperatie Oudeschip receives 10% of the revenue of the wind park. Since the Oostpolder wind park consists of 20 turbines, this can be viewed as being the revenues from two turbines. In order to get to this compensation, the developers of the Oostpolder proposed to place two extra turbines for the Energie Cooperatie Oudeschip.

The wind turbines placed for the Energie Cooperatie Oudeschip are produced by a company called Lagerwey. The model of these wind turbines is the L136 with a maximum power output of 4,5 MW. This wind turbine is unique, since the power from the turbine can be either Alternating Current (AC) or Direct Current (DC) at 690 V, while standard turbines only have alternating current as output. That is helpful, since electrolysers require direct current, while the standard on the electricity grid is alternating current, and the conversion from direct current to alternating current and vice versa includes losses. In order for the power to be fed in to the electricity grid, the power needs to be transformed from 690 V AC to 10 kV AC using a transformer.

The developers of the wind park need to pay for the connection between the turbines and the electricity grid, which is dependent on the capacity of the connection. The two 4,6 MW turbines add up to a required capacity of 9.000 kVA, if all the electricity needs to be transported through the electricity infrastructure. However, if an electrolyser is connected to the wind turbines, the required capacity is reduced, since part of the electricity will flow to the electrolyser. A 3 MW or 4 MW electrolyser reduces the required connection capacity to 6.000 kVA, which in turn reduces the investment cost. Table 3.1 shows the costs involved in such a connection, with a distance up to 25 meters from existing infrastructure. For every extra meter, an additional price needs to be paid. If the required capacity is 7.000 kVA, 8.000 kVA or 9.000 kVA, the 10.000 kVA connection is required, while a 5.000 or 6.000 kVA capacity requirement allows for the investment in a 6.000 kVA connection.

Table 3.1: Costs of new electricity connection Enexis (Enexis Netbeheer, n.d.)

Connection capacity	Supply voltage	Connection rate (excluding taxes)	Price additional meter (excluding taxes)
6000 kVA	10/20 kV	183.624	137,22
10000 kVA	10/20 kV	268.047	160,90

3.4.2 Electrolyser

Electrolysers use electricity and water to produce hydrogen and oxygen. There are currently three main electrolyser technologies: alkaline electrolysis, Polymer Electrolyte Membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs). *Alkaline electrolysis* is a mature technology and commercially available. Dynamic operation is limited which makes it unfavourable in combination with solar PV, but since wind generation is not as dynamic, an Alkaline electrolyser is a possibility (Schmidt et al., 2017). This type of electrolysis has relatively low capital costs due to the avoidance of precious materials. Since *PEM electrolysers* need electrode catalysts like platinum and iridium, and membrane materials, they are relatively expensive. Furthermore, their lifetime is shorter than alkaline electrolysers and they are less widely deployed. *SOECs* are less developed and not yet commercialised. Therefore, this type of electrolysis is not considered in this study.

Table 3.2: Techno-economic characteristics of different electrolyser technologies (IEA, 2019a)

	Alkaline electrolyser	**PEM electrolyser**
Electrical efficiency (%, HHV)	83	71
Energy per kg (kWh/kg H_2)	47.5	55.5
Operating pressure (bar)	1 - 30	30 - 80
Stack lifetime (years)	20	20
Cold-start time (min.)	<60	<20
Gas purity (%)	>99.5	99.99
CAPEX (€/kW)	500	1100
OPEX (%/year) [a]	2.7	2.7

[a] (Oldenbroek, Verhoef & van Wijk, 2017)

The electrolyser efficiency can be expressed in Lower Heating Value (LHV) and Higher Heating Value (HHV). The difference lies in the condensation energy. If the gas is burned and the exhaust water leaves the engine in vaporized form, the energy from gas condensation is not extracted and therefore the LHV is used. If the heat from the water is recovered using a condensator, the HHV is used. The LHV used to be an effective value to calculate with, but since current heating systems all have a condensator, the HHV is the appropriate value to use in current times. This research uses the HHV of hydrogen and corresponding HHV efficiency values.

The electrolyser uses electricity and water to produce hydrogen and oxygen. To ensure a long lifetime of an electrolyser, the feed-in water should be of a pure quality. Therefore, reversed osmosis for the water purification is necessary. The energy required for the purification of the water is taken into account, which is 1.3 kWh/kg H_2 (Oldenbroek et al., 2017). The supply of water can be rain water, surface water or tap water.

The electricity for electrolysis will either come from the wind turbines, or the electricity grid. Since the wind turbines are already have a grid connection, and the electrolyser only requires electricity from the grid when there is no wind power exported to the grid, there is no extra grid connection required for the electrolyser. Typical electrolysers have require DC power at a voltage which differs per producer and requirements by the customer. The electricity from these specific turbines is at 690 V and the electricity from the grid is at 10 kV. Therefore, the power from the grid is transformed from 10 kV AC to 690 kV AC with an AC/AC transformer, after which it is converted from AC to DC with a rectifier. It is assumed that the electrolyser has an internal DC/DC converter to get from 690 V to the required lower voltage. The efficiency of a DC/DC transformer is assumed to be 95% (van der Roest, Snip, Fens & van Wijk, 2020).

3.4.3 Hydrogen boiler

Dutch boiler manufacturer Remeha presented the first 100% hydrogen boiler, which is currently tested in a household setting in Rozenburg, The Netherlands (Remeha, 2019; Installatietechniek, 2020). For this boiler to work in current households, nothing needs to change, accept for the supplied gas. Worcester Bosch currently has a hydrogen boiler in development, which can run on 100% hydrogen, but also on a pure natural gas, or a mixture between the two (Woodfield, 2020). This makes it possible for a neighbourhood to smoothly transition to hydrogen.

Table 3.3: Comparison hydrogen and natural gas in boiler (van Wijk, 2020)

	Hydrogen	**Natural gas**	
CO_2 4	0	188	g/kWh
Efficiency [b]	115	108	% LHV
	97	97	% HHV

[a] at average gas consumption
[b] retour at 30$^\circ C$, 30% load
[c] Domestic hot water

The characteristics of the Remeha boiler are displayed in table 3.3. Since this hydrogen boiler is not yet in commercial production, it is assumed that a hydrogen boiler will cost the same as an average natural gas HR boiler, which is 1.500€(Homedeal, 2020), excluding installation. The average time to install a boiler is 4 hours, and the average labour costs are 50 €per hour, which results in an additional expense of 200 €for installation. This sums up to a total investment cost of 1.700 €.

3.4.4 Tractors

In order to decarbonize agricultural mobility, the diesel tractors used by the farmers in the area around Oudeschip need to convert to another type of fuel. The options discussed in this section are battery electric tractors, fuel cell electric tractors and hydrogen-diesel duel hybrid tractors.

Battery electric tractors

There are some battery electric tractors on the market, like the Fendt e100 Vario (Fendt, 2017) and the Rigitrac SKE 50 (Huiden, 2019) with a battery pack of 100 kWh and 80 kWh respectively.

Wouter Veefkind (W. Veefkind, personal communication, 31 March, 2020) from LTO Noord shared that an average tractors with 160 hp uses around 10-11 liters of diesel per hour. However, during harvesting season, this can go up to 24-26 liters per hour. Diesel contains 38.2 $MJ/Liter$ (HHV), which means that during peak season, $25 * 36.9 = 955$ MJ/hour is needed for the tractor. 1 MJ is equal to 0.27778 kWh, therefore, $955 * 0.27778 = 265, 28$ kWh of diesel is required to keep a tractor driving for an hour during high season. However, diesel engines have an efficiency of around 30%, while battery electric vehicles operate around 90% efficiency. Thus, for a battery electric tractor, the equivalent of $265, 28 * \frac{30}{90} = 88, 43$ kWh is required. In other words, the Rigitrac needs to be recharged within the hour of use during harvesting season, the Fendt tractor lasts for a little over an hour.

Fast charging the Fendt tractor can get to 80% in 40 minutes. This would mean that, when using the Fendt tractor during harvesting, after every hour on the land, it needs to be charged for 40 minutes. The Fendt and Rigitrac tractors are suitable for normal operation, when they could last several hours without charging, but not during peak demand. This is the major reasons why farmers are not converting to battery electric tractors (Reindsen, 2018), and why battery electric tractors are not considered as a viable option for Oudeschip.

Fuel cell electric tractors

Compressed hydrogen tanks have a higher energy density than lithium-ion batteries. Because there is a limited volume of energy storage available on a tractor, a fuel cell electric tractor has a greater range than a battery electric tractor has. The driving range and refuelling of a hydrogen tractor is comparable to internal combustion engine vehicles. Short refuelling time, less added weight for energy stored and zero tailpipe emissions contribute to the attractiveness of hydrogen for carbon free heavy-duty applications (IEA, 2019a).

Tractor manufacturer New Holland has a hydrogen tractor in service at a 'Energy Independent Farm' in La Belotta, Italy since 2012 (New Holland, 2011). It has a tank to store 8.2 kg of hydrogen at 350 bar and delivers 100 kW of power. There are currently no FCEV tractors commercially available, and if there were, it would be unlikely that all the farmers in the region simultaneously switch to a brand new tractor. Therefore, this research does not consider Fuel cell electric tractors either.

Hydrogen-diesel hybrid tractors

Several studies investigate the simultaneous combustion of hydrogen and diesel fuel, where hydrogen gas is added to the air intake, which show that this improves engine performance as well as reduces emissions compared to the case of neat diesel operation (Ghazal, 2013; Juknelevičius, Rimkus, Pukalskas & Matijošius, 2019; Putrasari et al., 2018).

From an engine production power point of view, for high engine speed the addition of hydrogen up to 40% increases the engine brake power by 14% compared to diesel (Ghazal, 2013). With a higher air/fuel ratio, the diesel fuel with 40% hydrogen has nearly 70% higher brake power compared with neat diesel fuel. Looking at the brake thermal efficiency, a hydrogen concentration between 30-40% with an air/fuel ratio between 15-20, give the highest brake thermal efficiency compared to diesel.

The smokiness, CO_2 emissions and CO emissions all decrease due to the supply of hydrogen. According to Juknelevičius et al. (2019), hydrogen addition reduced NO_x emissions by 26-28% at 1900 rpm and by 19-24% at 2500 rpm. Putrasari et al. (2018) show a decrease of NO_x emissions of up to 43% at 2000-2500 rpm, due to hydrogen addition to the fuel mixture. On the other hand, according to Dimitriou, Kumar, Tsujimura and Suzuki (2018), the NO_x emissions rise with any percentage of hydrogen addition. The literature review by Dimitriou and Tsujimura (Dimitriou & Tsujimura, 2017) shows that there is nearly unanimous agreement in the research about the reduction of CO_2 and CO, but the literature is divided on the impact on NO_x emissions.

In practice there are two known companies converting diesel engines to diesel dual fuel (DDF) engines. The first is Hydra Energy from Canada, where zero upfront investment is required for the conversion, but they require that the hydrogen is purchased from them. Their business model is hydrogen-as-a-service. The energy share of hydrogen in these systems is 40%. The second company is CMB Revolve Technologies from the UK, but nothing is publicly know about their conversion process or the involved costs.

Since there are no known conversion costs for tractors, these costs are not taken into account in this research. For the tractors in Oudeschip, it is assumed that an energy percentage of 60% is added to the diesel mixture, which is common in the research presented by Dimitriou and Tsujimura (2017). For heavy duty appliances it is common practice to have hydrogen tanks at 350 bar. The tractors could fit these hydrogen tanks on the roof, as it is done on the carbon free farm (Schmuecker, 2019). As will be mentioned in section 3.4.6, in the future energy system of Oudeschip, the Theo Pouw Groep will facilitate hydrogen fueling at the Eemshaven, where the hydrogen tanks of the tractors can be filled at 350 bar.

3.4.5 Fuel cell electric vehicles

Next to the hydrogen-diesel hybrid tractors, other Fuel Cell Electric Vehicle can fill their hydrogen tank at the fuel station as well. This can for example be hydrogen busses owned by Qbuzz for public transport, as there are already a few operational in the province of Groningen (Dagblad van het Noorden, 2019), or hydrogen trucks made by the Nicola Motor Company (*Nikola Motor Company*, n.d.). Another type of vehicle are FCEV passenger cars like the Toyota Mirai or Hyundai Nexo of which there are around 200 vehicles on the Dutch roads (Penders, 2020). Furthermore, there are garbage trucks driving on hydrogen in the Groningen (*Gemeente Groningen heeft tweede vuilniswagen op waterstof - RTV Noord*, 2019). Vehicles which might refuel hydrogen in the area of Oudeschip in the near future are hydrogen powered trains, like the one being tested between Groningen and Leeuwarden (van Gompel, 2020), and hydrogen ships, like the WEVA ship in construction which will transport goods from Delfzijl to Rotterdam (Topsector Energie, n.d.). The added value of these vehicles in comparison to other alternatives is that they do not emit greenhouse gasses during occupation, as internal combustion engines do. Next to that, while they have electric motors, their range is similar to a car with an internal combustion engine as is the fueling time, which is not the case for battery electric vehicles. These vehicles typically fill their hydrogen tank at 350 or 700 bar.

3.4.6 Fuelling Station

While there is currently a limited number of hydrogen refuelling stations in the Netherlands, the installation of hydrogen refuelling infrastructure has picked up momentum in the past few years. Refuelling stations can be operational within six months, but generally take up to two years to build. Current approaches to mitigate this delay related to infrastructure development include using refuelling stations at or near hydrogen production sites to serve dedicated fleets (IEA, 2019a). The investment costs for hydrogen refuelling stations depend on the delivery pressure of the hydrogen. Estimated cost for 700 bar are between 0.6 - 2 million USD, and 0.15 - 1.6 million at 350 bar. The compressor and storage tanks are the two largest cost components of this system. Bastiaan Bor (B. Bor, personal communication, 4 June, 2020) from Lagerwey shared that the cost of a fastfill station with a single dispenser at 700 bar costs 1.2 million euros. The operational costs are 1 %/year and the lifetime is 15 years (Oldenbroek et al., 2017). Since two dispensers are considered, one at 700 bar and one at 350 bar, 1.5 million is taken as the investment cost for the refuelling station (S. Holthausen, personal communication, 4 June, 2020). The compressor costs are already taken into account in this number, as well as storage at 440 and 880 bar, which are explained in the next section. The Theo Pouw Groep, a ground, road, water and concrete construction company has a big facility in the Eemshaven, with a fleet of heavy duty vehicles. They expressed interest in decarbonizing its fleet of heavy duty vehicles, and building a hydrogen fueling station.

3.4.7 Hydrogen storage

There are four main types of hydrogen storage: as a compressed gas, a refrigerated liquefied gas, a cryo-compressed gas or in hydrides. A hydride is a binary compound of hydrogen with a metal, like the combination of nitrogen and hydrogen in the form of ammonia. The most appropriate storage medium depends on the volume, duration, required speed of discharge, and geographic availability of different options. In this research, only hydrogen storage as a compressed gas is considered, since hydride and refrigerated storage add to the complexity and energy losses of the storage system.

Hydrogen tanks have high discharge rates and efficiencies of around 99%, making it appropriate for smaller-scale applications where local stock of fuel needs to be readily available. At 700 bar pressure, compressed hydrogen has a small energy density (15% of gasoline), so storing hydrogen at a vehicle refuelling station to replace gasoline, would require nearly seven times the space (IEA, 2019a). Storing hydrogen on a trailer has the advantage that the hydrogen can be sold and driven away if the production is higher than consumption. There are two types of hydrogen storage trailers: a tube trailer and a container trailer, which store at 200-250 and 500 bar respectively. Which of the two is more appropriate, depends on the required volume of seasonal hydrogen storage. For the system at Oudeschip, only tube trailers at 250 bar are considered. One trailer can fit 200 kg of hydrogen, if more storage is necessary, multiple trailers can be placed. This would add the benefit of being able to sell an entire tube trailer full of hydrogen if production is higher than consumption. The investment costs of a tube trailer are 730 €/kg H_2, the OM costs are 2 % per year, and the lifetime is 30 years (Oldenbroek et al., 2017). In short, a hydrogen tube trailer of 200 kg costs 146.000 €.

Compressed hydrogen storage in a tube trailer requires a compression step. When combined with a fuel station, there are two additional compression steps required. The first compression step is from 30 bar to 250 bar for storage in the tube trailer. This requires 1.5 kWh/kg H_2 (DOE, 2009). To be able to dispense hydrogen at the fueling station at 350 bar, the hydrogen needs to be compressed to 440 bar, which requires 2.23 kWh/kg H_2 when starting at 30 bar (DOE, 2009). Similarly, to be able to dispense at 700 bar, the hydrogen needs to be compressed to 880 bar, which requires 3.2 kWh/kg H_2 when starting at 30 bar (DOE, 2009). In practice, the hydrogen for fueling at 350 and 700 bar is pressurized by using the hydrogen at 250 bar from the tube trailer, which results in a lower energy requirement for the second compression step. Since the energy required to compress hydrogen from 30 bar to 880 bar is the same as the energy required for compression from 30 bar to 250 bar combined with the energy required for compression from 250 bar to 880 bar, the PtX model assumes that all hydrogen fueled at 700 bar requires 3.2 kwh/kg, which greatly simplifies the modelling steps. The same goes for fueling at 350 bar.

3.4.8 Transport infrastructure

If hydrogen needs to be transported for distances of less than about 1.500 km, transmission of hydrogen as a gas by pipeline is generally the cheapest option (IEA, 2019a). Besides that, many modern low-pressure gas distribution pipes are generally suitable to transport hydrogen with some minor upgrades. According to Kiwa Technology (2018) the Dutch natural gas grid is capable of transporting 100% sustainable gasses, like hydrogen and bio-methane. The most important alterations to the system are the measurement equipment of the utility providers, and the suitability of the devices on the consumer side like a hydrogen boiler or gas stove. Since hydrogen has an energy density which is approximately one third of the energy density of natural gas, three times the volume of hydrogen needs to be transported in order transport the same volume of energy. The lower energy density of hydrogen results in a higher flow rate, which means that the transport capacity of the gas pipes remains the same.

Figure 3.5 shows the natural gas grid around Oudeschip, owned and maintained by Enexis. If the residents of Oudeschip switch to hydrogen heating, this grid needs to be converted into a hydrogen grid, and it needs to be isolated from the rest of the natural gas grid. The sections where the grid needs to be cut off from the rest are shown with orange lines. If all the households shown as yellow dots in figure 3.2 are to switch to hydrogen, the isolated hydrogen grid for Oudeschip must span the homes in the lower bottom corner of the map. As shown as pink lines in figure 3.5, the gas grid needs new connections to make this happen. The total length of these two new 3 bar gas pipelines is 2.400 meters. Enexis shared that a new pipeline on average costs 261 €/meter (H. Smit, personal communication, 20 july, 2020), which would make the investment in these new connections 626.400 €. Enexis concluded that the hydrogen can be transported to the houses by feeding into the 3 bar pipes (H. Smit, personal communication, 11 February, 2020). The conversion costs of the gas infrastructure to support hydrogen, which includes the replacement of gas meters, is assumed to be 200 €per household, as suggested in a report by TNO (Weeda & Niessink, 2020). Since there are 180 households involved, this sums up to 36.000 €.

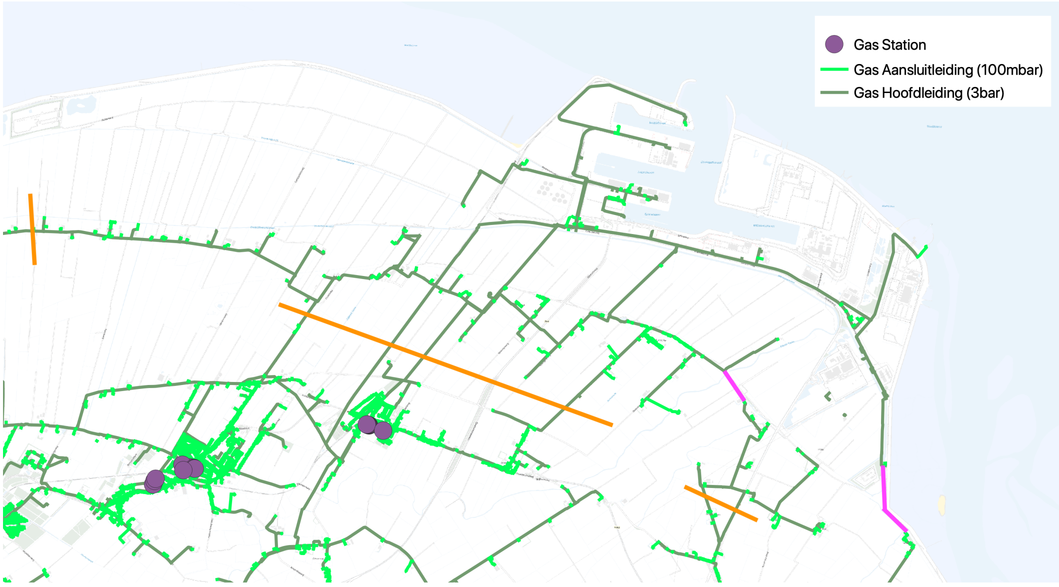


Figure 3.5: Natural gas infrastructure of Enexis around the Eemshaven (Enexis Netbeheer, 2018)

Next to the existing gas infrastructure, a new pipeline needs to be built to transport the hydrogen from the electrolyser next to the wind turbines to the fuel station of the Theo Pouw Group. It is unsure which exact wind turbine locations in the Oostpolder wind park are reserved for the Energie Cooperatie Oudeschip, but Erik Dijkshoorn from H2Oudeschip mentioned that it can be assumed to be around the Eemshavenweg around the N46, as shown in figure 3.6 (E. Dijkshoorn, personal communication, 13 May, 2020). This figure shows Oudeschip in the bottom and the fueling station of the Theo Pouw Group on the top right. The length of this new hydrogen pipeline is 2.6 kilometers. Since the hydrogen comes out of the electrolyser at 30 bar, is stored at the fuel station at 250 bar, and the compression costs are a relatively large cost component, it is preferred to keep the hydrogen at 30 bar. The hydrogen infrastructure of Groningen Seaports is constructed with SoluForce flexible composite material by PipeLife, which supports pressures up to 42 bar (PipeLife, n.d.). It is unclear what the exact investment costs are for this type of infrastructure, but Henk Smit from Enexis shares that 300 €/meter is a fair assumption for the investment in a new infrastructure (H. Smit, personal communication, 20 july, 2020). Since the length of the pipeline is 2.6 kilometers, this sums up to 780.000 €.

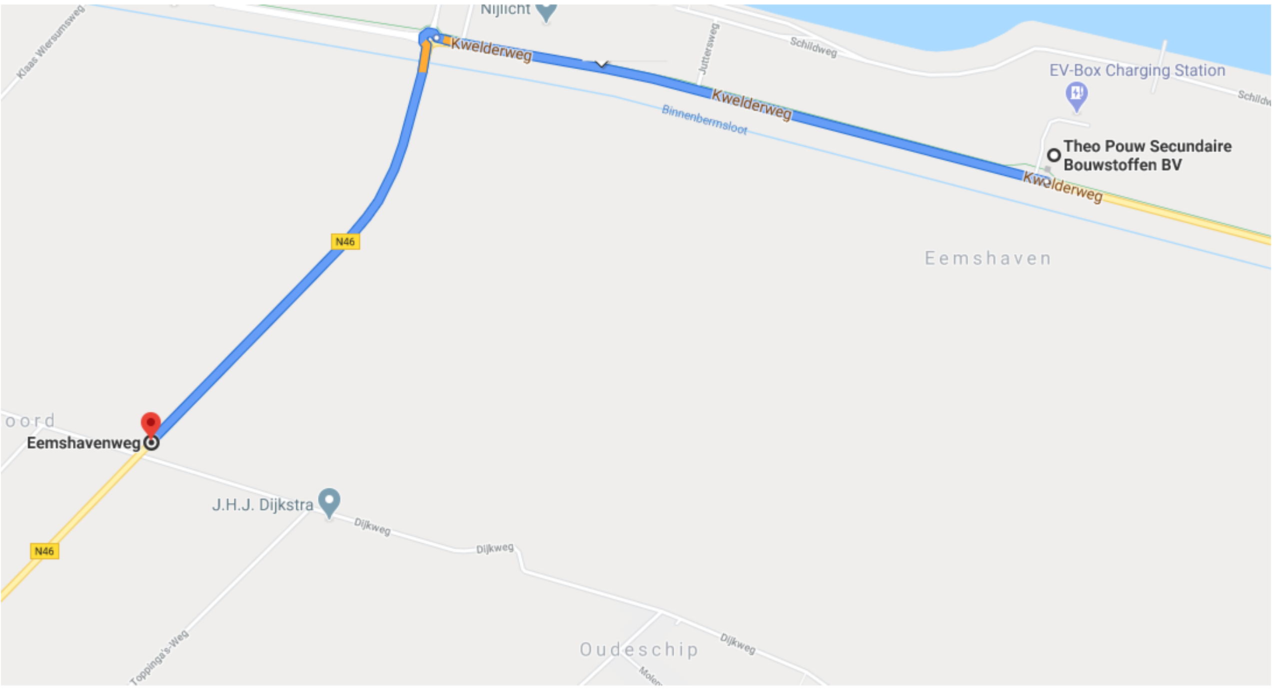


Figure 3.6: New hydrogen pipeline at 30 bar from the electrolyser to the fuel station

In order for the hydrogen gas to be transported from the hydrogen storage facility to the households, a connection to the 3 bar gas infrastructure of Enexis needs to be made. This connection involves costs for H2Oudeschip, which are presented in table 3.4. When a distance up to 25 meters from existing infrastructure is insufficient to reach the hydrogen storage, for every extra meter, an additional price needs to be paid.

Table 3.4: Costs of new gas connection Enexis (Enexis, n.d.)

Connection capacity	Connection rate (excluding taxes)	Price additional meter (excluding taxes
0 to 6 m^3/h	€ 780.07	23.38
0 to 10 m^3/h	€ 780.07	23.38
0 to 16 m^3/h	€ 1'478.00	28.85
0 to 25 m^3/h	€ 1'513.36	28.85
0 to 40 m^3/h	€ 2'080.15	28.85

3.5 Stakeholder Analysis

A stakeholder analysis provides an overview of the stakeholders involved in a project and groups them according to their levels of participation, interest and influence in the project. This chapter starts with an overview of the key stakeholders. For each stakeholder, their background, role, goal and issues/dilemmas are discussed. Afterwards, they are grouped in a power interest grid.

3.5.1 Key stakeholders

Households in the Energie Cooperatie Oudeschip

The Energie Cooperatie Oudeschip consists of the 180 households around the wind turbines of the Eemshaven. Their homes are to be renovated to be thermally and acoustically isolated. They are opposed to the wind turbines, which block their view and might cause noise disturbance, unless they can participate in the park. Since their homes are renovated due to the effects of gas extraction from the Slochteren gas field, they are eager to move away from using natural gas in their homes. Their goal is to not just receive compensation from the wind park, but also participate in the utilization of the generated wind power. Since natural gas contains 1,88 kg of CO_2 per m^3 (Emissiefactoren, n.d.), and the homes on average consume 1200 m^3 of natural gas per year, if they switch to a hydrogen boiler, they reduce their carbon emissions with 2.256 kg of CO_2 per year per household.

H2Oudeschip

H2Oudeschip is founded by two inhabitants of Oudeschip, Erik Dijkshoorn and Jaap Kap, to facilitate the ownership and operations of the electrolyser and tube trailer storage. This company imports wind power from the wind turbine developers or, if needed, from the electricity grid and converts this electricity into hydrogen using an electrolyser. The hydrogen is then transported to the tube trailer for storage on the property of the fuel station. From there, the hydrogen can either be sold to the households through the heat provider of the households and transported through the existing gas infrastructure of Enexis, sold to the fuel station, or a tube trailer full of hydrogen can be sold to an external party.

Farmers around Oudeschip

Farmers in the Netherlands are currently under pressure to reduce their greenhouse gas emissions, as is the case for the 15 farmers around Oudeschip. However, as discussed in section 3.4.4, the decarbonization of their tractors does not have a lot of options. By converting their tractor to a hydrogen-diesel hybrid, 60% of the energy used by the engine can come from hydrogen, which results in a reduction of CO_2 emissions. Diesel fuel contains 3,23 kg/L of CO_2, from well-to-wheel. As mentioned in section 4.3, the average farm consumes 12.000 liters of diesel per year. By converting their tractor and replacing 60% of their diesel use by hydrogen, they reduce their CO_2 emissions by around 23.256 kg per farmer per year.

Wind park developers

Waddenwind BV is a group of agricultural entrepreneurs and Innogy is an energy provider. They are the developers of the wind park next to Oudeschip of which Waddenwind BV owns 60% and Innogy owns 40%. Their goal is to build the wind park, and since the residents of Oudeschip were initially against the expansion of the park, they made a deal with the Energie Cooperatie Oudeschip to compensate the residents for their loss of view. The production of hydrogen from the generated wind energy benefits the wind park developers, since the congestion on the electricity grid currently forces them to stop the wind turbines on windy days. This curtailment is less of an issue if hydrogen is produced during these times, which allows them to continue the operation of the turbines.

Furthermore, the wind park developers are dependent on the revenues from selling the electricity on the electricity market, in combination with a subsidy called the Stimulering Duurzame Energie (SDE+). As will be explained into detail in section 4.1.2, the size of this SDE+ subsidy is dependent on the electricity price. As long as the electricity from the turbines is bought for the base tariff described in section 4.1.2, the wind park developers will favour selling the electricity to H2Oudeschip for hydrogen production instead of offering the electricity on the electricity market.

As discussed earlier in this chapter, the wind park developers need to pay for a grid connection in order for the wind power to be transported over the electricity grid. If the electrolyser is larger than 2 MW, these costs go down. Therefore, the wind park developers will opt for an electrolyser with a capacity larger than 2 MW.

Theo Pouw Groep

The Theo Pouw Groep is a ground, road, water and concrete construction company. They have a big facility in the Eemshaven, with a fleet of heavy duty vehicles. The Theo Pouw Group is interested in decarbonizing its fleet, starting with the electrification of several vehicles. In order to do this, they expressed interest in building and owning a fueling station at the Eemshaven, including the offering of hydrogen. The Theo Pouw Group is important for the realisation of a fueling facility.

Groningen Seaports

Groningen Seaports is the economic operator and authority of the port of Delfzijl and Eemshaven and the adjoining industrial sites. They are part of the hydrogen consortium Missie H2, and together with Pipelife, they signed a cooperation agreement to build the infrastructure for the transport of green hydrogen in the port of Delfzijl and in Eemshaven. If a hydrogen production by H2Oudeschip is operational by the time that the infrastructure of Groningen Seaports is in place, it might be possible to connect to this grid and trade hydrogen through their system. Since Groningen Seaports expressed the intention to play a prominent role in the regions energy transition, they are an advocate of this project.

Enexis

Enexis is the distribution grid manager in the north of the Netherlands. They manage the electricity and gas infrastructure. This includes the planning for the connection of wind parks, and investing in the electricity grid accordingly. At the moment, grid operators have difficulty with new wind parks, since building a new wind park is a faster process than expanding the electricity grid. Furthermore, since an increasing number of households is moving away from gas, they own a gas infrastructure which might become a stranded asset. Therefore, they are fond of green hydrogen projects like this, since it tackles both the before-mentioned problems: converting wind power to hydrogen reduces the strain on the electricity grid, and the gas grid receives a future proof purpose. If Oudeschip moves to a new energy system with hydrogen as an energy carrier, they do have to invest in the conversion of the natural gas grid for it to transport hydrogen.

Province of Groningen

One of the tasks of a province is spatial planning and development. It considers the placement of business parks, as well as nature reserves. In the spatial planning process, interests from businesses, as well as citizens, are considered. The climate agreement is supported by the province, for the province of Groningen, this means that they have the goal increasing the installation of wind parks, with minimal disturbance on surrounding inhabitants. In this project, they were key in securing the 10% for the Energie Cooperatie Oudeschip to make sure that the wind park could be built. In order for hydrogen to be produced and transported, they need to grant a building permit. Since this hydrogen project involves both businesses and citizens, the province of Groningen expressed that they are favourable towards the project.

FCEV owners

FCEV owners are the owners of fuel cell electric passenger cars like the Toyota Mirai or Hyundai Nexo. The public transport provider in the province of Groningen is Qbuzz, which also has several FCEV Next to that, there are FCEV vehicles like trucks, vans, garbage trucks, trains, etc. For these type of vehicles, there are currently 5 stations in the Netherlands to refuel. Their goal is to increase their own convenience, which in this project means that they encourage the increase of the number of fueling stations for hydrogen.

3.5.2 Power/interest

The power/interest grid is a matrix used to categorise stakeholders during a change project. By plotting the stakeholders on the grid, insight in their power and interest in respect of the project is retrieved. There are four categories in the power/interest grid: keep satisfied, manage closely, monitor and keep informed, as can be seen in figure 3.7.

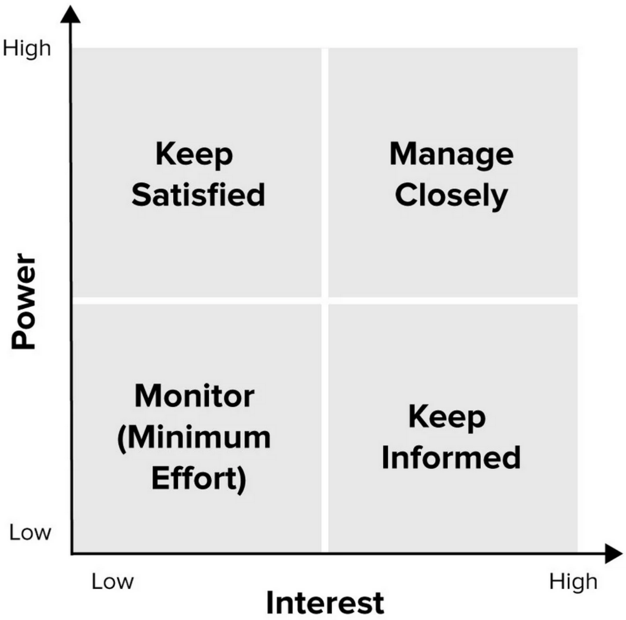


Figure 3.7: Power/interest grid

Table 3.5 shows the key stakeholders plotted in the power interest grid. It is clear that the most important stakeholders are Enexis, the Theo Pouw Groep, farmers and the Energie Cooperatie Oudeschip. They have a large influence on the continuation of the project, but also expressed their favourable intentions towards hydrogen in Oudeschip. In order for this project to continue, they should be fully engaged. Furthermore, the province of Groningen and Groningen Seaports have a large influence on the project, but it is not on top of their priority list. Therefore, their needs should be met in order to keep them engaged. The Energie Cooperatie Oudeschip is interested in the continuation of the project. The members of the cooperation should be kept informed adequately, but have limited influence on the development. Lastly, Lagerwey, Waddenwind BV and Innogy show both a limited interest in the project, while having low power over the continuation of the project. Therefore, they should solely be monitored.

Power	High	Provincie Groningen	Enexis Theo Pouw Groep Energie Cooperatie Oudeschip Farmers H2Oudeschip
	Low	Waddenwind BV & Innogy FCEV owners and Qbuzz Groningen Seaports	
		Low	High
		Interest	

Table 3.5: The power interest grid for hydrogen in Oudeschip

Chapter 4

Supply & Demand Patterns and Tariff

4.1 Wind generation

4.1.1 Generation pattern

The wind generation is calculated using the wind speeds measured at the nearest KNMI weather station at Lauwersoog. The power produced as a function of the wind speed at hub height is represented by a power curve. The power curve of the Lagerwey L136 turbine is shown in 4.1. When the speed is less than the cut-in wind speed, the turbine is not able to produce power. When the wind speed exceeds the cut-out speed, the wind turbine is stopped to prevent structural failures. In the case of the Lagerwey wind turbine, the cut-in speed is 2,5 m/s and the cut-out speed is 25 m/s.

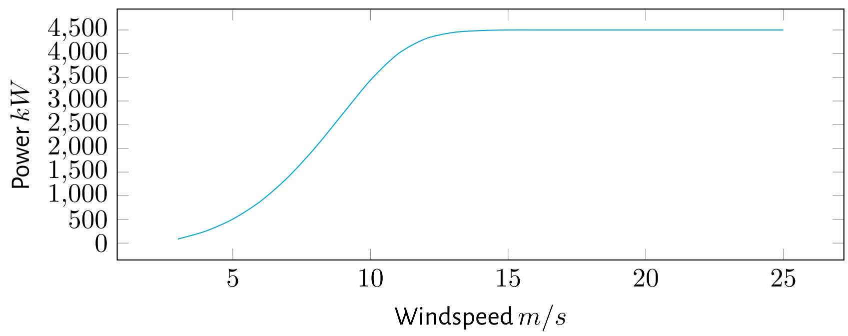


Figure 4.1: Power curve Lagerwey L136 wind turbine

The wind speed measurements at the KNMI weather station are measured at a height of 10 meters, while the wind speed at hub height is needed. The way in which the wind speed at hub height is calculated is presented in the next chapter in section 5.2.1.

The wind speed differs greatly from year to year, as can be seen from figure 4.2. Therefore, in order to have a realistic view of the future wind generation, multiple years are simulated. Since the KNMI offers hourly wind speed measurements at Lauwersoog from 2010 onward, the simulations will run for every hour from 2010 up to and including 2019. The average, minimum and maximum wind speeds per month over this period are shown in figure 4.3. The average wind speed at the Lauwersoog weather station between 2010 and 2019 is 6,17 m/s.

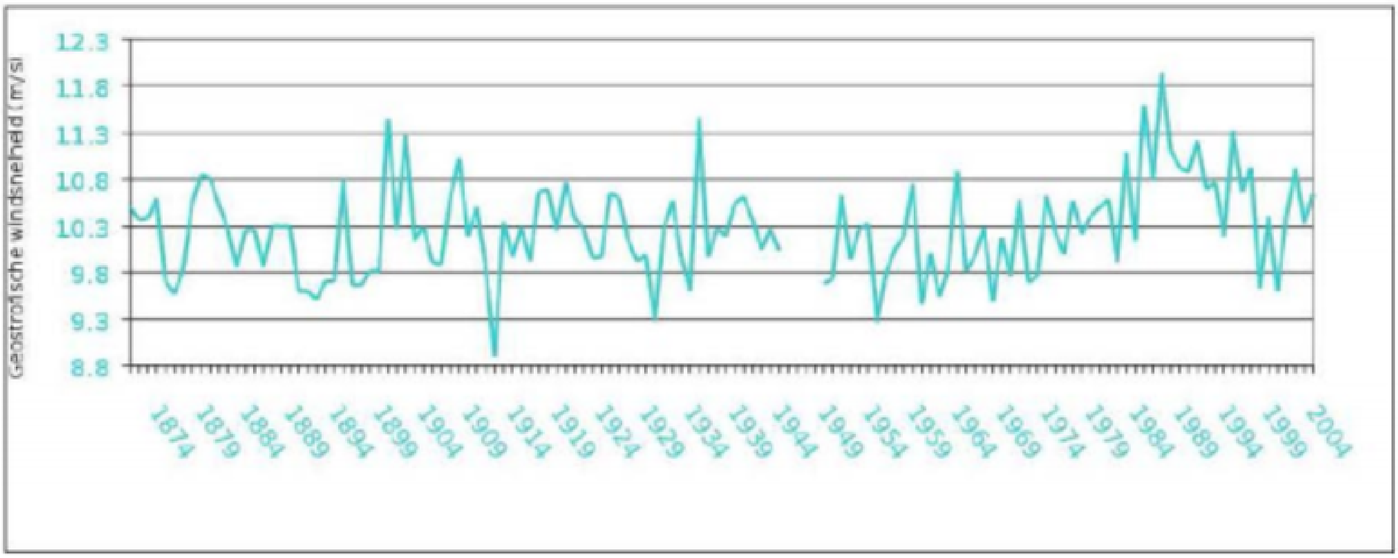


Figure 4.2: Yearly average wind speed over the North Sea (Homan, 2019)

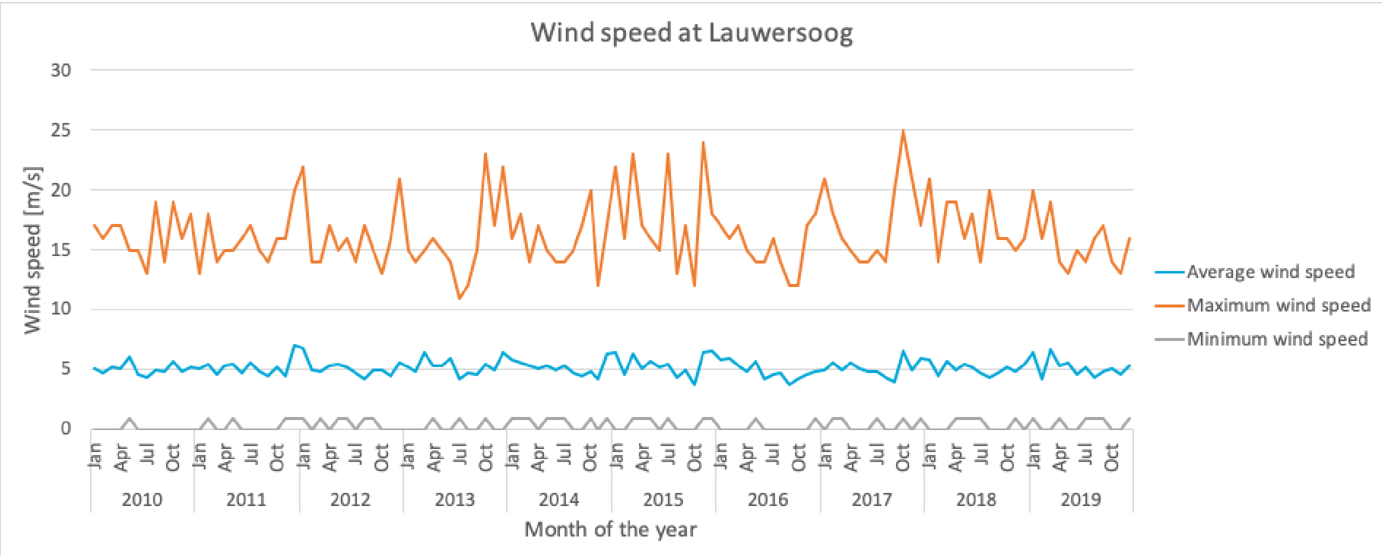


Figure 4.3: Wind speed measurements per month at Lauwersoog between 2010 and 2019

One of the risks when investing in wind energy is the inconsistency of the wind resource compared to the forecast. To build a reliable business plan, investors analyse wind generation according to a so called P90 value. The P90 figure is the level of annual generation that is predicted to be exceeded 90% over a year. In this research, the wind generation of every hour between 2010 and 2019 is subtracted by 10% in order to get to this P90 value and safely predict the actual wind generation.

4.1.2 Wind electricity tariff

The subsidy Stimulering Duurzame Energieproductie (SDE+) is an exploitation subsidy to subsidize renewable generation. In order to calculate the subsidy, it makes use of a base amount, and a base energy price. The base amount is the cost of production per kWh, including a profit margin. The subsidy covers the difference between the base amount and the market price for electricity. The base energy price is the minimum market price up to which the subsidy will rise. Oudeschip is in the municipality Het Hogeland, which has an average wind speed of more than 8 m/s (Rijksdienst voor Ondernemend Nederland, 2020). For this average wind speed, the base amount is 0,042 €/kWh, and the base energy price is 0,029 €/kWh. Therefore, if the market price is higher than 0,029 €/kWh, the subsidy will cover the difference between that market price and the base amount of 0,042 €/kWh, until the market price is higher than the base amount. When the market price for electricity dives below 0,029 €/kWh, the subsidy has reached its maximum.

For this research, it is assumed that the electricity from the wind turbines is bought by H2Oudeschip for 0,029 €/kWh, but when there is no wind generation and electricity needs to be bought from the grid, it is bought for 0,03 €/kWh plus 0,01 €/kWh for transport costs. Next to the electricity supply to the electrolyser of H2Oudeschip, the remainder of the electricity is sold on the electricity market for market price, which is not taken into account in this research.

4.2 Residential heat demand

4.2.1 Demand pattern

Residential energy demand within the Netherlands differs per region and is dependent on the type and size of the building, as well as the the isolation. Most households in and around Oudeschip are detached houses, with poor isolation, since they are relatively old. This is shown in the maps of figure 4.4 and figure 4.5.

Figure 4.4: Type of buildings in and around Oudeschip (Schoots et al., 2017)

Figure 4.5: Age of buildings in and around Oudeschip (Schoots et al., 2017)

The poor isolation results in a relatively high energy consumption per household. The average household of Oudeschip consumes 2.000 kWh of electricity and 2.000 m^3 of gas per year (CBS, 2020a). However, since the houses will be renovated, the homes will get from an F label to an A label isolation (J. van Ravenswaaij, personal communication, 6 September, 2019). This results in a reduction of gas consumption to 1.200 m^3 (Majcen, Itard & Visscher, 2013). The heat demand is zero in summer, and peaking in winter. The demand pattern for the heat is retrieved from the KNMI temperature data measured at Lauwersoog, by calculating degree hours. Every degree below the threshold of 16 degrees of outside temperature results in an average heat demand per m^2. The average floor area of a household in the Eemsmond area is 120 m^2 (CBS, 2018).

Next to space heating, part of the gas consumption is from tapwater heating. While spaceheating rarely is required in summer, tapwater demand is relatively stable over the year. The tapwater demand per person per year is assumed to be 4,2 GJ. Together the spaceheating and tapwater demand results in a heat demand pattern which is levelized by using the average gas consumption of Oudeschip. The higher heating value of natural gas is 35,17 MJ/m^3 and the higher heating value of hydrogen is 141,8 MJ/kg. As shown in table 3.3, the HHV efficiency of a natural gas and hydrogen boiler are the same. Therefore, the heat demand can be expressed in kilograms of hydrogen, which results in an average household hydrogen demand per household of 297,6 kg of hydrogen per year. The resulting demand pattern is shown in figure 4.6.

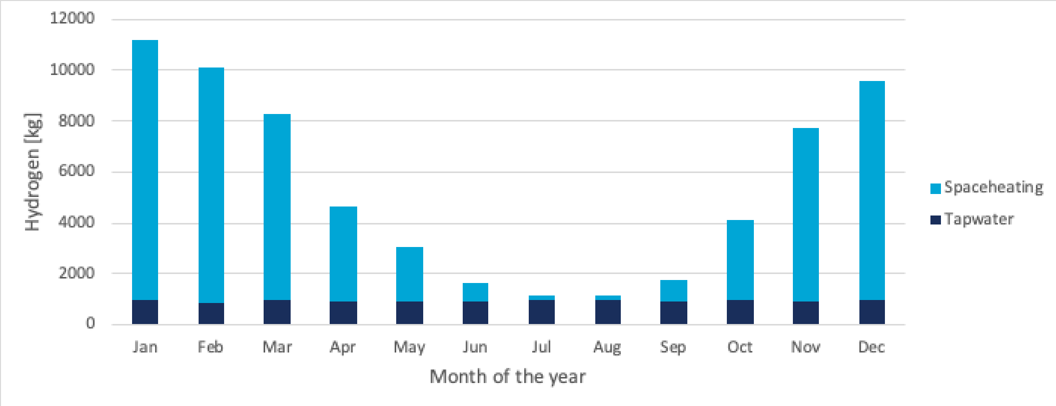


Figure 4.6: Average household hydrogen demand pattern

Since every hour between 2010 and 2019 is simulated, any fluctuation in heating pattern between years is covered.

4.2.2 Electric cooking

If the households in Oudeschip make the step towards the energy system proposed in section 3.3, there will be no option to cook with gas. Cooking with hydrogen gas is technically possible, but not considered in this research due to safety considerations. Therefore, the cooking will become electric, which increases the electricity consumption. The typical daily pattern for electric cooking is shown in figure 4.7.

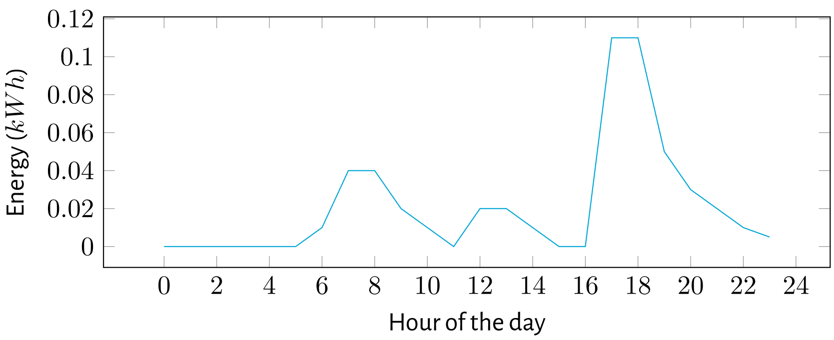


Figure 4.7: Electric cooking daily consumption pattern (van Melle et al., 2015)

It is clear that there are three peaks, each for one of the three meals in a day, with the highest energy consumption for cooking around dinner time. The area under the curve sums up to 15 kWh per month. Electricity consumption is not taken into account in this research, but the cost of additional electricity is added to the difference in yearly costs for households.

Since the households are not cooking with gas anymore, the total volume of used gas will decrease. Since the total volume of energy deduced from the gas consumption is $15 * 12 = 180kWh$ per year, hydrogen gas contains 2,8 kWh/m^3, and uncompressed hydrogen takes up around 11 m^3 per kilogram, this boils down to a reduction of 5,8 kg H_2/year.

4.2.3 Energy tariff

The average tariff per kWh of electricity for households in 2020 is 0,225 €/kWh , of which 7,5 cents are for the electricity and 15 cent is for energy tax and storage of renewable energy (ODE) (Mileu Centraal, 2020).

As mentioned in the previous section, cooking adds 15 kWh of electricity use per month, which adds up to 40,5 €/year.

The average gas price for households in 2020 is 0,814 €$/m^3$, of which approximately 32 cents are for the gas and 50 cents for taxes (Mileu Centraal, 2020). When the natural gas is replaced by hydrogen, it is assumed that the taxes will not be levied since green hydrogen is promoted. Furthermore, it is assumed that the delivery price of energy, as well as grid management costs remain the same. Using the calorific HHV value of the natural gas, which is 35,17 MJ$/m^3$, results in a gas price of 0,023 €$/MJ$. The HHV of hydrogen is 142 MJ/kg, therefore, the households should pay no more than 3,28 €/kg H_2 in order to prevent an increase in their energy bill.

As will be described in section 5.2.6 of the next chapter, a Levelized Cost of Hydrogen will be calculated per scenario. This is the cost price of the hydrogen produced by H2Oudeschip. In order to have a return on investment and payback the investment cost of the hydrogen production equipment, the assumption is made that a price of 0,05 €/kg is added to the LCOH in order to get to the hydrogen price for the households.

4.3 Agricultural fuel demand

4.3.1 Demand pattern

Where livestock farming has a relatively constant diesel use over the year, the average crop growing farm has a seasonality in diesel consumption, due to the periods of sowing and harvesting. The average farm consumes around 12.000 liters of diesel (LTO Noord, personal communication, 18 Februari, 2020). The typical diesel consumption pattern of an average sized agricultural farm in the Netherlands is shown in figure 4.8. This pattern is based on an article by van der Voort and Timmerman (van der Voort & Timmerman, 2019), but since the data is very coarse since it concerns one farm, it is smoothened to represent multiple farms with harvest a variety of crops. The graph was validated by LTO Noord (W. Veefkind, personal communication, 5 June, 2020).

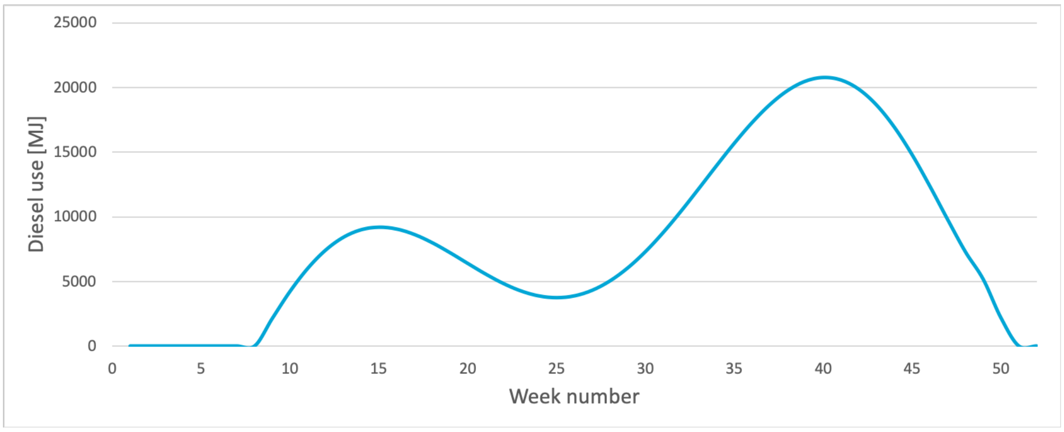


Figure 4.8: Average diesel use of a single farm

In order for this weekly demand pattern to be used in a model with hourly simulations, the weekly volume of diesel is divided into an hourly percentage of that weekly volume. Most farmers fill op the tractor with diesel at the end of the day, and often work 6 days per week (W. Veefkind, personal communication, 5 June, 2020). The resulting diesel fuelling pattern is shown in figure 4.9.

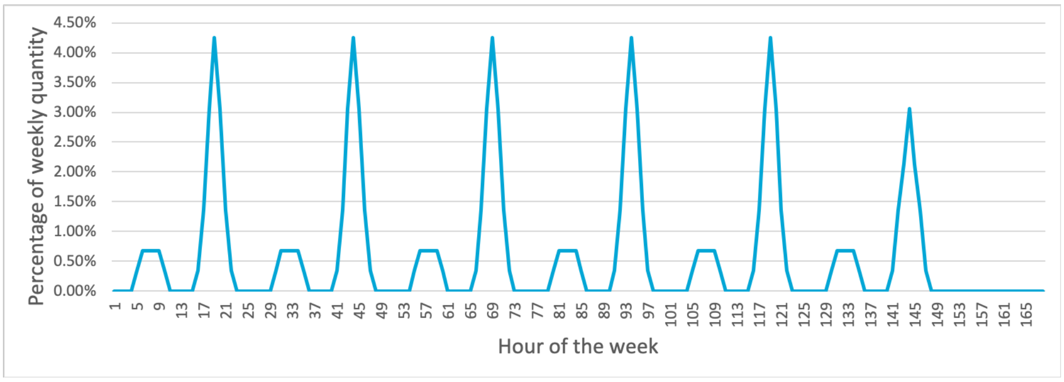


Figure 4.9: Fueling demand per week as a percentage of weekly diesel use

4.3.2 Agriculture fuel price

For diesel oil, the price structure is relatively complicated, but the production price for the diesel oil itself is 0,4041 €/L, and the duty and taxes add up to 0,7232 €/L (Oostvogels, 2017). This adds up to 1,1273 €/L, the remainder of the diesel price of 1,30 €/L is for the fuel station operator. Diesel fuel has a calorific value of 38,19 MJ/L (HHV), thus the price of the diesel, including duty, taxes and fuel station operator cost, is 0,034 €/MJ. To convert this to the price per kg of hydrogen, the HHV of hydrogen of 141,88 MJ/kg is used. Thus, the farmers should pay no more than 4,83 €/kg H_2 in order to spend the same amount of money or less on fuel as with a diesel engine. In order to keep the expenses for farmers the same, the simulations assume that the farmers will pay this price for the hydrogen.

4.4 External fuel demand

4.4.1 Demand pattern

Next to the tractors, other vehicles can also refuel hydrogen at the station. The demand pattern for these vehicles is shown in figure 4.10, which is provided by a business partner of the KWR. The graph shows two demand patterns per day, one for a weekday and one for a day in the weekend. This pattern is scaled to have an average fuel consumption per day of 200 kg hydrogen (Hydrogen Europe, 2018). As mentioned in section 3.4.5, these vehicles refuel at both 350 and 700 bar. However, the used demand pattern is not divided into these two groups, therefore it is assumed that all of these vehicles refuel at 700 bar.

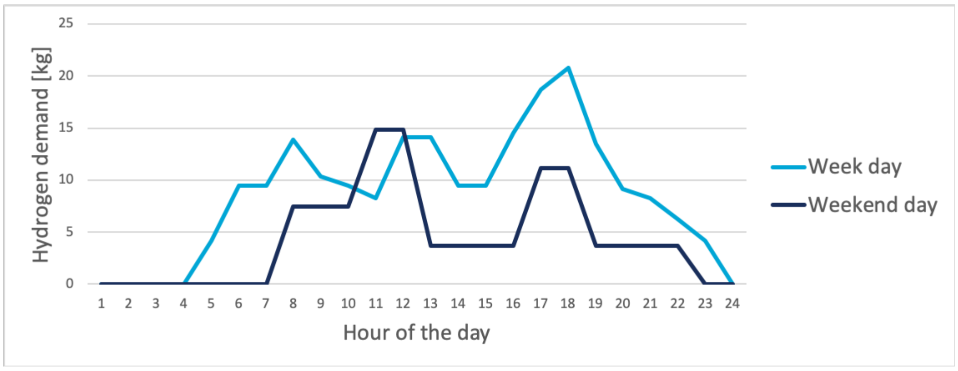


Figure 4.10: Fueling demand of FCEV vehicles

Together, the external fuel demand and agricultural hydrogen fuel demand add up to the graph shown in figure 4.11.

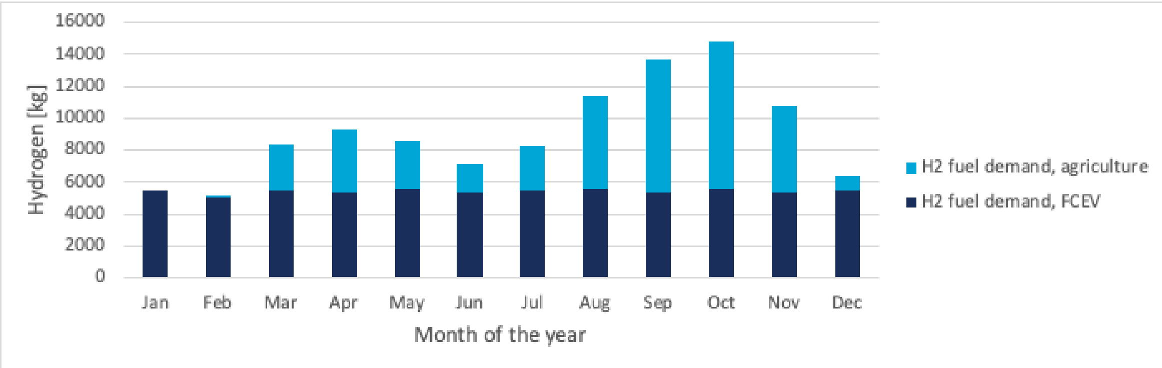


Figure 4.11: Hydrogen fuel demand at fuel station over a year

4.4.2 External fuel price

There are currently 5 hydrogen stations in the Netherlands, in Rhoon, Arnhem, Delfzijl, Helmond and The Hague. It is common practice to sell hydrogen at 10 €/kg H_2 (NU.nl/AutoWeek, 2019), which is why it is assumed that external parties fueling at the station will pay this price.

The fuel station operator buys the hydrogen from H2Oudeschip. It is assumed that the hydrogen is sold to the fuel station operator for 0,5 €/kg on top of the LCOH, which will be explained in section 5.2.6.

4.5 Hydrogen export and import

If there is more hydrogen produced than consumed by all of the above, a full tube trailer with 200 kg hydrogen can be driven to other consumers of hydrogen, e.g., other fuel stations, or chemical companies in the Delftzijl chemical park which already use grey hydrogen. The price for these customers is assumed to be 6 €/kg H_2.

If the demand for hydrogen exceeds the volume of stored hydrogen in addition to the produced hydrogen during a certain hour, hydrogen needs to be imported. It is assumed that hydrogen is imported for a price of 8 €/kg. In real life, a full tube trailer would need to be imported in order to get hydrogen to Oudeschip, but due to the complexity of the PtX model and time constraints it is assumed that hydrogen can be imported per kg.

Chapter 5

Description and use of the simulation model

The new energy system and its components are known, as is the supply pattern of wind power and demand patterns of household heating, agricultural mobility, and external mobility. While most of the components of the new energy system of Oudeschip have a set size, there are two components for which this is still an unknown. The largest flexible investment in the new energy system of Oudeschip is the electrolyser. It should be large enough to handle a significant power input from the wind turbines, but not too large since it would produce too much hydrogen and result in high investment costs. The gap between the supply and demand patterns must be filled with hydrogen storage, which makes the required capacity of this component unclear. By simulating the supply and demand for every hour during an entire year, it becomes clear how the capacity of the electrolyser and hydrogen storage facility influence the Levelized Cost of Hydrogen (LCOH) and payback time of the new energy system of Oudeschip.

A dynamic discrete-time abstract analytical modelling approach creates an energy balance and helps to compare different configurations of the system according to their technical characteristics and cost structure. *Dynamic*, because the state of the system varies over time e.g. the storage level of the system or power produced by the windmills. *Discrete time*, because all models and data in the energy sector is analysed per hour. *Abstract* since the physical representation of the different components of the system are irrelevant, only their technical and economic properties are of relevance. *Analytical*, since the functioning of the system and interaction between components will be mathematically described.

This chapter starts with a description of the PtX simulation model used in this research, and the alterations to the model in order to simulate the Oudeschip case. After that, the mathematical description of the total costs of the new energy system of Oudeschip, the levelized cost of hydrogen, and the payback time is presented. This chapter ends with an explanation of the design of experiments, which is performed to vary and compare the different configurations of the hydrogen storage capacity and electrolyser, according to their levelized cost of hydrogen and payback time.

5.1 Simulation model: PtX

The model used in this research is a deterministic model called the Power-to-X model (PtX), developed by Els van der Roest from the KWR Water Research Institute and used by van der Roest et al. (2020). As was mentioned in chapter 1, the PtX model was developed for a neighbourhood where locally produced renewable energy from wind turbines and solar PV is partly converted and stored in the form of heat and hydrogen. Next to that, rain water is collected, stored, purified and used in this model. The hydrogen is solely used for transport, while heat in the PtX model is stored in an aquifer and distributed using a heat network in order to fulfill household heat demand. An overview of the PtX model is shown in figure

5.1.

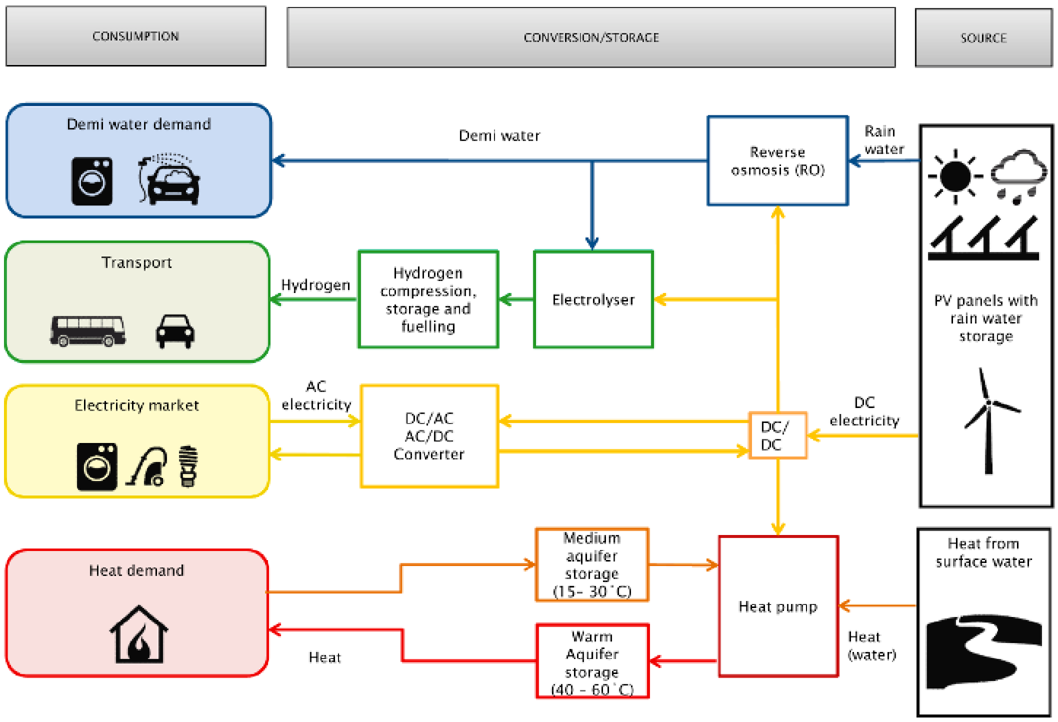


Figure 5.1: PtX

This simulation model takes various economic and technical parameters as input, as well a the supply and demand patterns. With this information as input, together with a scheduling strategy, the PtX model creates an energy balance and delivers the associated system costs. A conceptual overview of the input and output of the PtX simulation model is presented in figure 5.2.

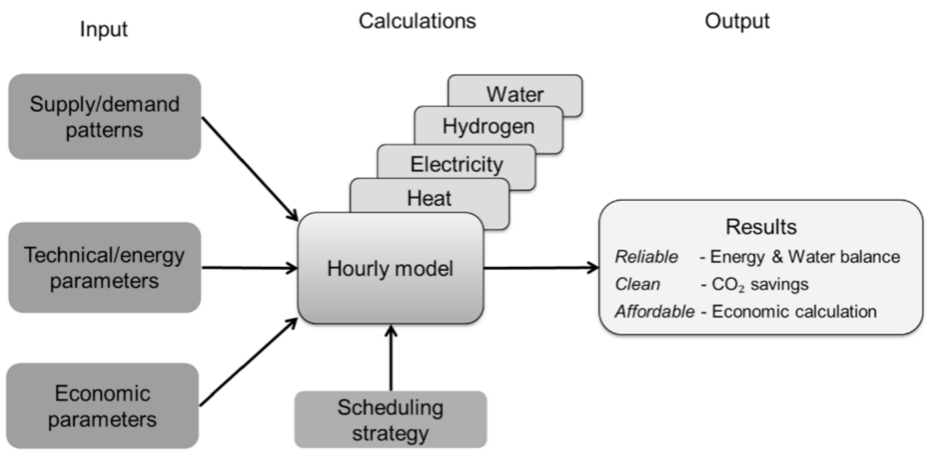


Figure 5.2: Flowchart PtX simulation model

This model is used, since it already takes heat demand and fuel demand from transport as input. Furthermore, there is a form of hydrogen incorporated in the model. Therefore, by adapting some parts of the model, it can be applied for the analysis of the new energy system of Oudeschip. Furthermore, the model is used because is programmed in the Python programming language, which is known by author of this thesis.

The PtX model does not perform dynamic optimization, instead it makes ad hoc decisions for every hour separately. This means that it does not take future hydrogen demand into account when the choice is made if a hydrogen tube trailer is sold or kept as storage for future demand. The way this ad hoc decision making is performed in the model is shown in figure 5.3.

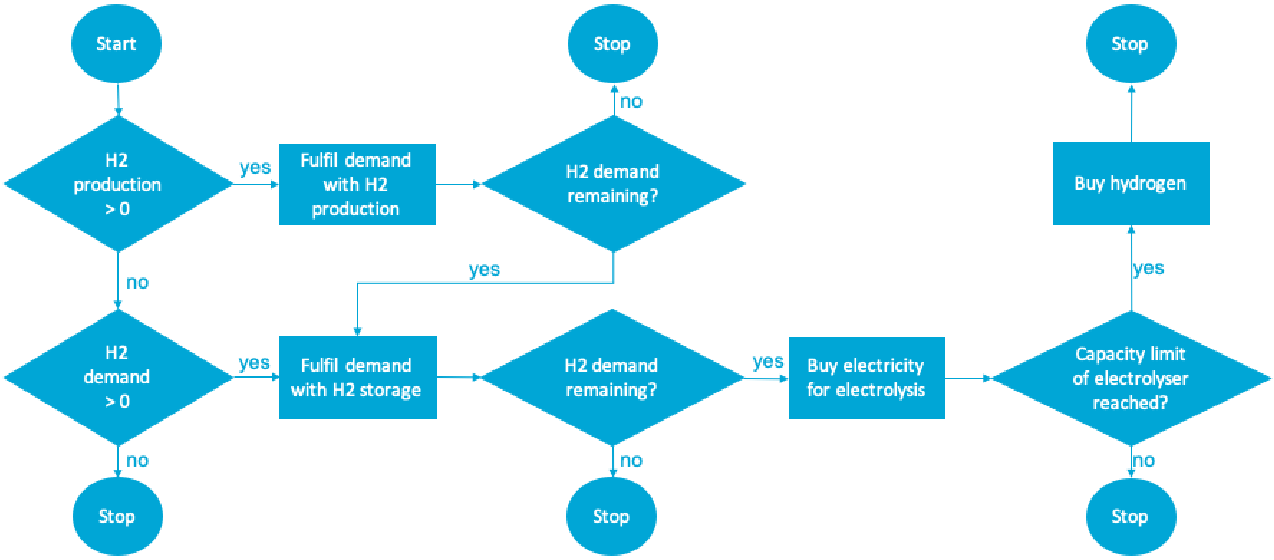


Figure 5.3: Ad hoc decision making in the PtX model

5.2 Alterations to PtX model

The new energy system of Oudeschip does not use a heat network, but fulfills the heat demand by utilizing the hydrogen gas infrastructure. Furthermore, the fuel demand for transport can be expanded to include the fuel demand of tractors. Thus, the model is altered to suit the Oudeschip case.

Several aspects of the PtX model are irrelevant for Oudeschip, such as:

- The collection of rain water and fulfillment of demi water demand
- The power generation by solar panels
- The heat production with a heat pump
- The heat storage in an aquifer
- The fulfilment of heat demand by the heat stored in the aquifer through a heat network

The points mentioned above are disabled in the simulation model in order to run the simulations without them influencing the results. Next to this, several elements are added in order for the Oudeschip case to be simulated. These elements are:

- The wind generation functions are improved
- The household heat demand is fulfilled with hydrogen
- The agricultural mobility demand is added to the hydrogen demand from transport in the PtX model
- In order to minimize the power used to compress hydrogen, the heat demand of the households is directly fulfilled with the produced hydrogen, before the remainder of the hydrogen production is compressed
- A compression function is added with three components: compression to 250 bar for hydrogen storage in the tube trailer, compression to 880 bar for refuelling at 700 bar by FCEV vehicles and

compression to 440 bar for refuelling at 350 bar by agricultural vehicles.
- The electrolyser efficiency curve changes when the input efficiency is altered
- The economic calculations in order to analyse the costs per stakeholder are added

An overview of the PtX model, altered for this research, is shown in figure 5.4.

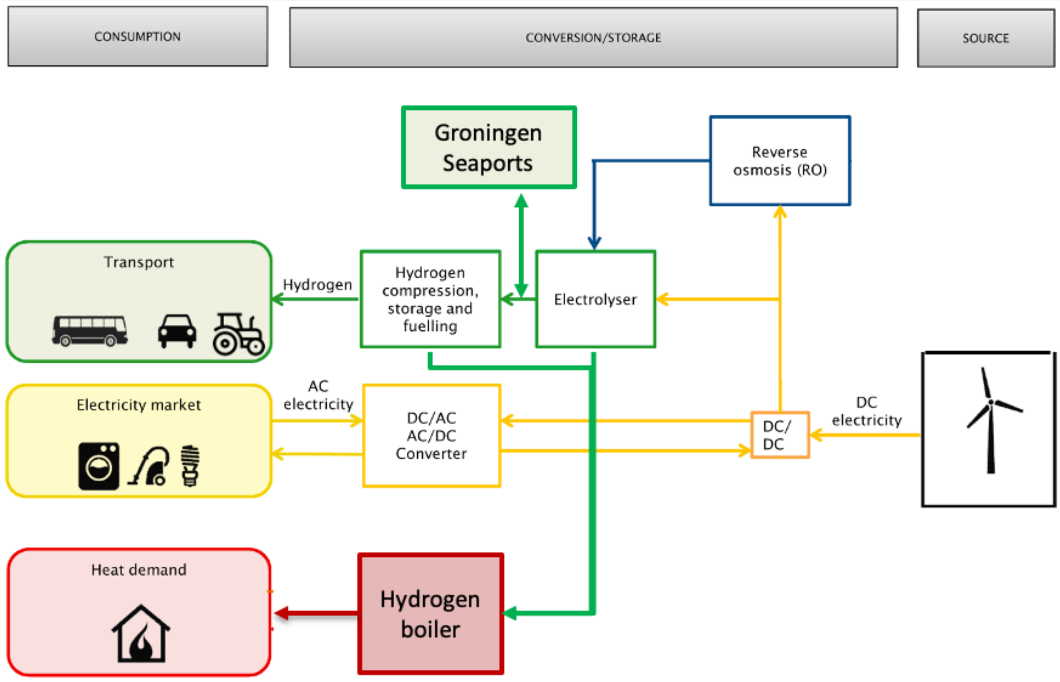


Figure 5.4: Overview of adapted PtX simulation model

The next sections describe how these additions to the PtX model are performed.

5.2.1 Addition: wind generation

In the original form, the PtX model multiplied the wind speed with the power curve of a specific wind turbine to calculate the wind generation. However, this is incomplete to get a realistic view of the generation. This section describes the additions to the functions calculating the wind generation.

The power production by a wind turbine varies with the wind speed in that area that strikes the rotor. This wind speed varies according to the height it is measured at. To calculate the power output of the wind turbine, it is common practice to use the wind speed at hub height as a reference. The hub height of the Lagerwey L136 is 120 meters.

The wind speed meter of the KNMI weather station is placed at a height of 10 meters. However, the wind speed is higher at the hub height of the wind turbine. Therefore, the wind speed measurements need to be adjusted to hub height. A common mathematical model for accounting the variation of the horizontal wind speed with height is the log law, which can be used until the height of 60 meters. The log law is described by equation 5.1 where $u(h_2)$ is the wind-speed at height h_2, $u(h_1)$ is the wind-speed at height h_1, and z_0 is the surface roughness.

$$u(h_2) = u(h_1) * \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \tag{5.1}$$

The surface roughness, or roughness length, represents the roughness of the surrounding terrain. Typical surface roughness length values can be found in table 5.1 with corresponding descriptions of the terrain.

Class name	Roughness length z_0 (m)	Landscape description
Sea	0.0002	Open water, flat plain
Smooth	0.005	Obstacle-free land with negligible vegetation, marsh, ridge-free ice
Open	0.03	Flat open grass, tundra, airport runway, isolated obstacles
Roughly open	0.10	Low crops or plant cover, occasional obstacles
Rough	0.25	Crops of varying height, scattered obstacles with separation
Very rough	0.5	Intensively cultivated landscape with large farms, orchards, bushland; or low well-spaced buildings and no high trees
Skimming	1.0	Full similar-height obstacle cover with interspaces (mature forest, suburban town area)
Chaotic	≥ 2	Irregular distribution of very large elements: high-rise city centre, big irregular forest with large clearings

Table 5.1: Terrain roughness classification (Wieringa & Rudel, 2002)

Since the area around the KNMI weather station is surrounded by a flat area, with only grass fields, a roughness length of 0,01 is used. At some height, the local effect of the earth surface roughness doesn't have any influence on the boundary layer profile anymore. This height is called the blending height. At this height, there is still an increase of wind speed with height, but the shape of that increase is no longer dependent on the Earth's surface. 60 meters is the blending height, at which the logarithmic lines converge. The wind speed at this height is called the meso wind speed. To calculate the wind speeds at heights above 100 meters, the power law of equation 5.2 is more appropriate. This equation also expresses the wind speed at the height h with the wind speeds at the reference height. The used reference height is the meso wind speed. Thus, the wind speed at meso height of 60 meters is calculated with the loglaw, after which this value is converted into the wind speed at hub height using the power law.

$$u(h_2) = u(h_1) * (\frac{h_2}{h_1})^{\alpha} \tag{5.2}$$

in which α is a constant value which differs for wind speeds over land and over sea. The constant used in this research is the standard value of α over land, which is $\alpha = 0,143$. With the roughness length value, equation 5.1 and equation 5.2, the hourly wind speed at hub height can be calculated. This is the wind speed at hub height for the location of the KNMI weather station. The required wind speeds are at the location of Oudeschip, with a different roughness length. However, since the landscape around the wind park at Oudeschip is relatively similar, and the hub height is above the blending height, the wind speeds at hub height at the weather station and at Oudeschip are assumed to be the same.

The wind speed that is acquired through the calculations presented above are combined with the power curve presented in figure 4.1 in order to calculate the generated wind power.

5.2.2 Addition: Household heating with hydrogen

In the original form, the PtX model converts all the generation and demand into the same units: kilowatt hours. The heat demand from households is calculated as described in section 4.2. Instead of fulfilling this heat demand with heat from the aquifer, this energy demand is added to the hydrogen demand from transport, which is already present in the PtX model, and fulfilled with hydrogen.

5.2.3 Addition: Agricultural demand

The fuel demand from agricultural mobility is calculated as described in section 4.3. As mentioned in section 3.4.4, it is assumed that an energy percentage of 60% of the diesel demand is replaced by hydrogen. Similar to the addition of household heat demand, the corresponding curve for hydrogen demand from agricultural mobility is added to the hydrogen demand from transport in the PtX model.

5.2.4 Addition: Compression energy

The compression energy required to compress hydrogen for storage in the tube trailer, as well as the compression for refuelling at 350 and 700 bar, are calculated using a compression function. The hydrogen required to fulfill household heat demand per hour is subtracted by the volume of hydrogen that can be fulfilled immediately from the production of hydrogen during that specific hour. The remainder of hydrogen demand for household heating is multiplied by the compression energy required to compress hydrogen from 30 bar to 250 bar. The hydrogen demand from agricultural mobility is multiplied with the compression energy required to compress hydrogen from 30 bar to 400 bar, and the hydrogen demand from FCEV vehicles is multiplied with the compression energy required to compress hydrogen from 30 bar to 880 bar, as described in section 3.4.7.

5.2.5 Addition: Electrolyser efficiency

In the original form, the PtX model only simulates a PEM electrolyser, which has a set efficiency curve. However, for the Oudeschip case, a PEM electrolyser is compared to an Alkaline electrolyser, as described at the end of this chapter in section 5.6. The efficiency of these two types of electrolysers differs, as mentioned in section 3.4.2. Therefore, the simulation model is slightly altered in order to take this change in efficiency into account. Since literature does not present a specific efficiency curve for alkaline electrolysers, it is assumed that the efficiency curve of an Alkaline electrolyser has the same form as the efficiency curve of a PEM electrolyser.

5.2.6 Addition: economic calculations

Since the original PtX model has a different configuration of components than is required for the Oudeschip case, the economic calculations are made from scratch. Since the components are grouped per stakeholder, as shown in the system design of figure 3.4, the total costs per stakeholder need to be calculated. Because the hydrogen price for the fuel station and households is based on the price of the hydrogen, the Levelized Cost of Hydrogen (LCOH) is calculated. Lastly, the formula for calculating the payback time of the investments per stakeholder is presented in this section.

Total cost of stakeholder

The Total Cost of Stakeholder (TCoS) in €/year is the sum of the total annual capital and operations and maintenance costs TC_i (€/year) of all the system components n of a single stakeholder s in the new energy system of Oudeschip in addition to its cost for importing electricity or hydrogen EC^s:

$$TCoS^s(€) = \sum_{i=1}^{n} TC_i + EC^s \tag{5.3}$$

The TC_i of an individual component are calculated with the annual capital cost CC_i (€/year) and operational and maintenance cost OMC_i (€/year):

$$TC_i(€/year) = CC_i + OMC_i \tag{5.4}$$

The CC_i (€/year) of a component is calculated with the annuity factor AF_i (%), installed component capacity Q_i (component specific capacity) and investment cost IC_i (€/component specific capacity):

$$CC_i(€/year) = AF_i * Q_i * IC_i \tag{5.5}$$

The annuity factor AF_i is based on the weighted average cost of capital WACC (%) and the economic lifetime of the component LT_i (years):

$$AF_i = \frac{1 - (1 + WACC)^{-LT_i}}{WACC} \tag{5.6}$$

The annual operations and maintenance costs OMC_i (€/year) are expressed as an annual percentage OM_i (%) of the Q_i and IC_i:

$$OMC_i(€/year) = OM_i * Q_i * IC_i \tag{5.7}$$

A WACC of 3% is used.

Levelized cost of hydrogen

The Levelized Cost of Hydrogen, $LCOH$ (€/kg H_2), is calculated by dividing the total cost of stakeholder H2Oudeschip $TCoS^{H2Oudeschip}$ by the annual hydrogen production HP (kg H_2/year), since this stakeholder produces the hydrogen:

$$LCOH(€/kgH_2) = \frac{TCoS^{H2Oudeschip}}{HP} \tag{5.8}$$

Payback time

The profit per stakeholder s per year is calculated by adding the revenues from selling hydrogen RH_2^s (€/year), and subtracting that with the costs of that stakeholder from operations and maintenance OMC_i in addition to buying hydrogen C_H^i and/or buying electricity C_E^i:

$$Profit^s = RH_2^s - C_H^s - C_E^s - \sum_{i=1}^{n} OMC_i \tag{5.9}$$

By summing up the investment costs of the components for a single stakeholder, together with the profit of that stakeholder, the payback time is calculated as follows:

$$Paybacktime^s = \frac{\sum_{i=1}^{n}(IC_i * Q_i)}{profit} \tag{5.10}$$

5.3 Overview of assumptions

At this point the interacting components of the new energy system, and their implementation in the model, are known. In the past chapters, several assumptions were made, which are listed below for the sake of clarity.

Technical assumptions

- Hydrogen demand from external FCEV vehicles is similar to an average hydrogen station
- An unlimited amount of tube trailers can be sold to external parties
- The electrolyser has an internal DC/DC converter
- The tractors of the 15 farmers can be converted to diesel-hydrogen hybrids
- The tractors replace 60% of the diesel by hydrogen
- The heat demand of the houses in Oudeschip are similar to an average household, per m^2
- The houses in Oudeschip have an average floor area of 120 m^2
- The 15 farms around Oudeschip are averagely sized and consume 12.000 liters of diesel per year
- Hydrogen can be imported per kg
- All external FCEV vehicles refuel at 700 bar

- The wind speed at hub height in Oudeschip is the same as the wind speed at hub height at Lauwersoog

Economic assumptions

- The cost, including installation, of a hydrogen boiler is similar to a traditional HR boiler
- There are no costs involved in the conversion of the tractors
- The conversion costs of the gas infrastructure costs 200 €per household
- The costs for the new 30 bar hydrogen pipeline is 300 €/m
- H2Oudeschip buys wind power for 0,029 €/kWh
- H2Oudeschip buys electricity from the grid for 0,04 €/kWh
- The farmers pay 4,83 €/kg
- Hydrogen is sold at the fuel station to external FCEV owners for 10 €/kg
- Hydrogen is sold by H2Oudeschip to the fuel station operator for LCOH plus an additional 0,5 €/kg
- Hydrogen is sold by H2Oudeschip to the local residents for LCOH plus an additional 0,05 €/kg
- A tube trailer full of hydrogen is sold for 6 €/kg
- Hydrogen is imported for 8 €/kg

Institutional assumptions

- It is allowed to transport 100% hydrogen through the natural gas grid of Oudeschip
- The households of Oudeschip receive an exemption to the energy tax on their energy bill
- H2Oudeschip can sell the hydrogen directly to the households, without an energy company in between

5.4 Model verification

"Computerized model verification ensures that the computer programming and implementation of the conceptual model are correct" (Sargent, 2010, p. 173). Because the simulation model is programmed in Python, which is a higher level programming language, verification is concerned with the determination that the simulation functions and that the computerized model has been programmed correctly. This is performed by:

- using programming skills to write and debug the program in sub-programs
- using 'structured walk-through' policy in which more than one person is to read the program
- By checking the simulation model output using various input combinations

During the conversion of the model for the Oudeschip case, and the addition of several components, errors were fixed on the go when they occurred. When the model was complete and there were no more running errors, the outputs as well as intermediate results were checked for irregularities. Furthermore, the program was read by Els van der Roest from the KWR Research institute who designed the original PtX model. Lastly, before running the model for the 16 different scenarios, the input parameters were altered so check if the outcomes changed in an expected manner.

5.5 Model validation

Validation of the model is to ensure that the simulation model and conceptual model represent the real world. "Conceptual model validity is determining that (1) the theories and assumptions underlying the conceptual model are correct and (2) the model's representation of the problem entity and the model's structure, logic, and mathematical and causal relationships are 'reasonable' for the intended purpose of the model" (Sargent, 2010, p. 173). Sargent(2010) mentions that there are four basic decision-making approaches to decide whether a model is valid. The first is to have the model development team itself make the decision if the simulation model is valid. The second is to have the user of the model involved in the development and decision of the validity. The third is called the 'independent verification and validation' method, in which a third independent party decides whether the model is valid. The fourth and last method is to use a scoring model. Due to time constraints, the determination of the validity of the model used in this research is performed by the development team itself.

There are various techniques for validating a model can be found in literature, the ones used in this research are:

- *Degenerate tests* in which the model's behavior is tested by varying the input and internal parameters for plausible values
- *Extreme condition tests* in which the outputs should be plausible for extreme combinations of input variables in the system
- *Face validity* where knowledgeable individuals are asked whether the model and its behaviour is reasonable
- *Traces* which involves the tracing of different types of entities in the model to determine if the logic is correct.

While the above mentions the validation of the model, data validation is also performed. The concerns are that accurate, sufficient and appropriate data are available. This validation are performed for the used wind speeds and temperatures.

The above mentioned validations of the model and the data are expanded in Appendix A. The conclusion is that both the model and used data are valid.

5.6 Design of experiments

A design of experiments is a systematic method to see the influence of process variables on the output of that process, as well as the relationship between those variables. As mentioned at the beginning of this chapter, the biggest influence on the costs and dynamics of the system are the hydrogen storage capacity and the electrolyser capacity. Therefore, in order to see their influence, a design of experiments (DOE) is performed with altering values for the electrolyser type/capacity and hydrogen storage capacity. Furthermore, as discussed in section 3.4.2, there are two types of electrolysers with different efficiencies and investment costs, which are both simulated. An overview of the controlled system variables is shown in figure 5.5.

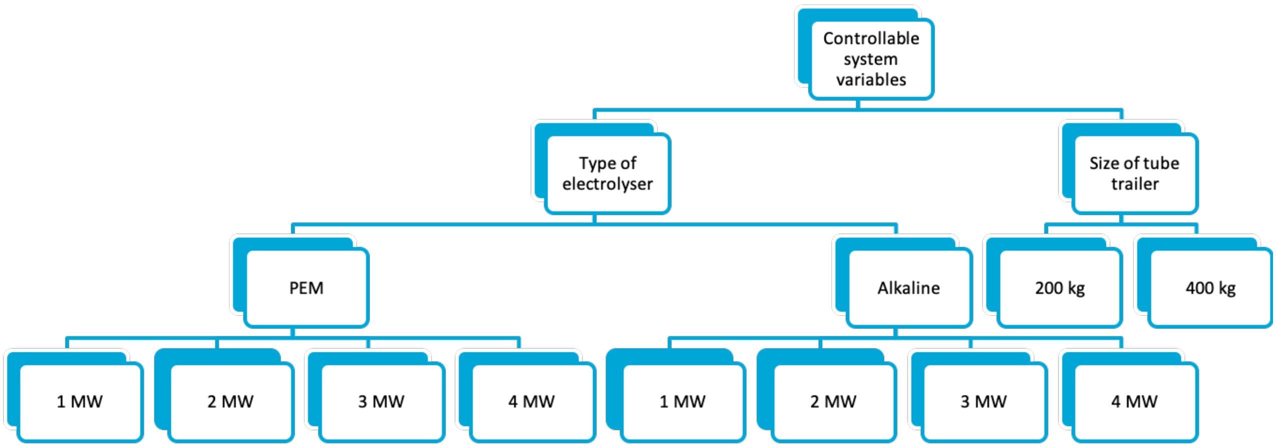


Figure 5.5: Input values for controllable system variables

Figure 5.6 shows the different input parameters of the design of experiments, as well as the controllable system variables. As described in chapter 4, the PtX model calculates the heat demand of the 180 households in Oudeschip by using the outside temperature data of the KNMI, and the wind generation by using the wind speed of the KNMI in combination with the power curve of the Lagerwey L136 wind turbines. If there is no wind generation, and the hydrogen storage is empty, electricity can be bought from the electricity market to feed in to the electrolyser to produce hydrogen.

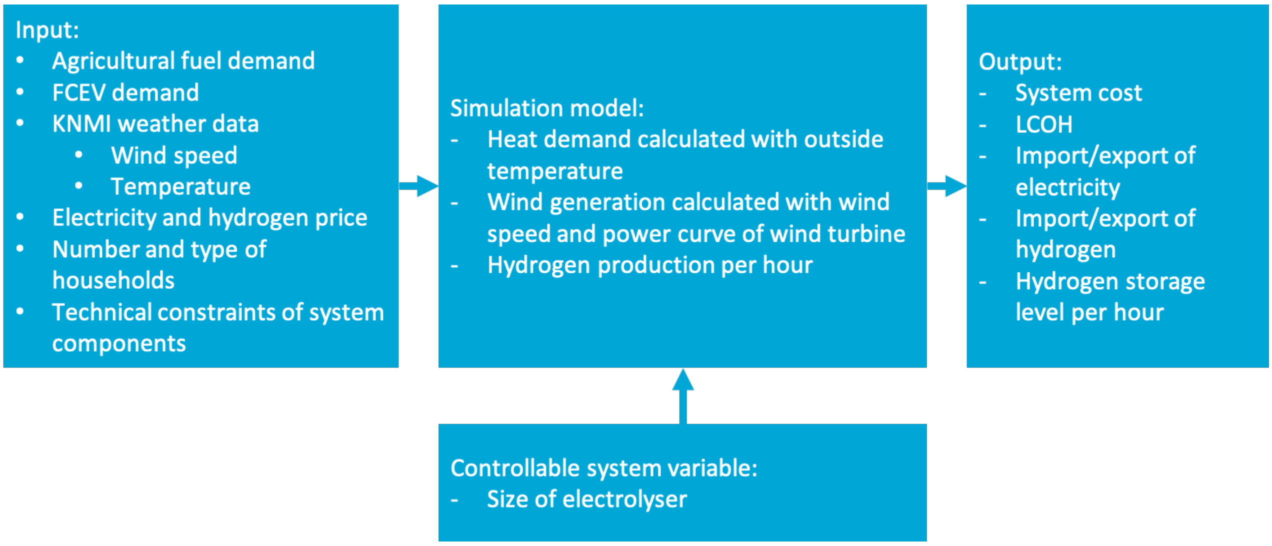


Figure 5.6: Flowchart of the DOE

As output, the PtX model gives the total system cost of energy, the levelized cost of hydrogen, and the payback time. Besides that, the model gives an overview of the hydrogen storage level per hour, the volume of hydrogen imported/exported per hour, as well as the volume of electricity bought and sold per hour.

Chapter 6

Simulation results

The design of experiments discussed in section 5.6 describes the comparison of different setups of the new energy system of Oudeschip, with electricity and hydrogen as energy carriers, on three different levels: the type of electrolyser, capacity of electrolyser and the capacity of the hydrogen storage. Each of these configurations results in a different LCOH, costs and payback time of the system. The consequences of each of these configurations are discussed in this chapter. The chapter starts with an overview of the generation profile of the two wind turbines. After that, the results of the simulations regarding the LCOH, type of electrolyser, capacity of electrolyser and capacity of the hydrogen storage are presented. Lastly, the impacts of the different configurations on the stakeholders is discussed. All the resulting graphs from the simulations are shown in Appendix B. Every graph in this chapter which presents the months over a whole year on the x-axis, is constructed by taking the average value of the 10 simulated years between 2010 and 2019.

6.1 Wind generation

By combining the wind speed pattern and power curve discussed in section 4.1.1 with the wind speed calculations discussed in section 5.2.1, the wind generation between 2010 and 2019 is obtained. This results in an average annual generation of 16.709.737 kWh per Lagerwey turbine, with an associated load factor of 42,4%. The total wind generation per month, is shown in figure 6.1.

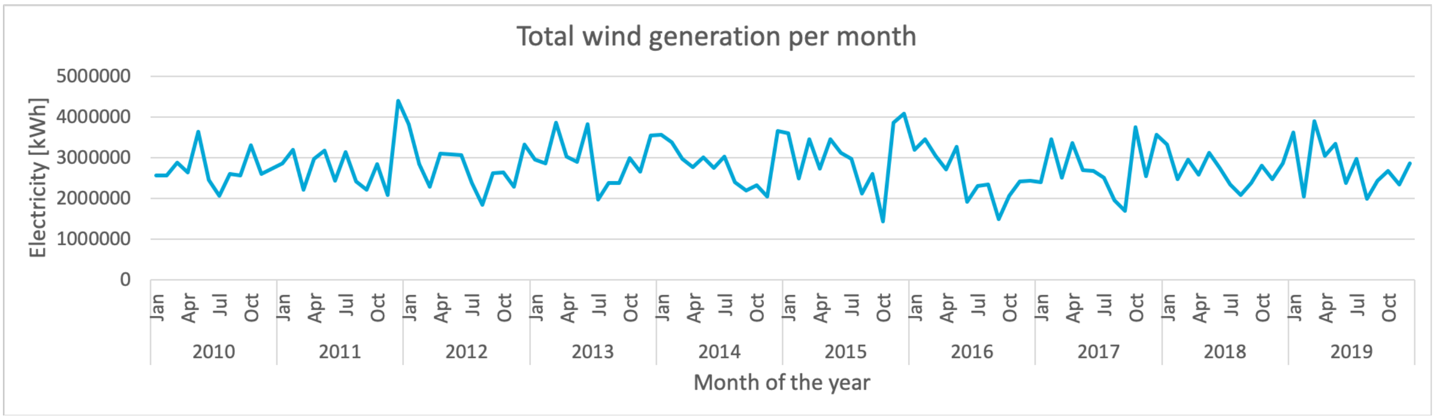


Figure 6.1: Wind power generation from 2010 to 2019 by two turbines at Oudeschip

There is a clear fluctuation per month and per year. There is also a fluctuation in hydrogen demand, which means that there is a mismatch between supply and demand. This gap can be overcome by storing a certain volume of hydrogen, which will be discussed later on in this chapter.

6.2 Levelized Cost of Hydrogen

The LCOH is crucial for the economic feasibility of a hydrogen based energy system in Oudeschip, since the hydrogen price for the fuel station as well as the households are based on this number. The LCOH is calculated as described in section 5.2.6. The effect of each configuration on the LCOH is shown in figure 6.2, of which the exact numbers are presented in Appendix B.1.

It is clear that an electrolyser larger than 1 MW results in a lower LCOH. The reason behind this is explained in section 6.4. Furthermore, the Alkaline electrolyser has a significantly lower LCOH. This is elaborated on in section 6.3. Lastly, having two tube trailers with a combined storage capacity of 400kg instead of a single tube trailer, has a minimal effect on the LCOH, which will be elaborated on in section 6.5.

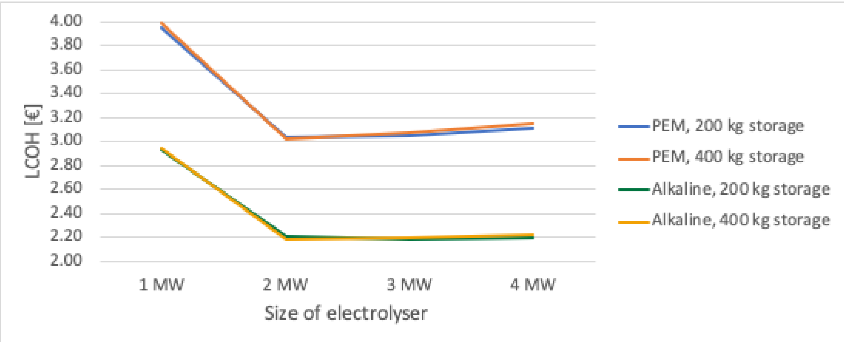


Figure 6.2: LCOH per scenario

6.3 Type of electrolyser

Section 3.4.2 described the differences between the Alkaline and PEM electrolyser. The investment cost of the PEM and Alkaline electrolyser are 1100 €/kW and 500 €/kW respectively. Furthermore, the efficiency of a PEM electrolyser is 71%, while the efficiency of an Alkaline electrolyser is 83%. Therefore, it is expected that the Alkaline electrolyser has both a lower LCOH and payback time for H2Oudeschip. The results presented in figure 6.2 and 6.17 clearly confirm this. Therefore, the remainder of the results will only discuss the differences between configurations with an Alkaline electrolyser.

6.4 Capacity of electrolyser

The capacity of the electrolyser has a large influence on the investment cost. However, since there is a relative abundance of wind generation, an electrolyser with bigger capacity remains to have a large load factor. The abundance of electricity is observable in figure 6.3.

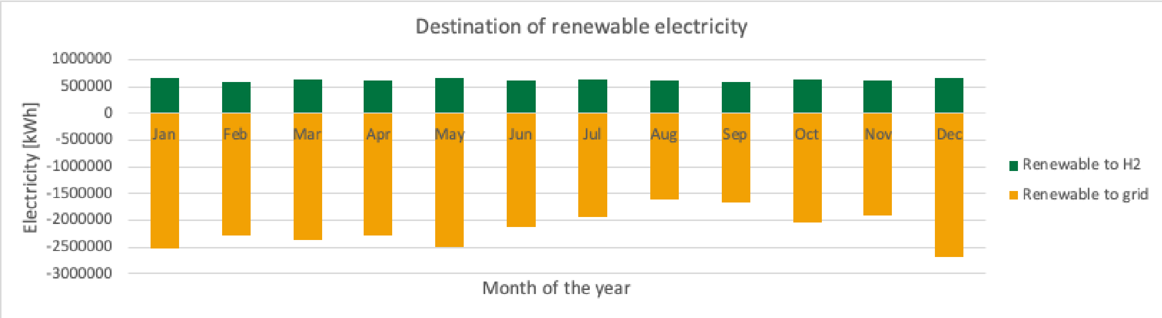


Figure 6.3: Destination of wind power, 1 MW electrolyser, 200 kg hydrogen storage

This results in situations where the capacity limit of the electrolyser is reached, but the demand for hydrogen remains larger than the volume of hydrogen produced. In order for the hydrogen consumption to be met, hydrogen needs to come from storage. However, if the hydrogen storage can not fill the gap between supply and demand, hydrogen needs to be imported, as can be seen in figure 6.4.

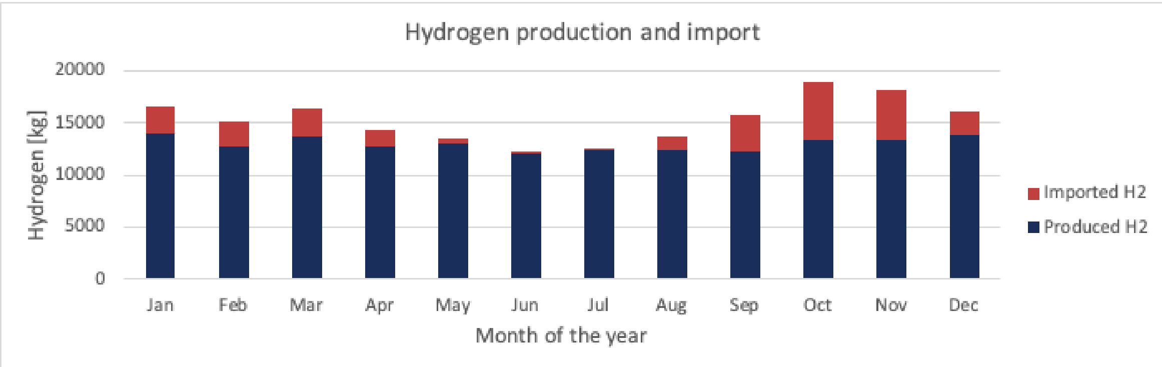


Figure 6.4: Source of hydrogen to fulfill demand, 1 MW electrolyser, 200 kg hydrogen storage

Figure 6.5 shows the distribution of wind power, the only difference to figure 6.3 being the capacity of the electrolyser. When comparing the wind power distribution with an electrolyser of 1 MW from figure 6.7 with an electrolyser of 4 MW in figure 6.5, the takeaway is that a larger part of the wind power can be utilized to produce hydrogen. Therefore, there is less capacity needed from the electricity grid.

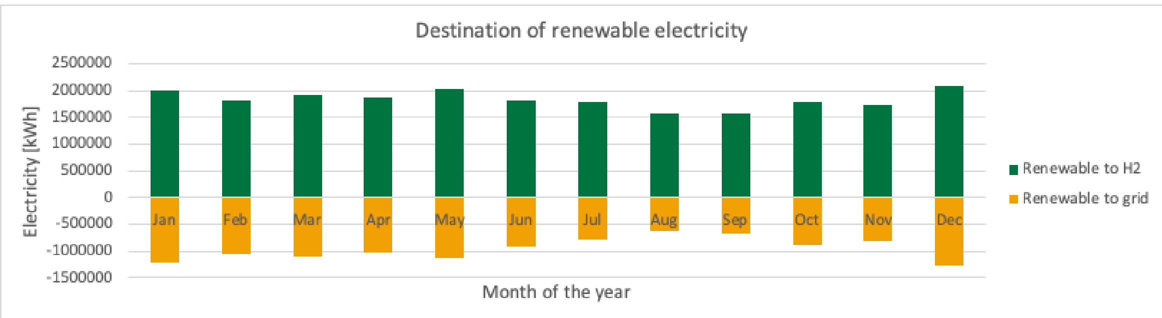


Figure 6.5: Destination of wind power, 1 MW electrolyser, 200 kg hydrogen storage

While a small electrolyser of 1 MW results in a large volume of imported hydrogen, a larger electrolyser is able to cover a larger part of the demand with local production. Figure 6.6 shows the hydrogen production and import over the year for a 4 MW electrolyser, which can be compared to figure 6.4 to show the difference in volume of imported hydrogen.

A smaller electrolyser may be accompanied with low investment cost, it also result in a higher LCOH, since it is more expensive to buy hydrogen than to produce with electricity, as is evident from figure 6.2.

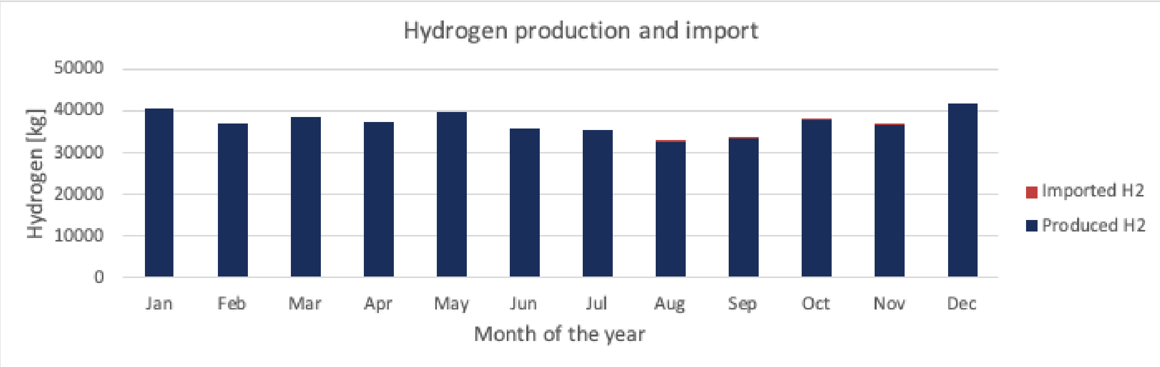


Figure 6.6: Source of hydrogen to fulfill demand, 4 MW electrolyser, 200 kg hydrogen storage

The hydrogen is needed to cover the cumulative hydrogen demand. In summer, this demand is low, since there is no peak in hydrogen demand from household heating, neither from agricultural mobility. As shown previously in figure 4.11, external FCEV demand is relatively constant through the year. As can be seen from figure 6.7, a 1 MW Alkaline electrolyser only produces an abundance of hydrogen during the summer period. As is apparent from figure 6.4, this is also the only period in which there is a low volume of hydrogen imported.

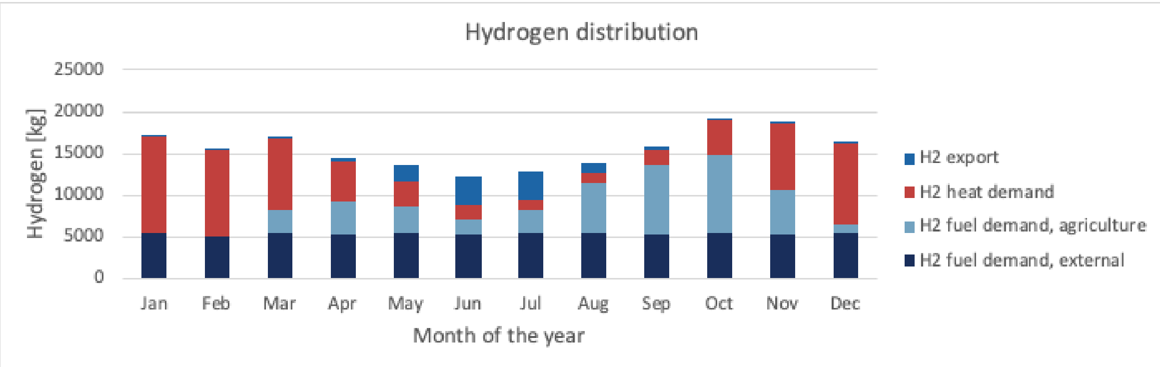


Figure 6.7: Distribution of hydrogen, 1 MW electrolyser, 200 kg hydrogen storage

Since the hydrogen demand for household heating and agricultural mobility stays the same, regardless of the capacity of the electrolyser or hydrogen storage facility, any excess hydrogen is sold to external parties. Figure 6.7 and figure 6.8 show a clear difference in the volume of hydrogen exported per year. A 4 MW electrolyser produces an abundance of hydrogen, while the local demand remains the same. Therefore, several tube trailers full of hydrogen are driven away each month.

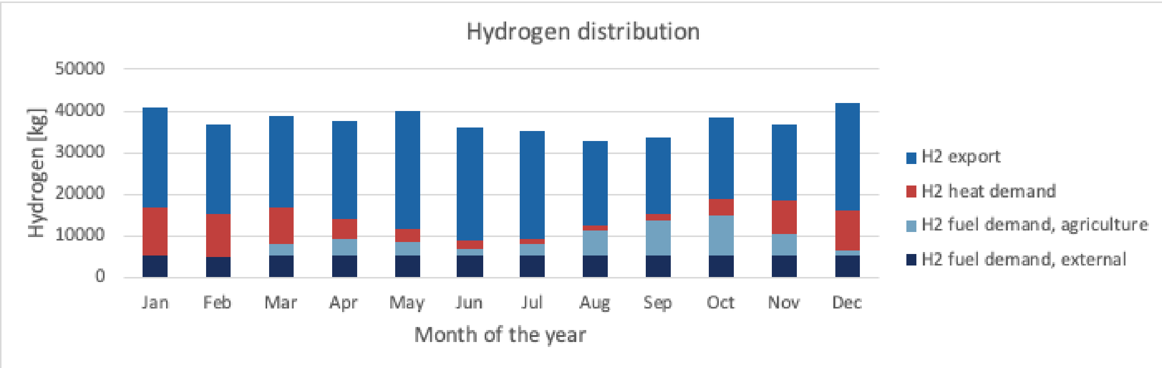


Figure 6.8: Distribution of hydrogen, 4 MW electrolyser, 200 kg hydrogen storage

In order to get a better idea of the consequence of a small electrolyser on the dynamics of the system, figure 6.9 shows a zoomed in view of 3 days in September 2013, the 12^{th}, 13^{th} and 14^{th}. The first day is a Wednesday, on which the hydrogen storage can build up due to low demand and constant maximum production. The electrolyser is producing at maximum capacity, which is 20,5 kg/hour for a 1 MW Alkaline electrolyser. At the end of the day, the farmers come to refuel, and even though the electrolyser is still working at maximum capacity, the tube trailer is quickly emptied out. Even though the storage was full for more than 60%, hydrogen needed to be imported. In the two days that follow, the electrolyser is producing at maximum capacity for most of the time, but the hydrogen demand is far greater than the produced volume, and every time the farmers come to refuel at the end of the day, the volume of hydrogen produced and in the tube trailer are not sufficient to meet the demand.

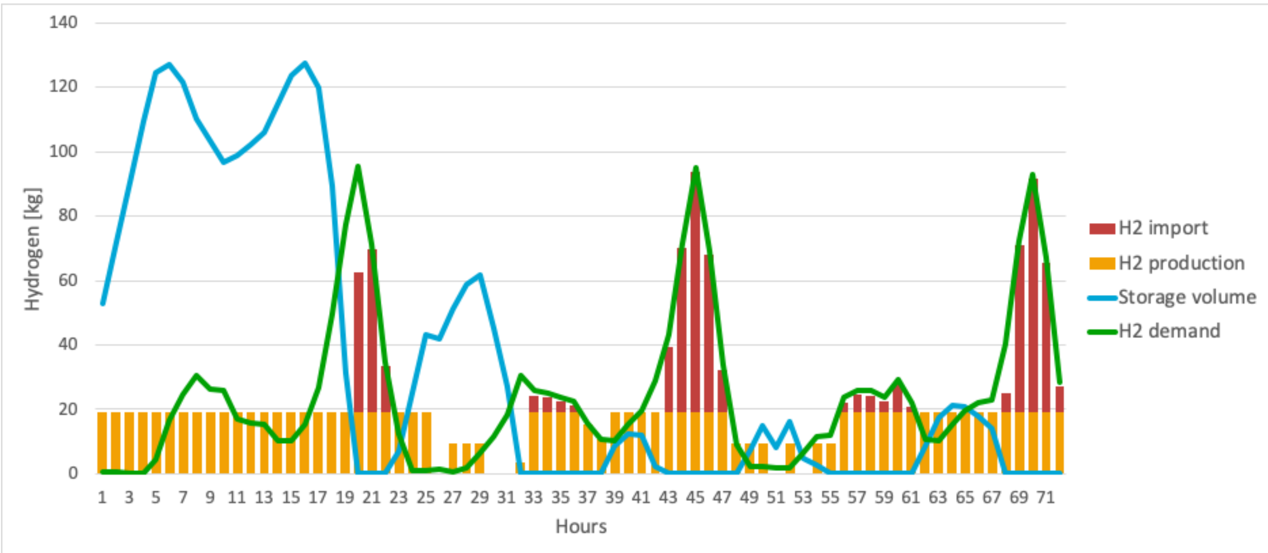


Figure 6.9: Hydrogen developments over a 3 day period, 1 MW Electrolyser, 200 kg hydrogen storage

As mentioned before, a larger electrolyser can cover more of the hydrogen demand directly from hydrogen production instead of relying on built up hydrogen storage. An increase from 1 to 2 MW electrolyser capacity, results in a much lower imported volume of hydrogen, as is evident from figure 6.10.

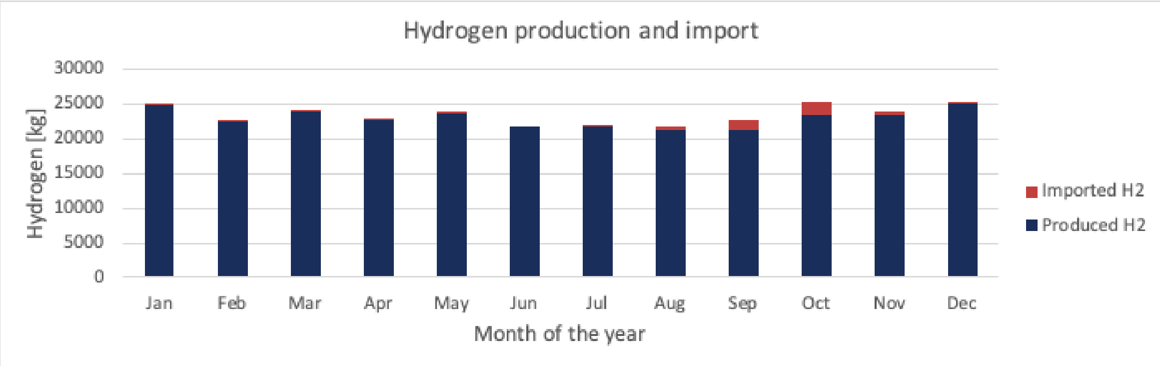


Figure 6.10: Source of hydrogen to fulfill demand, 2 MW electrolyser, 200 kg hydrogen storage

Apart from the decrease in import of hydrogen, an increase in electrolyser capacity to 2 MW increases the volume of exported hydrogen significantly, as can be seen in figure 6.11. Increasing the electrolyser capacity more, results in a higher volume of excessive hydrogen, which can be exported. Most of the need for import of hydrogen is fulfilled when the electrolyser capacity is 2 MW or bigger. This is the reason why the graph in figure 6.2 is plateauing after the electrolyser capacity transcends 2 MW.

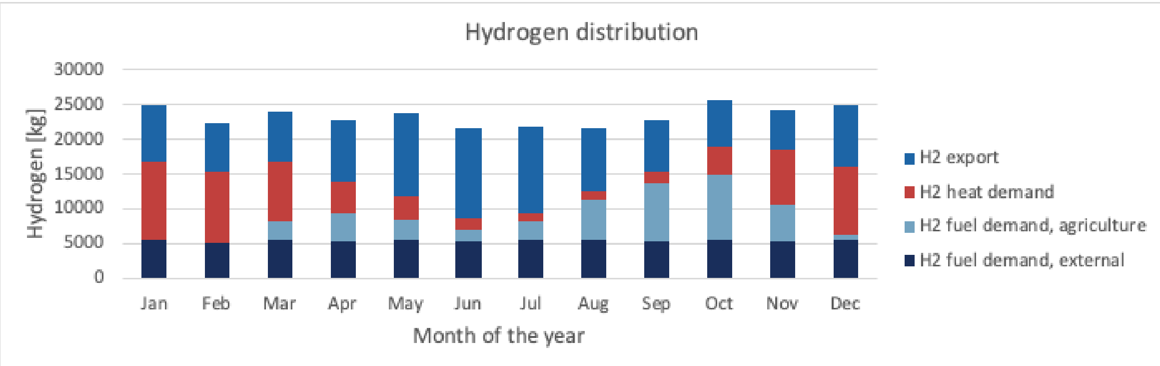


Figure 6.11: Distribution of hydrogen, 2 MW electrolyser, 200 kg hydrogen storage

Even though a 4 MW electrolyser produces a cumulative abundance of hydrogen, there is still hydrogen import required during the year, as can be seen from figure 6.6 in the month of August. The reason for this is that the tube trailer with hydrogen is sold when it is full. This will be explained further in the next section.

6.5 Capacity of hydrogen storage

As described in section 3.4.7, the investment cost of a single tube trailer is 146,000 €, which is low in comparison to the investment in an electrolyser. An Alkaline electrolyser costs around 500,000 euros per MW. Therefore, it is expected that it is preferable to invest in more storage, instead of investing in a large electrolyser, capable of producing an abundance of hydrogen. However, figure 6.2 does not show a significant difference in LCOH between the two sizes of hydrogen storage. Moreover, except for the configuration with an electrolyser capacity of 2 MW, having two tube trailers results in a higher LCOH. However, as can be seen from figure 6.10, there is hydrogen imported when there is only a single tube trailer available for storage. Figure 6.12 shows the sources of the used hydrogen for a configuration with the same electrolyser, but with two tube trailers for storage.

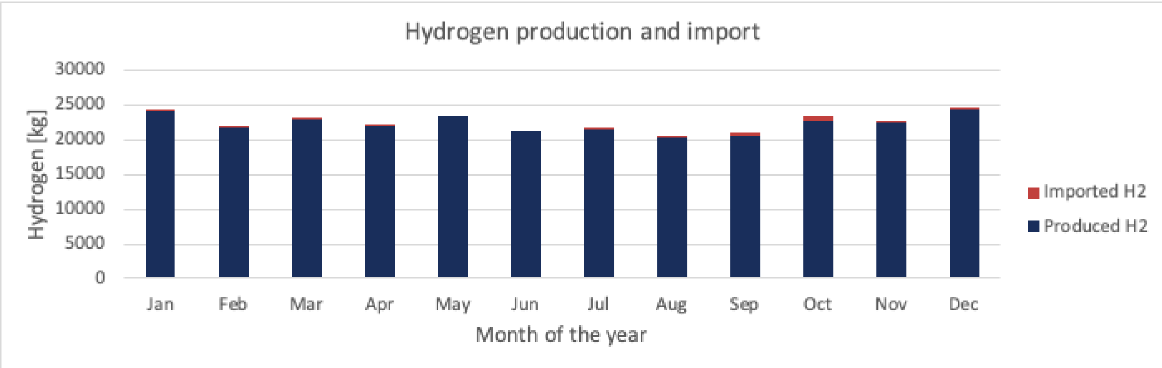


Figure 6.12: Source of hydrogen to fulfill demand, 2 MW electrolyser, 400 kg hydrogen storage

Since the hydrogen tube trailer is sold when it is full, and the model makes ad hoc decisions, without knowledge of the future, sometimes a hydrogen trailer is sold right before a peak in demand. When there are two tube trailers of 400 kg, this is not a major problem, since there is still 200kg of hydrogen left. However, when there is only a single tube trailer, which is sold instantly when it is full, the system is left with a very low storage level.

As shown in figure 6.13, this happens on the 1st and 2nd of October, 2013. The wind speed is relatively constant, which results in a constant maximum production of hydrogen by the electrolyser. On the second hour of the day, the tube trailer is sold, but because the demand for hydrogen remains low, there is no need for imported hydrogen. At 15:00, the tube trailer is full again, which results in it being sold and driven away. Unfortunately, between 16:00 and 22:00, there is a peak in hydrogen demand, which can not be fulfilled by the combination of hydrogen production and hydrogen storage. Therefore, hydrogen needs to be imported.

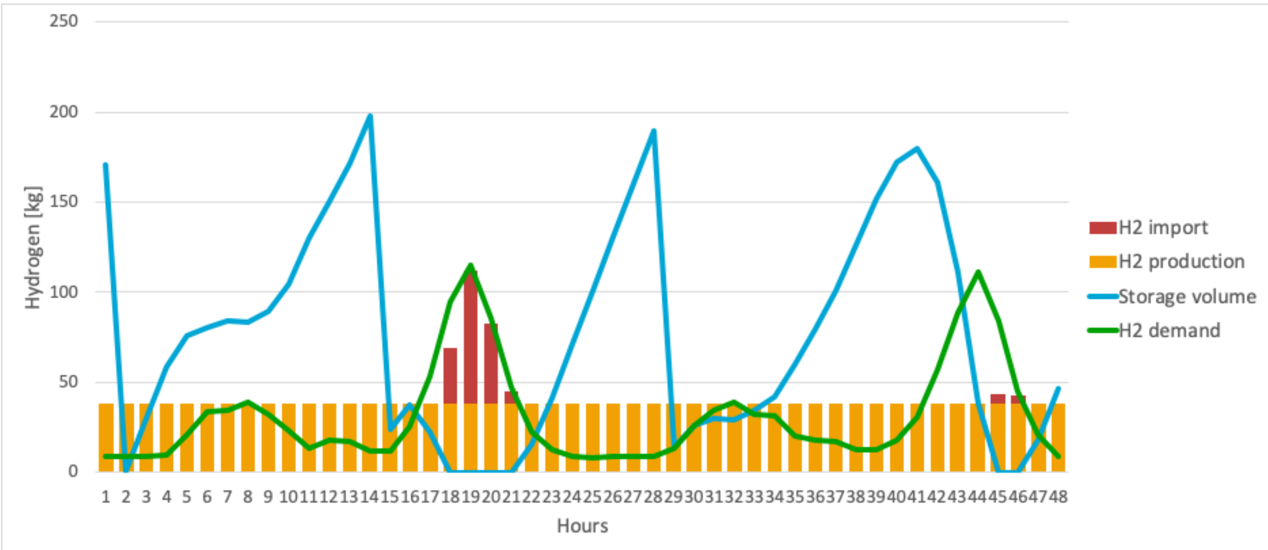


Figure 6.13: Hydrogen development 1/10/2013 - 2/10/2013, 2 MW electrolyser, 200 kg hydrogen storage

Therefore, for these situations, it might be preferable to have two tube trailers. Figure 6.14 shows the same two days, but with two tube trailers. The electrolyser can remain to produce at full capacity, multiple tube trailers are sold, while the local hydrogen demand is still fulfilled by the remainder of stored hydrogen.

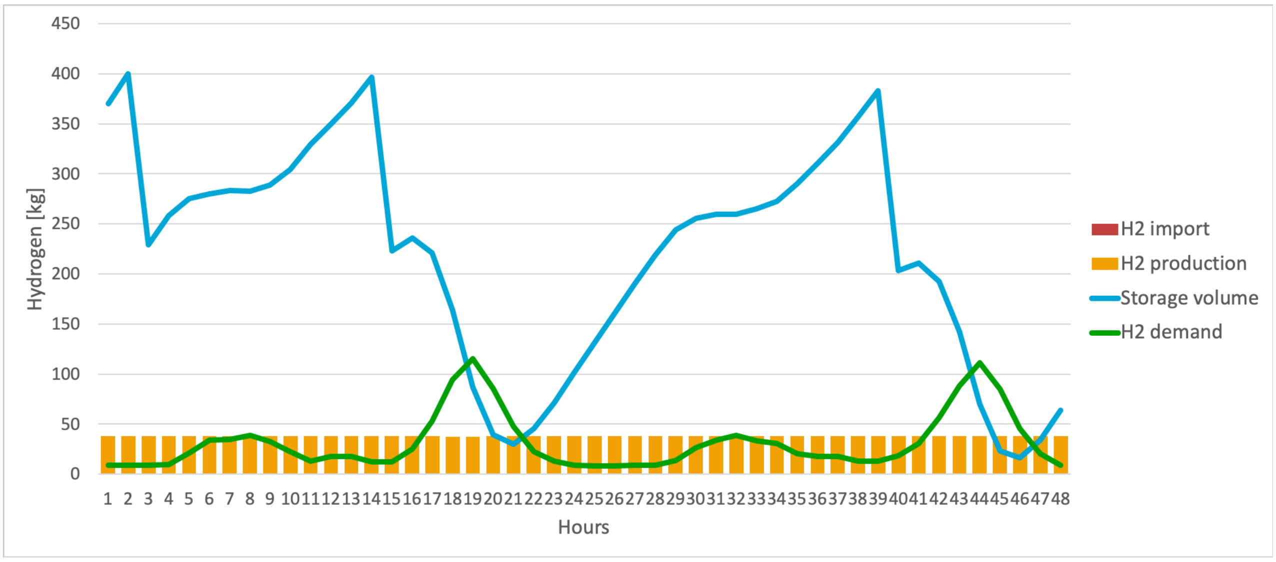


Figure 6.14: Hydrogen development 1/10/2013 - 2/10/2013, 2 MW electrolyser, 400 kg hydrogen storage

If the simulation model would take future demand into account, the tube trailer would have been kept a little longer, and the electrolyser would have produced less hydrogen, in order to avoid the import of hydrogen. On the other hand, turning down the electrolyser while the wind turbines are generating at full power, might cause congestion on the electricity grid, which results in curtailment of the wind turbines, which would be unfavourable for the wind park developers.

6.6 Implications for stakeholders

The simulations result in varying costs for some of the involved stakeholders. For others, the type/capacity of the electrolyser, as well as the capacity of the hydrogen storage, does not have an impact on the involved costs. The implications of the different configurations of the new energy system of Oudeschip are discussed in this section.

6.6.1 H2Oudeschip

For H2Oudeschip, the initial investments depend greatly on the type/capacity of the electrolyser and capacity of the hydrogen storage. As mentioned before, the investment cost of a single tube trailer is 146,000 €, an Alkaline electrolyser costs around 500,000 euros per MW, a PEM electrolyser costs around 1.100.000 €. This is clearly seen in the results, as presented in figure 6.15, of which the exact numbers are presented in table B.2. It is clear that an Alkaline electrolyser is preferable over a PEM electrolyser from an investment point of view. Secondly, the bigger the electrolyser, the higher the initial investment is. Lastly, while the relative difference is not as big as the difference between a PEM and Alkaline electrolyser, it is more expensive to have multiple tube trailers. However, a bigger initial investment might pay off in return on investment.

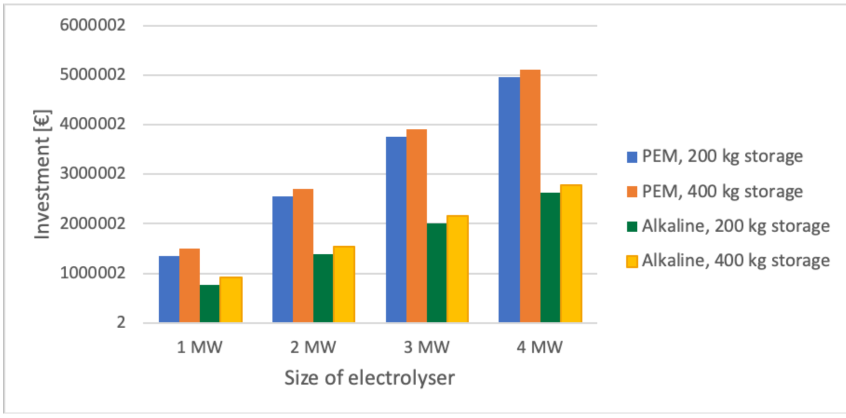


Figure 6.15: Investment cost of H2Oudeschip per scenario [€]

Figure 6.16 shows the profit per year for each of the configurations of the energy system, of which the exact numbers are presented in table B.3. This graph shows that indeed the profits are greater with a bigger electrolyser, which is expected, since the bigger the electrolyser, the more hydrogen is sold. Furthermore, the graph shows that the profits decrease when a second tube trailer is used. The simulations show that the investment in a second tube trailer for 146.000 €is not worth the investment in the simulated scenarios.

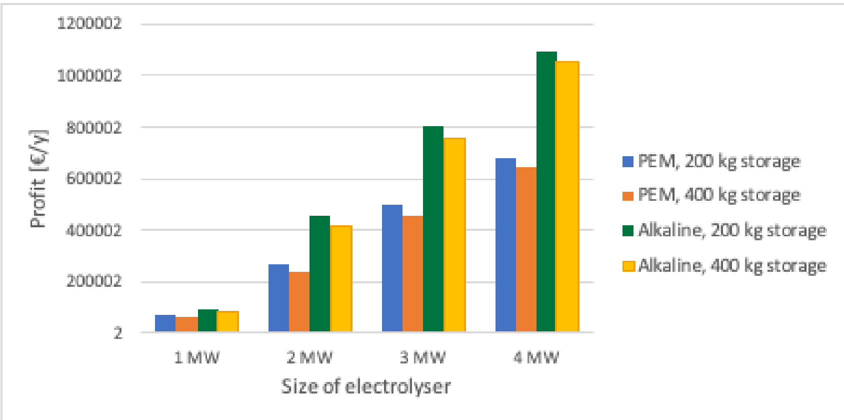


Figure 6.16: Profit of H2Oudeschip per scenario [€/year]

Lastly, the payback time for the investments is plotted in figure 6.17, the exact numbers behind this graph are presented in table B.4. As was already apparent from the previous two graphs, a PEM electrolyser has a higher investment cost and lower profits compared to an Alkaline electrolyser, which is why the payback time for this type of electrolyser is greater than the payback time of an Alkaline electrolyser. Secondly, for an electrolyser of 1 MW, the payback time with a second tube trailer is far greater than the scenario with a single tube trailer. With an electrolyser of larger capacity, the difference is not as big.

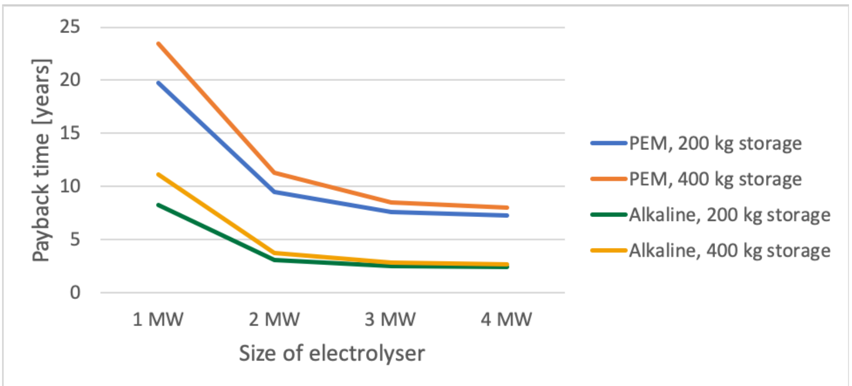


Figure 6.17: The Payback time of the investments for H2Oudeschip per scenario

Concluding, for H2Oudeschip, an Alkaline electrolyser is a better investment. Furthermore, the electrolyser should be bigger than 1 MW and the simulations show that a second tube trailer is not necessary.

6.6.2 Households in the Energie Cooperatie Oudeschip

To recap, the 180 households in the Energie Cooperatie Oudeschip currently use 1.200 m^3 of natural gas per year, as mentioned in section 4.2. With a natural gas price of 0,814 €/m^3, this sums up to a gas bill of 976,8 €. As mentioned in the same section, the electricity bill goes up by 40,5 €/year due to the switch to electric cooking, which also diminishes the demand for hydrogen by 5,8 kg/year. The resulting hydrogen demand per household is 291,8 kg/year. The price the households pay per kg of hydrogen is dependent on the LCOH, with an additional 0,05 €/kg. In order for the households to not spend more on energy, the total expense on hydrogen should not be greater than 936,3 €/year. The simulations result in the total yearly expense on hydrogen as presented in figure 6.18.

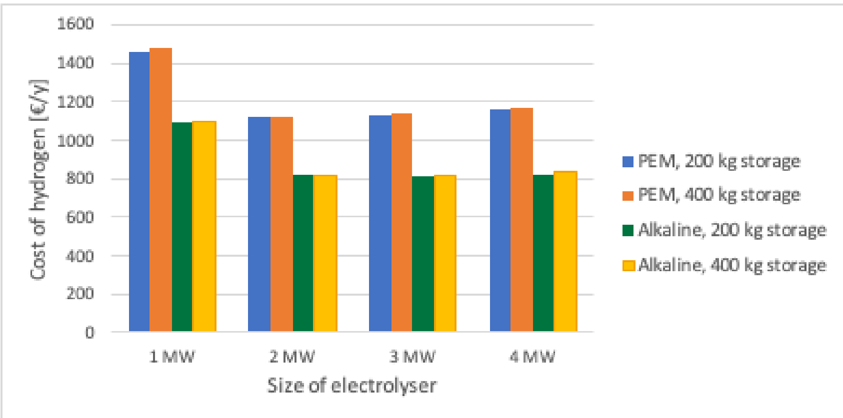


Figure 6.18: Yearly hydrogen expense per household [€/year]

Clearly, in any scenario with a PEM electrolyser, the expenses on household heating are greater than with natural gas. For the situation with a 1 MW alkaline electrolyser, the expenses on heating are also bigger. When an Alkaline electrolyser is used, which is bigger than 1 MW, the expenses on household heating are all relatively similar. The expenses are slightly higher when two tube trailers are used, but this difference is insignificant.

6.6.3 Farmers around Oudeschip

As described in section 4.3, the hydrogen price is chosen so that they pay the same amount of money on hydrogen as fuel as they do now with diesel. Their yearly expense on fuel, with an average fuel consumption of 12.000 liters of diesel per year and a price of 1,30 €/liter, remains at 15.600 €/year.

6.6.4 Wind park developers

For the developers of the wind park, the configuration of the new energy system poses a single influence, namely the capacity of the electrolyser. When the electrolyser is bigger than 2 MW, the investments in a grid connection to the wind turbines becomes lower, as already mentioned in section 3.4. The difference is shown in figure 6.19. Therefore, the wind park developers will opt for a 3 MW or 4 MW electrolyser.

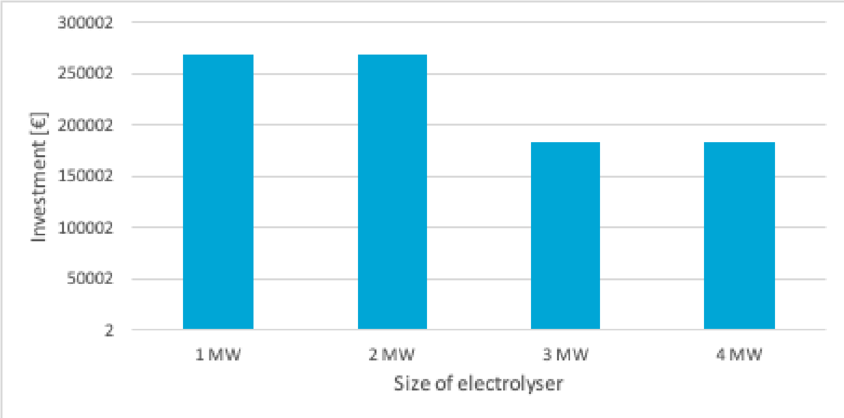


Figure 6.19: Investment of grid connection by wind park developers [€]

6.6.5 Fuel station of the Theo Pouw Groep

For the Theo Pouw Groep, the fuel station operator, the initial investments are not dependent on the configuration of the new energy system. However, the selling price of hydrogen to FCEV vehicles at 700 bar is set at 10 €/kg and the selling price of hydrogen to farmers at 350 bar is set to 4,83 kg. Next to this income, the electricity for compression to 880 bar and 440 bar needs to be bought from the electricity grid. Therefore, the purchasing price of hydrogen, which is equal to the LCOH + 0,5 €, is very important for the economic feasibility of the fuel station.

The profits of the fuel station are presented in figure 6.20, of which the exact numbers are presented in table B.5. Again, the Alkaline electrolyser is more favourable than the PEM electrolyser. This is obvious, since figure 5.2.6 points out that the LCOH is greater for a PEM electrolyser than for an Alkaline electrolyser. The second conclusion is that the use of a second tube trailer does not influence the profits of the fuel station operator significantly. lastly, as long as the electrolyser is bigger than 1 MW, the profits are relatively similar.

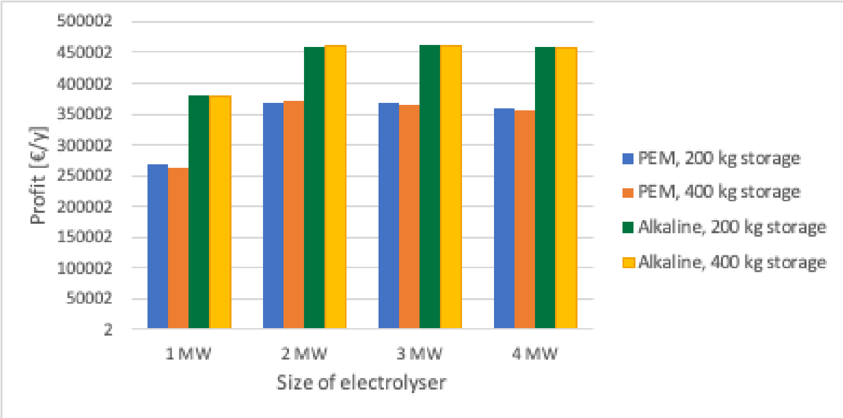


Figure 6.20: Profit of fuel station operator [€/year]

As expected from a fixed investment cost and relatively similar profits, the payback time of the fuel station is relatively similar when an electrolyser bigger than 2 MW is installed. Concluding, the fuel station operator will prefer the installment of an electrolyser, bigger than 1 MW. The use of a second tube trailer is not important for the fuel station operator.

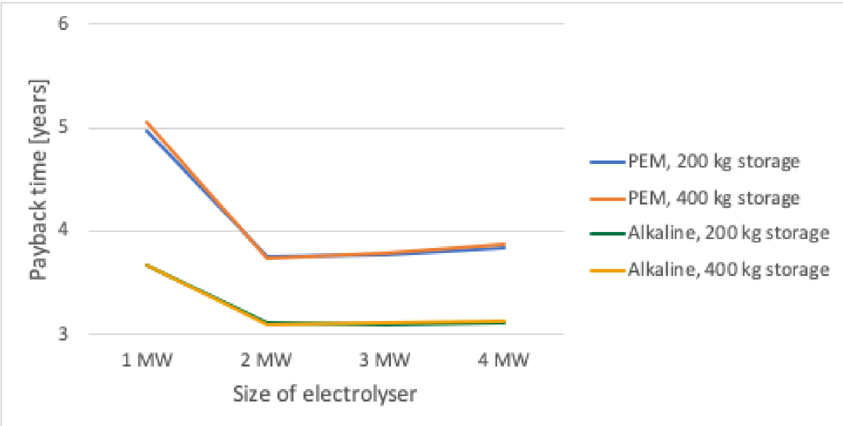


Figure 6.21: The Payback time of the investments for the fuel station operator per scenario

6.6.6 Enexis

For the utility provider in Oudeschip, Enexis, the costs do not change per simulation. The gas infrastructure needs to be altered and expanded, regardless of the type/capacity of the electrolyser and capacity of hydrogen storage. These costs are the following:

Table 6.1: Investments by Enexis

Type of investment	Costs [euro]
Conversion natural gas infrastructure	35.000
New 30 bar hydrogen infrastructure	1.040.000
Expansion of natural gas infrastructure	626.400
Total investment	**1.701.400**

6.6.7 Other stakeholders

Other stakeholders mentioned in chapter 3 are: FCEV owners, Groningen Seaports and the Province of Groningen. For these stakeholders, there are no changes when the configuration of the new energy system of Oudeschip is altered.

Regardless of the type/capacity of the electrolyser or the capacity of the hydrogen storage, the FCEV owners can refuel hydrogen at the fuel station for 10 €/kg. For Groningen Seaports, the simulations do not have any effect yet since a connection to their hydrogen grid is not simulated. However, a future connection to their hydrogen grid has the implication that there is more hydrogen transported through their infrastructure. Since there is no knowledge of the capacity or price of hydrogen in the hydrogen grid of Groningen Seaports, this should be examined in further research. For the Province of Groningen, the sizes of the components in the new energy system have no implications.

Chapter 7

Discussion

The research shows that hydrogen as an energy carrier in Oudeschip is possible. However, the design of the new energy system, as well as the simulations, were based of a few assumptions. Some of these assumptions are discussed in this chapter.

In the current system, there is no limit on the volume of hydrogen export. Therefore, all the excess hydrogen is always sold, and the electrolyser can always produce at full capacity as long as there is enough wind generation. In real life, it might not be possible to always sell the excess hydrogen, which negatively influences the load capacity of a larger electrolyser, and with it, the LCOH and payback time of the system. As seen from figure 6.2 and figure 6.17, when there are no limitations on the export of hydrogen, the bigger the electrolyser, the better. There will be a certain electrolyser capacity for which the wind turbines will become the limiting factor, but since there are two wind turbines of 4.5 MW, this is not the case for the simulated scenarios with electrolysers of 4 MW or less.

Next to the volume of hydrogen exported, the assumed price for hydrogen export is 6 €/kg. The current market price for hydrogen is between 1 and 2 euros, which makes this price high. However, the majority of hydrogen on the market is currently grey hydrogen, which is made from natural gas. There are buyers of hydrogen willing to pay a premium price for low carbon, green hydrogen. However, the price they are willing to pay and volume of consumption, greatly influences the possibility to export the excess hydrogen for 6 €/kg.

In all the scenarios, it is assumed that the excess electricity can be sold on the electricity market. However, there are currently barriers with the connection of new wind parks due to the limiting electricity grid capacity. Moreover, there is an increasing number of hours for which turbines are stopped while there is sufficient wind, due to a lack of electricity demand, which is called curtailment. If this is the case, then a larger electrolyser might be more favourable, since it shaves a part of the peak generation which otherwise would have congested the electricity grid or resulted in curtailment. A limited electricity grid connection, as well as the electricity demand, can be taken into account in the PtX model to review these effects for the wind turbine developers.

In this research, the conversion cost to turn the diesel tractors into diesel-hydrogen hybrid engines are unknown, but should be taken into account if the new energy system of Oudeschip is to be implemented. While there are companies in neighbouring countries which perform this conversion, and the ratio of diesel substitution (60%) is comparable to the ratio found in literature, there is still uncertainty around this part of the research since it is not performed in the Netherlands yet and the technology is immature. Furthermore, the simulations ran with the assumption that the farmers pay a hydrogen price which results in zero change on their fuel bill. However, as the conversion of their tractors is most likely a major investment, the only return on that investment would be that they emit less carbon and nitrogen. It might give a better incentive if the hydrogen price they pay, results in a lower fuel bill.

The implications for the residents of Oudeschip were based on an average household size in the area, linked to an average energy consumption. For individual homeowners, the situation might differ greatly from the average, since the size of a house and behaviour of a resident greatly influences their heat demand.

It is assumed that hydrogen can be imported per kilogram, which is not the case in real life, since there is no hydrogen infrastructure in place. One would not import a tube trailer with solely a single kilo of hydrogen inside. This assumption was made due to the complexity of the PtX model and time constraints of the research. In practice, a full tube trailer with 200 kg of hydrogen would be imported. This implementation in the simulations has a bigger negative influence on the scenarios with a small electrolyser capacity than with a larger electrolyser capacity, as these scenarios rely more on the import of hydrogen. Moreover, it might negatively influence the scenarios with a 200 kg capacity of hydrogen storage more than with 400 kg of storage, since the hydrogen is only imported if the storage facility can not cope with the difference between hydrogen production and consumption.

One of the economic assumptions is that the conversion costs of converting the gas infrastructure to hydrogen is equal to 200 €per household. However, these costs are based on a national conversion of the grid, which might prove to be more or less expensive for Oudeschip. Moreover, in order for all the 180 households to heat their home with hydrogen, two extra pipelines need to be constructed, solely to connect several parts of the gas infrastructure. The developers of this project need to analyse the possibility that it is more favourable to start with a smaller part of the households in order to make the project more cost effective for the distribution grid operator.

The simulations ran for electrolyser capacities of 1 MW, 2 MW, 3 MW and 4 MW. With an electrolyser capacity larger than 1 MW, the LCOH is relatively stable, and a 2 MW electrolyser is able to cover most of the local hydrogen demand. However, it might be that a 1,5 MW electrolyser in combination with two tube trailers, is already capable of covering the local hydrogen demand.

Lastly, it is assumed that it is allowed to transport 100% hydrogen through the natural gas grid in Oudeschip, and that this project has exceptions from paying taxes. These exceptions need to be given by the Government, which is plausible, given that the Government of the Netherlands has aspirations to promote the development of a (green) hydrogen economy, but not a given.

Chapter 8

Conclusion and recommendation

8.1 Conclusion

The government of the Netherlands is picking up the pace in the energy transition, of which the Climate Agreement is the embodiment. However, the increased installation of wind parks is facing congestion challenges, it is not always possible to electrify residential heat demand due to grid constraints and the same goes for heavy duty vehicles due to long charging times. Furthermore, the seasonality in consumption of agricultural mobility and household heat demand increases the burden on energy storage. These are the problems which occur together in the rural areas of the Netherlands. Solutions are not only dependent on existing and innovative technology, but also on the existing infrastructure, distribution channels, as well as interests of local parties and human behaviour. Therefore, this research proposes to view these problems together as a complex socio-technical environment, and solve them with an integrated approach. This integrated approach is demonstrated on the case of Oudeschip.

The main objective of this research was to provide H2Oudeschip with insights into the required components for a new energy system in Oudeschip with hydrogen as energy carriers, and the required capacity of these components. Furthermore, the research should provide insight into the consequences for involved stakeholders. The main research question has set the end goal of this research, the objective is fulfilled in the process of pursuing this end goal. This chapter starts by repeating and answering the sub questions, answers the main research question, and discusses the scientific an societal relevance of this research. The chapter finishes with recommendations for further research.

8.1.1 Answering the sub questions

While the full answers to the sub questions are given throughout the report, the main conclusion per sub question is presented in this section.

What would a decarbonized energy system in Oudeschip look like?

The main option for Oudeschip is to utilize hydrogen as an energy carrier, next to electricity. The homes in and around Oudeschip can use a hydrogen boiler for heating, the farmers can convert their diesel tractors to hydrogen-diesel hybrids, and part of the electricity from the wind turbines, can be used to produce hydrogen. Since Oudeschip is a rural area, electrification is not an option for household heating, since the investments in the electricity grid would be too large. Furthermore, to decarbonize the tractors of the local farmers, electrification is neither an option, since battery electric vehicles have an operational time which is not sufficient for the peak demand during harvesting and sowing. Next to that, there are no FCEV tractors available and if they were, it is unlikely that all the farmers will switch to an expensive new type of tractor. Lastly, green electricity is already putting a large strain on the electricity grid due to its intermittent nature. More and more wind generation is curtailed, and planned wind parks are delayed due to congestion on the electricity grid. By using this wind electricity to produce hydrogen, the strain on the electricity grid is reduced, and wind turbines do not have to be curtailed.

What are the major components in the new energy system of Oudeschip, their technical and economic parameters, and reasonable sizes for those components?

The main components of the future energy system of Oudeschip are: two wind turbines, an electrolyser, hydrogen boilers, a hydrogen fueling station, one or two tube trailers, hydrogen-diesel tractors and a natural gas grid which is converted to transport hydrogen. It is clear that an Alkaline electrolyser is more favourable than a PEM electrolyser. If there is no limit on the volume of hydrogen export, the bigger the electrolyser, the better, however, a 2 MW electrolyser is sufficient to fulfill the local hydrogen demand. With a 2 MW electrolyser, the simulations show some hydrogen import. However, due to the ad hoc decision making of the model, hydrogen is exported at moments when it results in hydrogen import shortly after. If the choice of hydrogen export is optimized, hydrogen import might be limited to extreme circumstances like a 'Dunkelflaute' in the harvesting week of the local farmers.

What is the energy profile of Oudeschip including generation and demand?

The household heating demand has a seasonal pattern with its maximum in the winter and a minimum in summer. There is a continuous demand for tapwater over the entire year. For the agricultural mobility demand, there are two peaks during the sowing and harvesting times in spring and autumn. Over summer the demand is relatively stable and in winter there is no demand for hydrogen from agricultural mobility at all. The demand from FCEV busses and cars is stable over the entire year. These three sources of demand are relatively equal in size when summed up for an entire year. Next to these three, any extra produced hydrogen is assumed to be exported to external companies. The volume of this export is dependent on the volume of excess hydrogen. The simulations show the wind generation over ten years, which fluctuates greatly. It is clear that the volume of electricity from two wind turbines is bigger than the volume of energy needed to fulfill the local hydrogen demand. Which ratio of this electricity is used to produce hydrogen is dependent on the capacity of the electrolyser.

Which stakeholders are involved in the new energy system of Oudeschip and what are their incentives?

The stakeholders involved in a future energy system of Oudeschip with hydrogen as an energy carrier are: the households in the Energie Cooperatie Oudeschip, H2Oudeschip, the farmers around Oudeschip, the developers of the wind park (Waddenwind BV and Innogy), the Theo Pouw Groep, Groningen Seaports, Enexis, the province of Groningen and owners of FCEV vehicles. These stakeholders have different interests in and power over the continuation of the project, but the most important stakeholders are: Enexis, the Theo Pouw Group, the Energie Cooperatie Oudeschip, H2Oudeschip, the local farmers and the province of Groningen. The province of Groningen should be involved and kept satisfied, while Enexis, the Theo Pouw Groep, the Energie Cooperatie Oudeschip, H2Oudeschip and local farmers should collaborate and be managed closely in order for the proposed future energy system of Oudeschip to emerge.

What are the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for stakeholders in the new energy system?

The CAPEX and OPEX depend greatly on the capacity of the electrolyser, since it has a relatively high investment cost and corresponding cost of operations and maintenance. Since an Alkaline electrolyser proved to be more favourable than a PEM electrolyser, and a 2 MW electolyser is arguably the minimum to cover the local hydrogen demand, it is recommended for H2Oudeschip to invest in a 2 MW Alkaline electrolyser. As discussed in chapter 7, if hydrogen is imported per tube trailer instead of per kilogram, it is more favourable to have two tube trailers to cover the difference between the production and demand for hydrogen. An overview of the CAPEX and OPEX per stakeholder of the energy system with this configuration is presented in table 8.1.

Table 8.1: Summary of costs for an energy system with a 2 MW Alkaline electrolyser and 400kg storage

Stakeholder	CAPEX [\euro]	OPEX [\euro/year]	Payback time [years]
H2Oudeschip	1.537.055	42.495	3,7
Theo Pouw Groep	1.500.000	100.000	2.6
Enexis	1.701.400.	-	-
Households	1700	817	10,6
Wind park developer	268047	-	-

The CAPEX for the wind park developer shown in table 8.1 only includes the costs for the grid connection. The investment costs for the farmers are unknown, and the rest of the stakeholders mentioned in this research do not have a financial stake in this energy system.

8.1.2 Main research question

The main research question in this research is:

How can the agricultural mobility and residential heat demand of Oudeschip be fulfilled by wind generation with a combination of electricity and hydrogen as energy carriers?

A summary of the answer: with a 2 MW Alkaline electrolyser, hydrogen boilers, a fueling station with a 350 bar and 700 bar dispenser, preferably two tube trailers, and by converting the local natural gas grid to a hydrogen grid as well as diesel tractors to diesel-hydrogen hybrids. A 2 MW electrolyser is large enough to cover the local hydrogen demand and shaves a significant volume of wind generation, especially during peak generation. A 2 MW Alkaline electrolyser reduces congestion on the electricity grid and, together with two tube trailers, results in a LCOH of 2,19 €/kg. The choice of two tube trailers makes sure that there is significant volume of storage hydrogen for windless periods during the year, and allows for a single tube trailer to be driven away when it is full, while the other remains as a buffer.

8.1.3 Scientific relevance

The literature review pointed out that an integrated approach to investigate synergies between sectors in rural areas, is missing. Literature discusses the combination of different sources of (renewable) energy to supply heat and power to households, but it was unclear how the single use of wind power can be combined with residential heat demand and the demand of agricultural mobility in rural areas like Oudeschip, by making use of both electricity and hydrogen as energy carriers. Looking at the energy system of the specific context in Oudeschip shows that by combining the peaks in household heat demand and agricultural mobility, a smoother demand curve over the entire year is obtained. Academic literature looks at demand response and seasonal storage to deal with the intermittency of renewables, but the sectoral integration presented in this research shows that the combination of different sectors results in a more stable demand over the year. Furthermore, peak wind generation which might be curtailed under normal circumstances, can still be generated, which relieves the burden on the electricity grid.

8.1.4 Societal relevance

This thesis report points out that an energy system with a combination of hydrogen and electricity in rural areas like Oudeschip is a feasible solution for decarbonization. The electrolyser diminishes the strain of wind power on the grid, especially during peak wind generation, which decreases congestion. Furthermore, hydrogen gives the natural gas infrastructure a future-proof purpose. Regarding domestic energy use, this research gives rural areas with sparse buildings where electrification is not an option, the potential to decarbonize. Lastly, heavy-duty vehicles like tractors, for which batteries are too limiting, can be revised to replace a large part of the fossil fuel with a green alternative. This removes the need to invest in heavily in a new vehicle, and gives older vehicles a second life. In the Netherlands, households in rural areas were originally against the construction of wind turbines in their vacinity, because it blocks their view and might cause shadow flicker. By using hydrogen as an energy carrier, households and farmers around wind parks have the opportunity to participate in the utilization of the wind generation, and become a front-runner in the energy transition. The techno-economic analysis in combination with a stakeholder analysis, as presented in this report, is applicable to other rural areas near wind generation as well.

8.2 Recommendations for further research

For further research, it is recommended that the PtX model is expanded from an ad hoc decision making model to a dynamic decision making model. Optimization of the choices made in the model will result in lower operational costs and a lower levelized cost of hydrogen. Moreover, the simulation could be upgraded to include the import of hydrogen per tube trailer instead of per kilogram. Apart from these improvements, this model can be applied to other cases with alternate input, which influence the optimal capacity of the electrolyser and hydrogen storage. This can include more or less farmers or households, or a larger/smaller wind turbine in an area with a different wind profile.

Currently, the simulations run for a set market price of electricity, and set price of wind power. However, it might prove interesting to take the capital cost of curtailment into account in the research of such a hydrogen based energy system.

The uptake of home solar PV, in combination with wind power, increases the stability of electricity generation. This is favourable for the cost recovery of a hydrogen system, since a more stable supply of electricity results in a larger utilization of the electrolyser capacity, which in turn decreases the levelized cost of hydrogen. Thus, solar PV can be included as well to see its effect on the operations of a hydrogen-based energy system in rural areas. Furthermore, a hybrid system for household heating, with a heat pump for the baseload and a hydrogen boiler for peak load, might reduce the costs of the energy system significantly. If solar PV is added to the mix, systems like the Solenco Powerbox give home owners not only the option to generate and deliver electricity, but also produce their own hydrogen.

Lastly, as mentioned in previous chapters, Groningen Seaports is constructing a hydrogen network in the region. A connection to this hydrogen grid can remove the cost of a tube trailer and compression for storage. Further research can investigate the implications of the connection to such a local hydrogen infrastructure.

Chapter 9

Reflection

In this chapter I will reflect on my master thesis process. It has been a fun and educational journey, which had several challenges and learning points.

Instead of graduating at a company, I chose to graduate at the University. This gave me a lot of freedom, but also a lot of responsibility. I loved that the research covered a very practical case study, but it was also quite technical sometimes, which is not what I was used to from the master courses at TPM. Ad van Wijk had to correct me sometimes when I completely forgot to include a certain efficiency value somewhere, or when I left out a zero. Similarly, Theo Fens needed to corrected my knowledge of AC and DC a bit. My 'feel' for the size, efficiency or costs associated to certain technologies are still in development, but due to this project, it is getting a lot better.

Due to the sole responsibility I had regarding this project, I met with external stakeholders by myself, and made most of the choices in the project by myself. This thesis report might have proven to be of higher quality if I consulted Zofia Lukszo and Martijn Warnier more, but this way I learned a lot more and I enjoy to have a certain sense of personal leadership in the choices I make.

I decided to work with a simulation model written in Python called the Power-to-X model. Python programming was never part of my curriculum, everything I know about this programming language was self taught. I could have chosen to build my own simulation model, but I found it very interesting to work with something which was already working. The coding in this model was of a higher quality than I was capable of producing, which forced me learn a lot about Python and the required structuring of my code. Luckily I had Els van der Roest to help me out if I got stuck somewhere, which saved me quite some times. The problem with using the PtX model was that it was more complex than needed for my research. I took quite some time to figure out how it all worked before I even got started on altering the model. All in all I am glad that I used this model, because my alterations can be used by other users of the PtX model and it gave me the opportunity to meet Els van der Roest and Theo Fens. I could ask them questions about my model, whom already knew what the code was doing. If I would have made my own model, I would have been on my own.

The biggest challenge during my graduation period was that Covid-19 hit. Theoretically, the impact on my graduation project should have been minimal, since I had to do everything by my self, behind my own computer. However, I am a social person, and I always used to work at the University, since it allowed me to talk to other students, have coffee together, and talk about each others thesis challenges. Now, I was stuck at my desk at home. My room became a place I was doing everything in: sleeping, graduationg, relaxing, working out... Luckily I had Daan, who was in the same situation as I was in, and proved to be a valuable distraction. I learned that I am not made to always work from home. One or two days a week are fine, but I need social interaction, and a separation between work and personal life.

I am proud of the student period behind me and the work that lies before you. I hope to be present when the first hydrogen comes out of the electrolyser at Oudeschip.

Thank you for reading.

References

Alahäivälä, A., Ekström, J., Jokisalo, J. & Lehtonen, M. (2017, jan). A framework for the assessment of electric heating load flexibility contribution to mitigate severe wind power ramp effects. *Electric Power Systems Research*, *142*, 268–278. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0378779616303789 doi: 10.1016/j.epsr.2016.09.026

Alavi, F., Park Lee, E., van de Wouw, N., De Schutter, B. & Lukszo, Z. (2017, apr). Fuel cell cars in a microgrid for synergies between hydrogen and electricity networks. *Applied Energy*, *192*, 296–304. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0306261916315288 doi: 10.1016/j.apenergy.2016.10.084

CBS. (2018). *Woonoppervlakte in Nederland*. Retrieved 2020-06-08, from https://www.cbs.nl/nl-nl/achtergrond/2018/22/woonoppervlakte-in-nederland

CBS. (2019, sep). *Lagere broeikasgasuitstoot*. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2019/37/lagere-broeikasgasuitstoot

CBS. (2020a). *Energieverbruik particuliere woningen; woningtype en regio's*. Retrieved 2020-04-15, from https://opendata.cbs.nl/statline/{#}/CBS/nl/dataset/81528NED/table?ts=1586951099071

CBS. (2020b). *Productie groene elektriciteit in stroomversnelling*. Retrieved 2020-03-05, from https://www.cbs.nl/nl-nl/nieuws/2020/10/productie-groene-elektriciteit-in-stroomversnelling

da Silva Veras, T., Mozer, T. S., da Costa Rubim Messeder dos Santos, D. & da Silva César, A. (2017, jan). Hydrogen: Trends, production and characterization of the main process worldwide. *International Journal of Hydrogen Energy*, *42*(4), 2018–2033. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S036031991632715X doi: 10.1016/j.ijhydene.2016.08.219

Dagblad van het Noorden. (2019, nov). *Vijftig nieuwe waterstofbussen in het openbaar vervoer, waarvan in elk geval twintig in Groningen en Drenthe*. Groningen. Retrieved from https://www.dvhn.nl/groningen/Vijftig-nieuwe-waterstofbussen-in-het-openbaar-vervoer-waarvan-dertig-in-Groningen-en-Drenthe-25048369.html

Dimitriou, P., Kumar, M., Tsujimura, T. & Suzuki, Y. (2018, jul). Combustion and emission characteristics of a hydrogen-diesel dual-fuel engine. *International Journal of Hydrogen Energy*, *43*(29), 13605–13617. Retrieved from https://doi.org/10.1016/j.ijhydene.2018.05.062https://linkinghub.elsevier.com/retrieve/pii/S0360319918315775 doi: 10.1016/j.ijhydene.2018.05.062

Dimitriou, P. & Tsujimura, T. (2017, sep). A review of hydrogen as a compression ignition engine fuel. *Inter-*

national Journal of Hydrogen Energy, *42*(38), 24470–24486. Retrieved from http://dx.doi.org/10.1016/j.ijhydene.2017.07.232https://linkinghub.elsevier.com/retrieve/pii/S0360319917331464 doi: 10.1016/j.ijhydene.2017.07.232

DOE. (2009). DOE Hydrogen and Fuel Cells Program: Hydrogen Storage. *U.S Department Of Energy*, *25*, 6. Retrieved from http://www.hydrogen.energy.gov/storage.html

Emissiefactoren, C. (n.d.). *Lijst emissiefactoren.* Retrieved 2020-06-15, from https://www.co2emissiefactoren.nl/lijst-emissiefactoren/

Enexis. (n.d.). *Kosten werkzaamheden.* Retrieved 2020-08-11, from https://www.enexis.nl/consument/aansluiting-en-meter/tarief/kosten-werkzaamheden?stap=Waarvanwiltudekostenweten{_}1{_}1

Enexis Netbeheer. (n.d.). *Eenmalige kosten.* Retrieved 2020-07-23, from https://www.enexis.nl/zakelijk/aansluitingen/tarieven/tarievenoverzicht/eenmalige-kosten?stap=Waarvanwiltudekostenweten{_}1{_}2

Enexis Netbeheer. (2018). *Open data | Enexis - Energie in goede banen.* Retrieved 2020-04-14, from https://www.enexis.nl/over-ons/wat-bieden-we/andere-diensten/open-data

Environmental Data Compendium. (2016). *Temperature trends: the Netherlands and worldwide, 1906-2015.* Retrieved 2020-08-05, from https://www.clo.nl/en/indicators/en0226-temperature-trends-the-netherlands-and-worldwide

Evers, D., Nabielek, P. & Tennekes, J. (2019). *Wind-op-land: lessen en ervaringen* (Tech. Rep.). Den Haag: PBL Planbureau voor de Leefomgeving. Retrieved from https://www.pbl.nl/publicaties/wind-op-land-lessen-en-ervaringen

Farahani, S. S., van der Veen, R., Oldenbroek, V., Alavi, F., Park Lee, E. H., van de Wouw, N., … Lukszo, Z. (2019, jan). A Hydrogen-Based Integrated Energy and Transport System: The Design and Analysis of the Car as Power Plant Concept. *IEEE Systems, Man, and Cybernetics Magazine*, *5*(1), 37–50. Retrieved from https://ieeexplore.ieee.org/document/8616925/ doi: 10.1109/MSMC.2018.2873408

Fendt. (2017). *Fendt e100 Vario - Fendt.* Retrieved 2020-04-02, from https://www.fendt.com/int/fendt-e100-vario

Franco, A. & Fantozzi, F. (2016, feb). Experimental analysis of a self consumption strategy for residential building: The integration of PV system and geothermal heat pump. *Renewable Energy*, *86*, 1075–1085. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0960148115303098 doi: 10.1016/j.renene.2015.09.030

FuelCellsWorks. (2019). *Netherlands: Groningen, Drenthe and Friesland Become a "Hydrogen Valley" - FuelCellsWorks.* Retrieved 2020-06-07, from https://fuelcellsworks.com/news/netherlands-groningen-drenthe-and-friesland-become-a-hydrogen-valley/

Gemeente Groningen heeft tweede vuilniswagen op waterstof - RTV Noord. (2019, oct). Retrieved from https://www.rtvnoord.nl/nieuws/214368/Gemeente-Groningen-heeft-tweede-vuilniswagen-op-waterstof

Ghazal, O. H. (2013, nov). Performance and combustion characteristic of CI engine fueled with hydrogen enriched diesel. *International Journal of Hydrogen Energy*, *38*(35), 15469–15476. Retrieved from http://dx.doi.org/10.1016/j.ijhydene.2013.09.037https://linkinghub

.elsevier.com/retrieve/pii/S0360319913022283 doi: 10.1016/j.ijhydene.2013.09.037

Government of The Netherlands. (2019). *Climate Agreement.* Ministry of Economic Affairs and Climate Policy. Retrieved from https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands

Groningen Seaports. (2018). *Groningen Seaports en Pipelife ontwikkelen infrastructuur voor groene waterstof.* Retrieved 2020-04-18, from https://www.groningen-seaports.com/nieuws/groningen-seaports-en-pipelife-ontwikkelen-infrastructuur-groene-waterstof/

Groningen Seaports. (2020). *Europe's largest green hydrogen project starts in Groningen.* Retrieved 2020-04-18, from https://www.groningen-seaports.com/en/nieuws/europes-largest-green-hydrogen-project-starts-in-groningen/

GTS. (2020). *Ontwerp Investeringsplan GTS 2020-2030* (Tech. Rep.). Gasunie Transport Services. Retrieved from https://www.gasunietransportservices.nl/gasmarkt/investeringsplan/investeringsplan-2020

Hacatoglu, K., Dincer, I. & Rosen, M. A. (2016, may). Sustainability of a wind-hydrogen energy system: Assessment using a novel index and comparison to a conventional gas-fired system. *International Journal of Hydrogen Energy*, *41*(19), 8376–8385. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0360319916002123 doi: 10.1016/j.ijhydene.2016.01.135

Heinen, S. & O'Malley, M. (2015, jun). Power system planning benefits of hybrid heating technologies. In *2015 ieee eindhoven powertech* (pp. 1–6). IEEE. Retrieved from http://ieeexplore.ieee.org/document/7232421/ doi: 10.1109/PTC.2015.7232421

Holtz, G. (2011, dec). *Modelling transitions: An appraisal of experiences and suggestions for research* (Vol. 1) (No. 2). Elsevier B.V. doi: 10.1016/j.eist.2011.08.003

Homan, C. (2019, jun). *KNMI - Hoe waait de wind?* Retrieved from https://www.knmi.nl/over-het-knmi/nieuws/hoe-waait-de-wind

Homedeal. (2020). *Cv-ketel prijzen [Kostenoverzicht + Mogelijkheden & Tips] | Homedeal.* Retrieved 2020-04-18, from https://www.homedeal.nl/cv-ketel/cv-ketel-prijzen/

Hughes, L. (2010, aug). Meeting residential space heating demand with wind-generated electricity. *Renewable Energy*, *35*(8), 1765–1772. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S096014810900490X doi: 10.1016/j.renene.2009.11.014

Huiden, F. (2019, jan). *100% elektrische trekker van Rigitrac.* Retrieved from https://www.boerderij.nl/Mechanisatie/Nieuws/2019/1/100-elektrische-trekker-van-Rigitrac-378842E/

Hussin, H., Pustjens, W. & Rooijmans, P. (2017). *Productieberekening Windpark Oostpolder* (Tech. Rep.). Hengelo: Pondera Consult.

Hydrogen Europe. (2018). *HYDROGEN, ENABLING A ZERO EMISSION EUROPE: TECHNOLOGY ROADMAPS FULL PACK* (Tech. Rep. No. September). Hydrogen Europe. Retrieved from https://hydrogeneurope.eu/sites/default/files/2018-10/Public{_}HETechRoadmaps{_}fullpack{_}0.pdf

IEA. (2018). *CO2 Emissions from Fuel Combustion 2018* (Tech. Rep.). International Energy Agency. Retrieved from https://webstore.iea.org/co2-emissions-from-fuel-combustion-2018

IEA. (2019a). *The Future of Hydrogen for G20* (Tech. Rep. No. June). International Energy Agency. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen

IEA. (2019b). *Natural gas information 2019* (Tech. Rep.). International Energy Agency. Retrieved from https://webstore.iea.org/natural-gas-information-2019

Installatietechniek, E. (2020). *Waterstofketel Hydra van Remeha.* Retrieved 2020-04-02, from https://www.ew-installatietechniek.nl/nieuws/open/waterstofketel-hydra-van-remeha

Jones, B. W. & Powell, R. (2015, feb). Evaluation of distributed building thermal energy storage in conjunction with wind and solar electric power generation. *Renewable Energy*, *74*, 699–707. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S096014811400490X doi: 10.1016/j.renene.2014.08.031

Juknelevičius, R., Rimkus, A., Pukalskas, S. & Matijošius, J. (2019, apr). Research of performance and emission indicators of the compression-ignition engine powered by hydrogen - Diesel mixtures. *International Journal of Hydrogen Energy*, *44*(20), 10129–10138. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0360319918338461 doi: 10.1016/j.ijhydene.2018.11.185

Khalid, F., Aydin, M., Dincer, I. & Rosen, M. (2016, nov). Comparative assessment of two integrated hydrogen energy systems using electrolyzers and fuel cells. *International Journal of Hydrogen Energy*, *41*(44), 19836–19846. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0360319916325125 doi: 10.1016/j.ijhydene.2016.08.121

Kiwa Technology. (2018). *Toekomstbestendige gasdistributienetten* (Tech. Rep.). Apeldoorn: Kiwa Technology. Retrieved from https://www.netbeheernederland.nl/{_}upload/Files/Toekomstbestendige{_}gasdistributienetten{_}133.pdf

Koninklijk Nederlands Meteorologisch Instituut. (2017). *Update hazardkaart Groningen.* Retrieved 2020-04-14, from https://www.knmi.nl/kennis-en-datacentrum/achtergrond/update-hazardkaart-groningen-seismische-dreiging-nauwelijks-gewijzigd

Kontu, K., Rinne, S., Olkkonen, V., Lahdelma, R. & Salminen, P. (2015, apr). Multicriteria evaluation of heating choices for a new sustainable residential area. *Energy and Buildings*, *93*, 169–179. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0378778815000973 doi: 10.1016/j.enbuild.2015.02.003

Li, J., Fang, J., Zeng, Q. & Chen, Z. (2016, apr). Optimal operation of the integrated electrical and heating systems to accommodate the intermittent renewable sources. *Applied Energy*, *167*, 244–254. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0306261915012817 doi: 10.1016/j.apenergy.2015.10.054

Majcen, D., Itard, L. & Visscher, H. (2013). Energy labels in Dutch dwellings – their actual energy consumption and implications for reduction targets. In *Eceee* (pp. 1947–1952).

McKenna, R., Merkel, E. & Fichtner, W. (2017, mar). Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects. *Applied Energy*, *189*, 800–815. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0306261916303828 doi: 10.1016/j.apenergy.2016.03.062

McPherson, M., Johnson, N. & Strubegger, M. (2018, apr). The role of electricity storage and hydrogen technologies in enabling global low-carbon energy transitions. *Applied Energy*, *216*, 649–661. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0306261918302356 doi: 10.1016/j.apenergy.2018.02.110

Middel, M. (2019). *Te weinig ruimte voor alle opgewekte stroom - NRC.* Retrieved from https://www.nrc.nl/nieuws/2019/10/10/te-weinig-ruimte-voor-alle-opgewekte-stroom-a3976268

Milan, C., Bojesen, C. & Nielsen, M. P. (2012, dec). A cost optimization model for 100% renewable residential energy supply systems. *Energy*, *48*(1), 118–127. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0360544212004148 doi: 10.1016/j.energy.2012.05.034

Mileu Centraal. (2020). *Jouw energierekening 2020 uitgelegd.* Retrieved 2020-06-09, from https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/energierekening/

Moerkerken, A. & Smit, I. (2016). *De Nederlandse landbouw en het klimaat* (Tech. Rep.). Utrecht: RVO. Retrieved from https://www.rvo.nl/sites/default/files/2016/12/RVO{_}DeNederlandselandbouwenhetklimaat{_}Broch{_}def.pdf doi: RVO-075-1601/BR-DUZA

Nakata, T., Kubo, K. & Lamont, A. (2005, jan). Design for renewable energy systems with application to rural areas in Japan. *Energy Policy*, *33*(2), 209–219. Retrieved from https://www.sciencedirect.com/science/article/pii/S0301421503002180https://linkinghub.elsevier.com/retrieve/pii/S0301421503002180 doi: 10.1016/S0301-4215(03)00218-0

New Holland. (2011). *New Holland presents the first NH2™ hydrogen powered tractor ready to go into service on a farm | NHAG.* Retrieved 2020-04-15, from https://agriculture.newholland.com/eu/en-uk/about-us/whats-on/news-events/2011/nh2

Nikola Motor Company. (n.d.). Retrieved 2020-08-03, from https://nikolamotor.com/

NOS. (2019, sep). *Gaswinning Groningen stopt al in 2022.* Retrieved from https://nos.nl/artikel/2301110-gaswinning-groningen-stopt-al-in-2022.html

NU.nl/AutoWeek. (2019). *Is waterstof snel bij meer tankstations beschikbaar?* Retrieved from https://www.nu.nl/auto/5723202/is-waterstof-snel-bij-meer-tankstations-beschikbaar.html

Oldenbroek, V., Verhoef, L. A. & van Wijk, A. J. (2017, mar). Fuel cell electric vehicle as a power plant: Fully renewable integrated transport and energy system design and analysis for smart city areas. *International Journal of Hydrogen Energy*, *42*(12), 8166–8196. Retrieved from http://dx.doi.org/10.1016/j.ijhydene.2017.01.155https://linkinghub.elsevier.com/retrieve/pii/S036031991730321X doi: 10.1016/j.ijhydene.2017.01.155

Oostvogels, B. (2017). *Zo is de literprijs van benzine, diesel of LPG opgebouwd.* Retrieved from https://autorai.nl/zo-is-literprijs-benzine-diesel-lpg-opgebouwd/

Park Lee, E., Chappin, E., Lukszo, Z. & Herder, P. (2015, jun). The Car as Power Plant: Towards socio-technical systems integration. In *2015 ieee eindhoven powertech* (pp. 1–6). Eindhoven: IEEE. Retrieved from https://ieeexplore.ieee.org/document/7232756/ doi: 10.1109/PTC.2015.7232756

Penders, R. J. (2020, apr). *Waterstof tanken in 2020: zo staat het er wereldwijd voor.* Retrieved from https://zerauto.nl/waterstof-tanken-in-2020-zo-staat-het-er-wereldwijd-voor/

PipeLife. (n.d.). *SoluForce gecertificeerd voor waterstoftoepassingen.* Retrieved 2020-07-23, from https://www.pipelife.nl/nl/news/6391-soluforce-gecertificeerd-voor-waterstoftoepassingen.php

Provincie Groningen. (2017). *Windenergie Eemshaven (Structuurvisie Eemsmond-Delfzijl) | Data overheid.* Retrieved 2020-04-14, from https://data.overheid.nl/dataset/10705-windenergie-eemshaven--structuurvisie-eemsmond-delfzijl-

Putrasari, Y., Praptijanto, A., Nur, A., Santoso, W. B., Pratama, M., Dimyani, A., … Lim, O. (2018, dec). Thermal efficiency and emission characteristics of a diesel-hydrogen dual fuel CI engine at various loads condition. *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, *9*(2), 49. Retrieved from http://mevjournal.com/index.php/mev/article/view/437 doi: 10.14203/j.mev.2018.v9.49-56

Reijnen, B. (2019, jul). *Iedereen moet van het gas af: vrijwillig of gedwongen | RTLZ.* Retrieved from https://www.rtlz.nl/life/personal-finance/artikel/4787061/iedereen-moet-van-het-gas-af-vrijwillig-gedwongen

Reindsen, H. (2018, may). *Boer stapt niet zomaar over op elektrische trekker - Nieuwe Oogst.* Retrieved from https://www.nieuweoogst.nl/nieuws/2018/05/09/boer-stapt-niet-zomaar-over-op-elektrische-trekker

Remeha. (2019). *Waterstofgas en de waterstofketel.* Retrieved 2020-04-02, from https://www.remeha.nl/actueel/waterstofgas-en-waterstofketel/

Rijksdienst voor Ondernemend Nederland. (2020). *Berekening SDE+ | RVO.nl | Rijksdienst.* Retrieved 2020-06-08, from https://www.rvo.nl/subsidie-en-financieringswijzer/sde/aanvragen-sde/berekening-sde

Sargent, R. G. (2010, dec). Verification and validation of simulation models. In *Proceedings of the 2010 winter simulation conference* (pp. 166–183). IEEE. Retrieved from http://ieeexplore.ieee.org/document/5679166/ doi: 10.1109/WSC.2010.5679166

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J. & Few, S. (2017, dec). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, *42*(52), 30470–30492. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0360319917339435 doi: 10.1016/j.ijhydene.2017.10.045

Schmuecker, J. (2019, nov). The carbon-free farm. *IEEE Spectrum*, *56*(11), 30–35. Retrieved from https://ieeexplore.ieee.org/document/8889970/ doi: 10.1109/MSPEC.2019.8889970

Schoots, K., Hekkenberg, M. & Hammingh, P. (2017). *Nationale Energieverkenning 2017* (Tech. Rep.). Amsterdam/Petten: Energieonderzoek Centrum Nederland. Retrieved from https://pico.geodan.nl/pico/map.html

Sichilalu, S., Tazvinga, H. & Xia, X. (2016, oct). Optimal control of a fuel cell/wind/PV/grid hybrid system with thermal heat pump load. *Solar Energy*, *135*, 59–69. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0038092X16301232 doi: 10.1016/j.solener.2016.05.028

Sorgulu, F. & Dincer, I. (2018, mar). A renewable source based hydrogen energy system for residential applications. *International Journal of Hydrogen Energy*, *43*(11), 5842–5851. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0360319917341411 doi: 10.1016/j.ijhydene.2017.10.101

The Dutch Ministry of Economic Affairs and Climate Policy. (2020). *HyWay 27 kick-off: Gasunie and TenneT look into using national gas grid to develop hydrogen infrastructure.* Retrieved 2020-07-23, from https://www.government.nl/latest/news/2020/06/15/hyway-27-kick-off-the-dutch-ministry-of-economic-affairs-and-climate-policy-gasunie-and-tennet-look-into-using-national-gas-grid-to-develop-hydrogen-infrastructure

Topsector Energie. (n.d.). *Eerste binnenvaartschip op waterstof komt eraan.* Retrieved 2020-08-03, from https://www.topsectorenergie.nl/spotlight/eerste-binnenvaartschip-op-waterstof-komt-eraan

Topwind. (n.d.). *Windpark Oostpolder | Topwind.* Retrieved 2020-06-07, from https://topwind.nl/consultancy/project/windpark-oostpolder/

United Nations / Framework Convention on Climate Change. (2015). Paris Agreement. In *Adoption of the paris agreement, 21st conference of the parties* (p. 25). Paris.

van der Roest, E., Snip, L., Fens, T. & van Wijk, A. (2020, jan). Introducing Power-to-H3: Combining renewable electricity with heat, water and hydrogen production and storage in a neighbourhood. *Applied Energy*, *257*, 114024. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0306261919317118 doi: 10.1016/j.apenergy.2019.114024

van der Voort, M. & Timmerman, M. (2019). *Energie & Landbouw : modelbedrijven* (Tech. Rep.). Wageningen: Wageningen Research. Retrieved from http://library.wur.nl/WebQuery/wurpubs/553806https://research.wur.nl/en/publications/fe1c0ace-a18c-4480-8094-5c7d36a50a44 doi: 10.18174/498921

van Gompel, M. (2020, feb). *Eerste waterstoftrein rijdt vrijdagnacht tussen Groningen en Leeuwarden.* Retrieved from https://www.spoorpro.nl/spoorbouw/2020/02/27/eerste-waterstoftrein-rijdt-donderdagnacht-tussen-groningen-en-leeuwarden/?gdpr=accept

van Melle, T., Menkveld, M., Oude Lohuis, J., de Smidt, R. & Terlouw, W. (2015). *De systeemkosten van warmte voor woningen* (Tech. Rep.). Utrecht: Ecofys.

van Wijk, A. (2020). *The Green Hydrogen Economy.* Energy Academy.

Wang, D., Zhi, Y.-q., Jia, H.-j., Hou, K., Zhang, S.-x., Du, W., … Fan, M.-h. (2019, apr). Optimal scheduling strategy of district integrated heat and power system with wind power and multiple energy stations considering thermal inertia of buildings under different heating regulation modes. *Applied Energy*, *240*, 341–358. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0306261919302119 doi: 10.1016/j.apenergy.2019.01.199

Warmtepompenadvies.be. (n.d.). *Het rendement van een warmtepomp | Warmtepompen Advies.* Retrieved 2020-06-07, from https://warmtepompenadvies.be/warmtepomp-rendement/

Weeda, M. & Niessink, R. (2020). *Waterstof als optie voor een klimaatneutrale warmtevoorziening in de bestaande bouw* (Tech. Rep.). Amsterdam: TNO. Retrieved from https://energy.nl/publication/waterstof-als-optie-voor-een-klimaatneutrale-warmtevoorziening-in-de-bestaande-bouw/?fbclid=IwAR3VA{_}czC25NQ6ZJN0i

-BHzKZ5DOra1K7C5h0yXrmZj9M4LIOfIaVGdO96w

Wieringa, J. & Rudel, E. (2002, jan). Station Exposure Metadata needed for judging and improving Quality of observations of Wind, Temperature and other parameters. *WMO/TD-No.1123,*, *Instrument*.

Woodfield, J. (2020, feb). *Hydrogen Gas Boiler Prototype Unveiled by Worcester Bosch.* Retrieved from https://www.homebuilding.co.uk/news/hydrogen-gas-boiler-prototype-unveiled-by-worcester-bosch/

Xydis, G. & Mihet-Popa, L. (2017, apr). Wind energy integration via residential appliances. *Energy Efficiency*, *10*(2), 319–329. Retrieved from http://link.springer.com/10.1007/s12053-016-9459-2 doi: 10.1007/s12053-016-9459-2

Appendix A

Appendix: Validation

As mentioned in section 5.5, there are four types of validation performed in this research, namely:

- *Degenerate tests* in which the model's behavior is tested by varying the input and internal parameters for plausible values
- *Extreme condition tests* in which the outputs should be plausible for extreme combinations of input variables in the system
- *Face validity* where knowledgeable individuals are asked whether the model and its behaviour is reasonable
- *Traces* which involves the tracing of different types of entities in the model to determine if the logic is correct.

First of all, the validation of the data used in the model is discussed, after that, the validation of the model itself is elaborated upon.

A.1 Data Validity

In this research, various data sets are used to analyse supply and demand patterns. First of all, the supply pattern of wind power is calculated by using the wind speeds measured at the KNMI weather station. Next to that, the demand pattern for household heating is constructed by using the temperatures measured at the same KNMI weather station, and calculating degree hours from that. The tank pattern of hydrogen for agricultural mobility is extracted from literature. Lastly, the demand pattern for external FCEV vehicles was already present in the PtX model, provided by a partner of the KWR.

A.1.1 Wind speed

The KNMI weather station at Lauwersoog started measuring on the 18^th of March in 1991. Therefore, the average wind speed over almost 30 years is known, which is 6,34 m/s. This research looks at the wind speeds from 2010 up to and including 2019. The average wind speed for these 10 years is 6,19 m/s. Thus, the last 10 years has seen relatively lower wind speeds than over the past 30 years. However, wind speeds over the years are very volatile. It might be that the future wind speeds will be slightly lower, but it is assumed that the wind speed data used for this research is accurate for future wind speeds.

A.1.2 Temperature

Similar to the wind speeds, the average temperature since the 18^th of March in 1991 at the KNMI weather station of Lauwersoog was 10,03 °C. For the 10 years between 2010 and 2019, the average temperature was 10.41 °C. Therefore, the temperatures used to calculate degree hours in the PtX model were slightly higher than the 30 year average. However, since 1906, annual mean temperature in the Netherlands has increased by 1.7 °C (Environmental Data Compendium, 2016). Therefore, it is concluded that a slightly higher average temperature than the 30 year average is valid for the calculations in this research.

A.1.3 Agricultural mobility

The tank pattern for agricultural mobility is calculated by smoothing a pattern of diesel use for a single model agricultural farm presented by van der Voort and Timmerman (2019). The model farm in that paper is a 60 ha farm in the Hoeksche Waard with a diesel consumption of 8.130 liter per year. The area around Oudeschip consists of 18 farms and it is unlikely that these farmers all fuel up at the same moment. Therefore, the diesel use presented by van der Voort and Timmerman (2019) is smoothened and scaled to an average diesel consumption of a Dutch farm, which is 12.000 liters of diesel (LTO Noord, personal communication, 18 Februari, 2020). The retrieved diesel consumption pattern is validated using the face validation method by expert Wouter Veefkind from LTO Noord (W. Veefkind, personalcommunication, 5 June, 2020).

A.1.4 Hydrogen for FCEV

The hydrogen demand pattern for external vehicles is based on a demand pattern from the PtX model, provided by a partner, based on real life data. This pattern is scaled to an average fuel demand per day of 200 kg hydrogen (Hydrogen Europe, 2018), which is the average for a hydrogen fuel station. Since the demand pattern is based on real life data, the data set is valid for use in this research.

A.2 Model validity

The model validity is tested by various means. Degenerative tests are performed during the formation of the model, which are unrecorded.

The calculated wind generation is validated with research of the Oostpolder wind park by Pondera Consult (Hussin, Pustjens & Rooijmans, 2017). In this paper, three different park designs are compared. Wind park design A consists of 14 4,2 MW turbines with a hub height of 165 meters and a rotor diameter of 141 meters. The net load factor of these turbines in park design A is 48,5 %. Wind park design B consists of 15 4,2 MW turbines with a hub height of 135 meters and a rotor diameter of 126 meters. The net load factor of these turbines in park design B is 42%. Wind park design C consists of 23 2,35 MW turbines with a hub height of 120 meters and a rotor diameter of 103. The net load factor of the turbines in park design C is 39%. The Lagerwey wind turbines analysed in this research are 4,5 MW turbines with a hub height of 120 meters and a rotor diameter of 136 meters. The load factor calculated in this research is 42.2%. The turbines analysed in this research are most similar to the turbines from park design A and park design B by Pondera Consult, while the Lagerwey turbines have a higher generation capacity. In real life, the generation could be slightly higher, but in order to draw safe conclusions about future generation, it is concluded that the 42.2 % load factor is valid.

A.2.1 Extreme condition tests

Extreme conditions tests are performed by setting certain input data to extreme values. The wind speed, outside temperature, external FCEV demand and agricultural demand are all set to extreme values one by one while keeping the rest of the input data to their standard values. When the model runs, the outcomes are compared to normal settings to see if the difference is logical or not. The wind speed is set to 0 m/s for every hour during the year, as well as to 15 m/s. The cut off speed of the Lagerwey turbine is at 25 m/s, however, that is at hub height. A 25 m/s speed at 10 meters altitude will result in a higher wind speed at hub height, which in turn results in zero wind power generation. The outside temperature is set to 0 °C. Since the outside temperature is merely used by the model to form a household heating demand pattern using degree hours, which is then multiplied with the average household energy use per year, this results in a constant hydrogen demand from the households. If the outside temperature is set to 16 °C, the households never turn on their boiler, since 16 °C is set as the threshold value for household heating. The FCEV demand pattern is set to a constant value which sums up to a demand of 0 kg/day or 400 kg/day. This results in a constant demand pattern from FCEV vehicles, instead of the hourly pattern. The agricultural demand is originally retrieved from the diesel demand per hour. For the validation it is varied to be 0 l/day or 3000 l/day per farm. The demand pattern from agricultural mobility has a strong seasonal pattern, which is not the case during these validations. Lastly, all the above mentioned values are set to zero to see the effects on the model. A complete overview of the altered variables and the resulting outcomes is presented in table A.1. As all the results are as expected, the model is deemed valid according to the extreme condition tests.

Table A.1: Data altered for extreme condition tests

Altered variable	**Min value**	**Outcome**	**Max value**	**Outcome**
Wind speed	0 m/s	No wind generation, all hydrogen produced from grid electricity, higher LCOH	15 m/s	Constant wind power generation, partly for hydrogen production until capacity limit of electrolyser, party exported to the grid. No electricity bought from the grid, large amount of hydrogen exported
Temperature	0 °C	Due to degree hours calculations, constant hydrogen demand for household heating	16 °C	No hydrogen demand from households, more hydrogen exported
FCEV demand	0 kg/day	Hydrogen production stays the same, More hydrogen exported	400 kg/day	Higher total hydrogen demand resulting in lower hydrogen export and more electricity imported from the grid
Agricultural demand	0 l/day	Hydrogen production stays the same More hydrogen exported	3000 l/day	Hydrogen production stays the same Constant agricultural hydrogen demand
All zero	0	No hydrogen demand, except for household heating due to degree days calculations. All this demand is fulfilled with hydrogen production from grid electricity		

During the formation of the model to suit the Oudeschip case, multiple trial runs were performed, of which the intermediate outcomes were traced and reviewed to filter out mistakes in the model. These validations were not logged and are therefore not presented here. The values were often face validated with expert consultations by Ad van Wijk, as well as Els van der Roest. Similarly, all the used technical and economic parameters used in the model were face validated.

The four validation methods discussed at the beginning of this appendix were mixed to form a more comprehensive validation of the model. The methods result in the conclusion that the model is valid.

Appendix B

Appendix: Results

This appendix provides all the graphs resulting from the simulations, as well as the tables with exact numbers behind some of the graphs, for those who would like to dive deeper into the numbers.

B.1 Tables with results

Table B.1: LCOH [€/kg]

		Type and size of electrolyser							
		PEM				Alkaline			
		1 MW	2 MW	3 MW	4 MW	1 MW	2 MW	3 MW	4 MW
Storage size	200 kg	3.95	3.03	3.04	3.11	2.93	2.21	2.18	2.20
	400 kg	3.99	3.02	3.07	3.15	2.94	2.19	2.20	2.22

Table B.2: Investment cost H2Oudeschip [€]

		Type and size of electrolyser							
		PEM				Alkaline			
		1 MW	2 MW	3 MW	4 MW	1 MW	2 MW	3 MW	4 MW
Storage size	200 kg	1351584	2556971	3760753	4965822	768584	1391055	2013124	2633820
	400 kg	1497584	2702971	3906753	5111822	914584	1537055	2159124	2779820

Table B.3: Profit H2Oudeschip [€/year]

		Type and size of electrolyser							
		PEM				Alkaline			
		1 MW	2 MW	3 MW	4 MW	1 MW	2 MW	3 MW	4 MW
Storage size	200 kg	68389	270545	495824	681176	92827	456331	802523	1096596
	400 kg	63840	238720	459129	641153	81937	415381	759689	1052542

Table B.4: Payback time H2Oudeschip [years]

		Type and size of electrolyser							
		PEM				Alkaline			
		1 MW	2 MW	3 MW	4 MW	1 MW	2 MW	3 MW	4 MW
Storage size	200 kg	19.76	9.45	7.58	7.29	8.28	3.05	2.51	2.40
	400 kg	23.46	11.32	8.51	7.97	11.16	3.70	2.84	2.64

Table B.5: Profit fuel station operator [€/y]

		Type and size of electrolyser							
		PEM				Alkaline			
		1 MW	2 MW	3 MW	4 MW	1 MW	2 MW	3 MW	4 MW
Storage size	200 kg	268215	368753	367058	360002	379329	458472	461543	459531
	400 kg	263730	369728	364083	355631	377982	460748	459827	456891

B.2 PEM 1MW 200kg

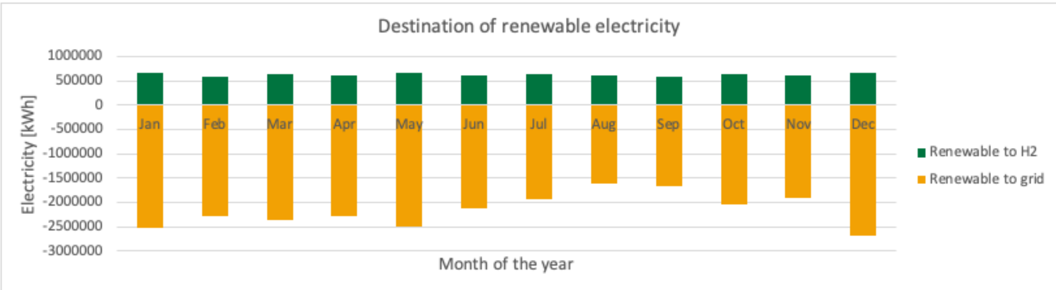


Figure B.1: Destination of wind power

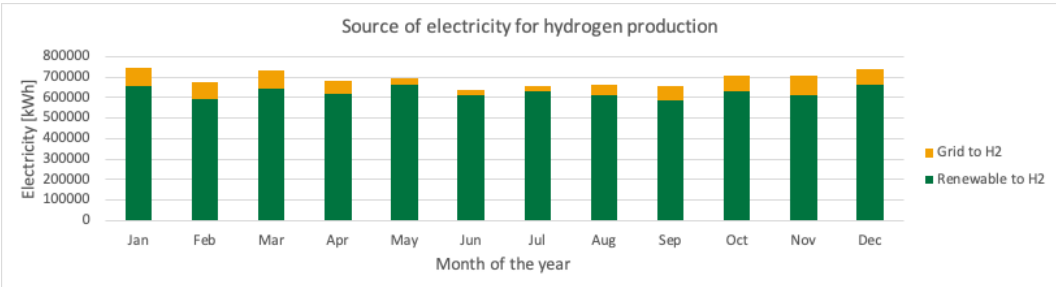


Figure B.2: Source of electricity for hydrogen production

Table B.6: Payback time fuel station [years]

		Type and size of electrolyser							
		PEM				Alkaline			
		1 MW	2 MW	3 MW	4 MW	1 MW	2 MW	3 MW	4 MW
Storage size	200 kg	4.47	3.25	3.27	3.33	3.16	2.62	2.60	2.61
	400 kg	4.55	3.25	3.30	3.37	3.17	2.60	2.61	2.63

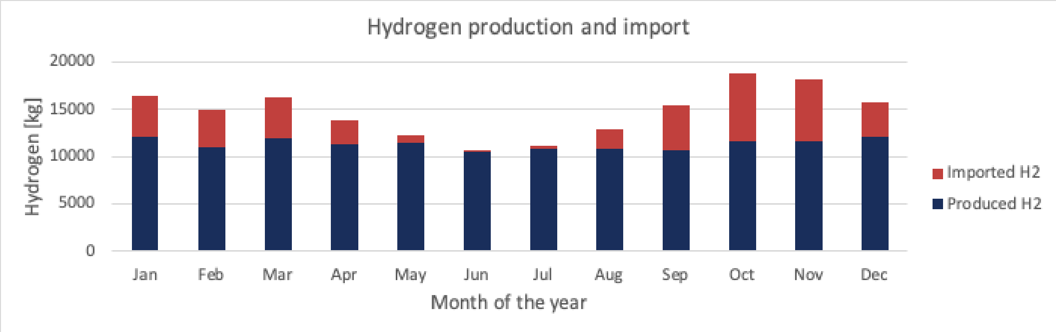


Figure B.3: Source of hydrogen to fulfill demand

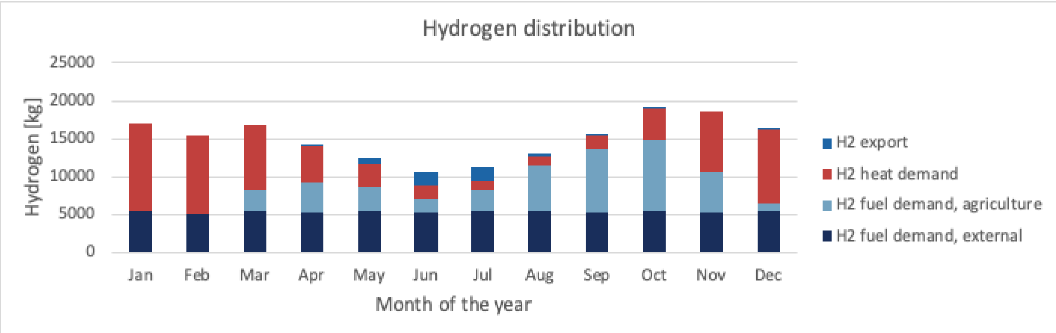


Figure B.4: Distribution of hydrogen

B.3 PEM 2MW 200kg

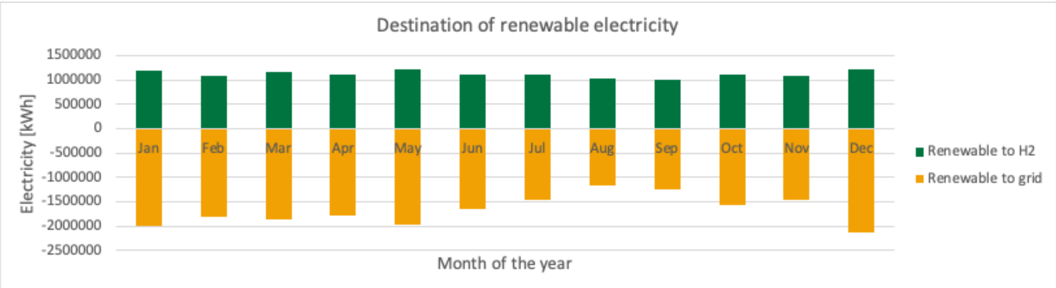


Figure B.5: Destination of wind power

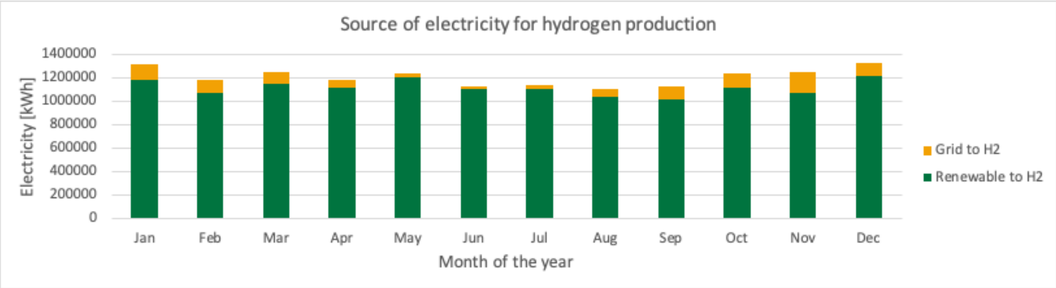


Figure B.6: Source of electricity for hydrogen production

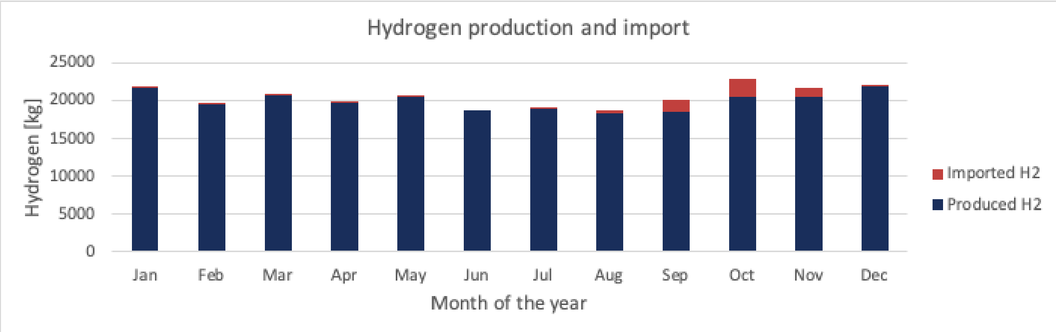


Figure B.7: Source of hydrogen to fulfill demand

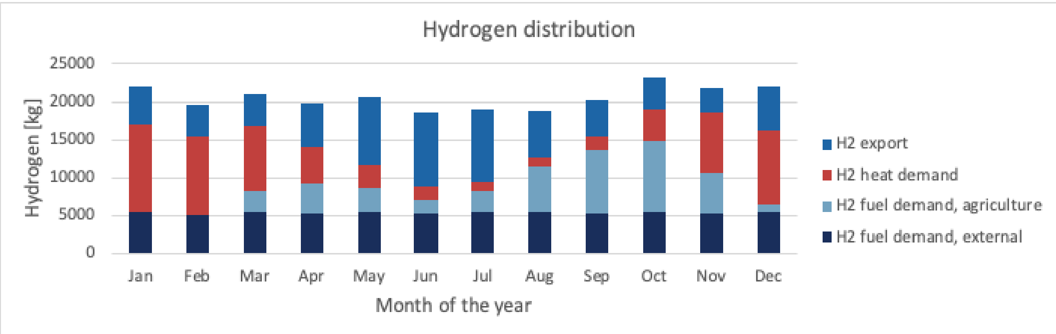


Figure B.8: Distribution of hydrogen

B.4 PEM 3MW 200kg

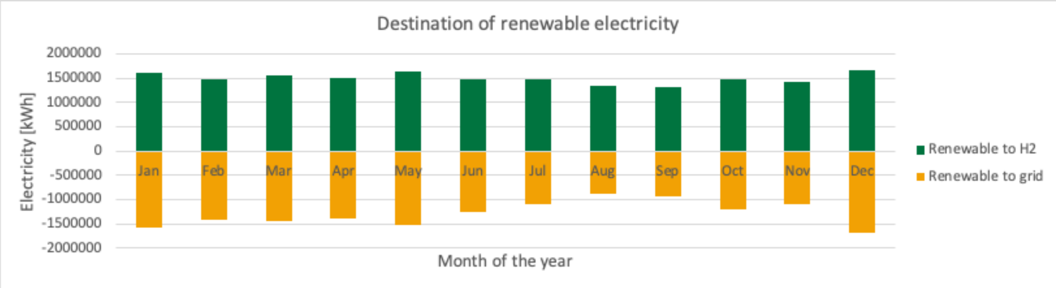


Figure B.9: Destination of wind power

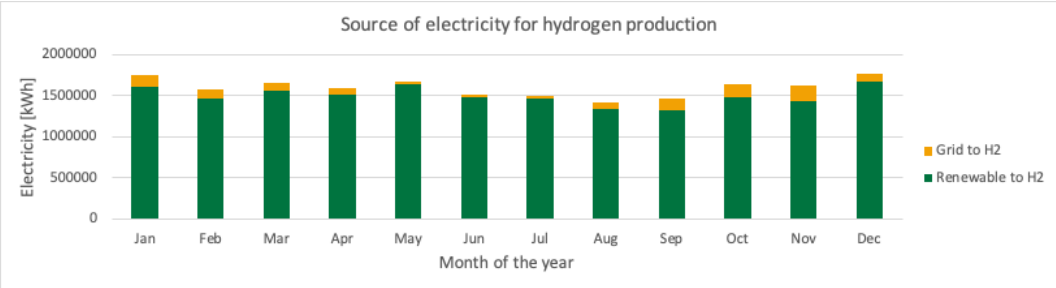


Figure B.10: Source of electricity for hydrogen production

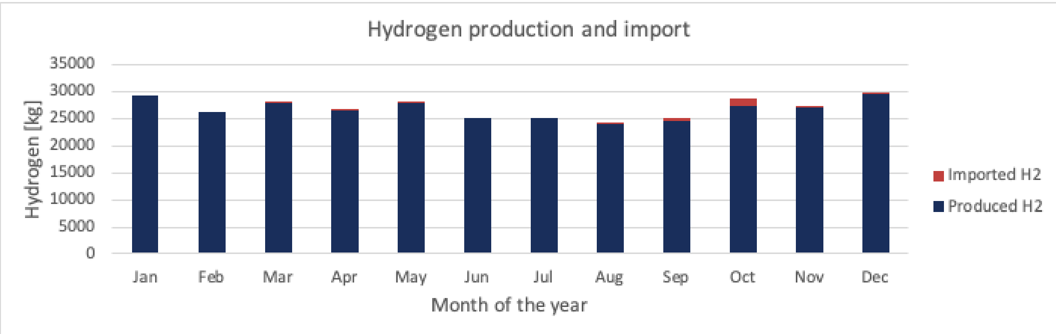


Figure B.11: Source of hydrogen to fulfill demand

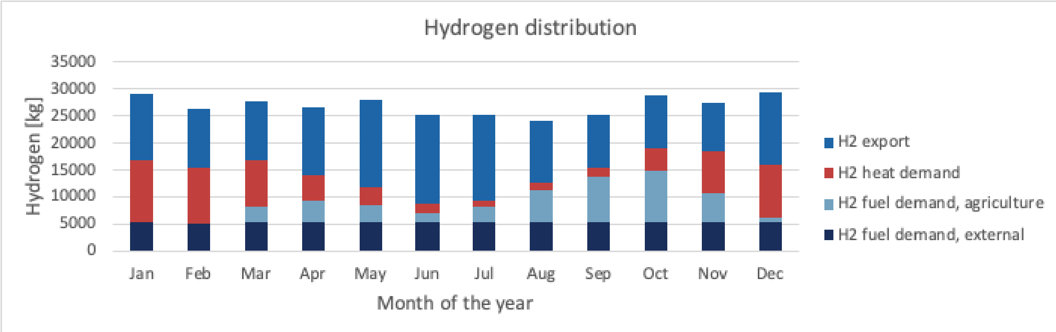


Figure B.12: Distribution of hydrogen

B.5 PEM 4MW 200kg

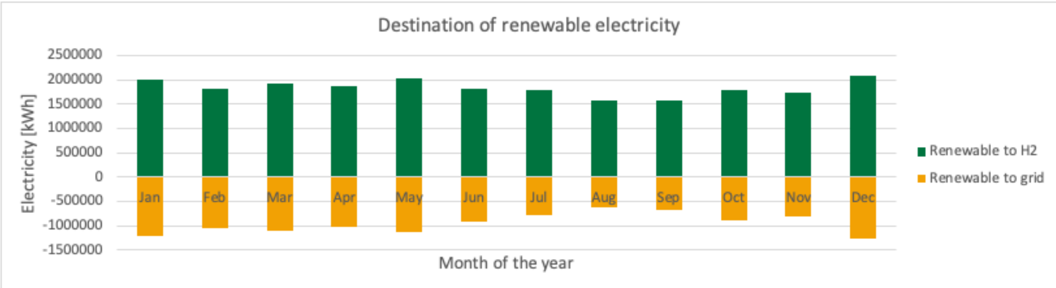


Figure B.13: Destination of wind power

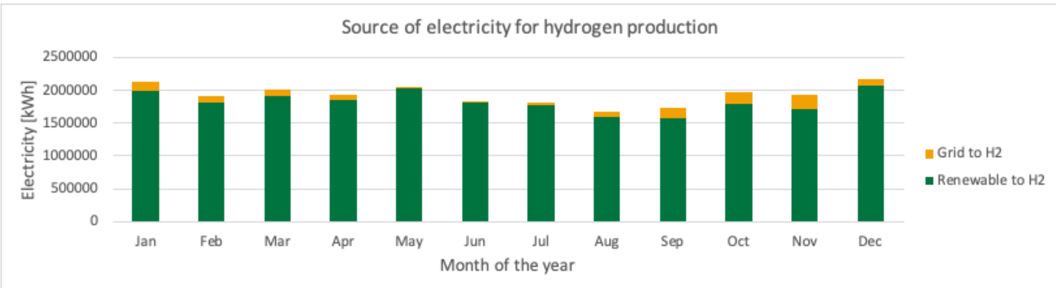


Figure B.14: Source of electricity for hydrogen production

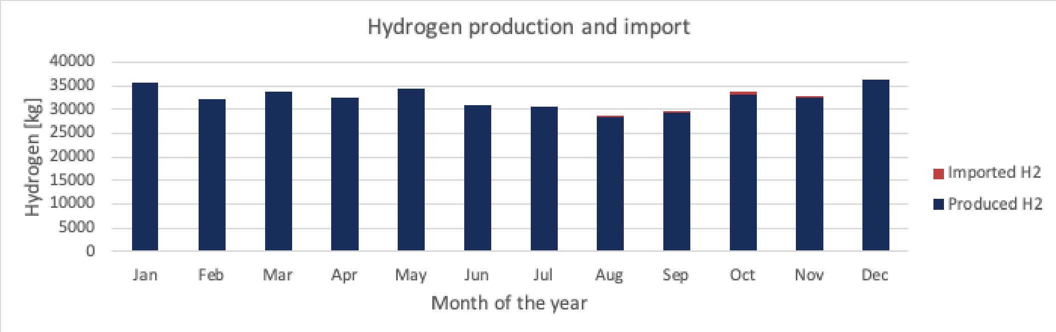


Figure B.15: Source of hydrogen to fulfill demand

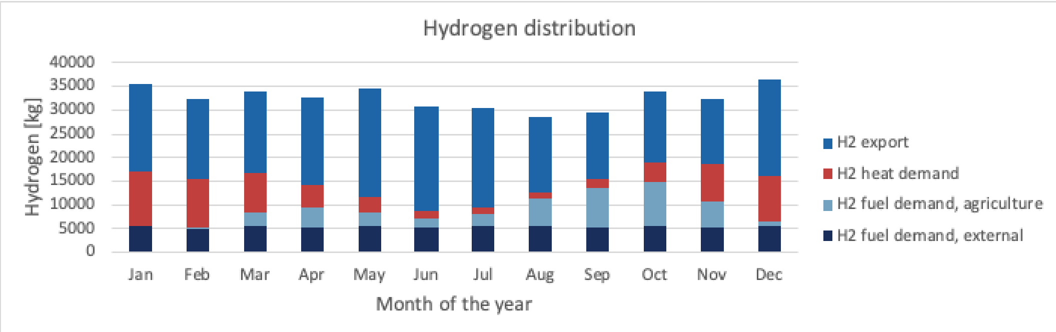


Figure B.16: Distribution of hydrogen

B.6 PEM 1MW 400kg

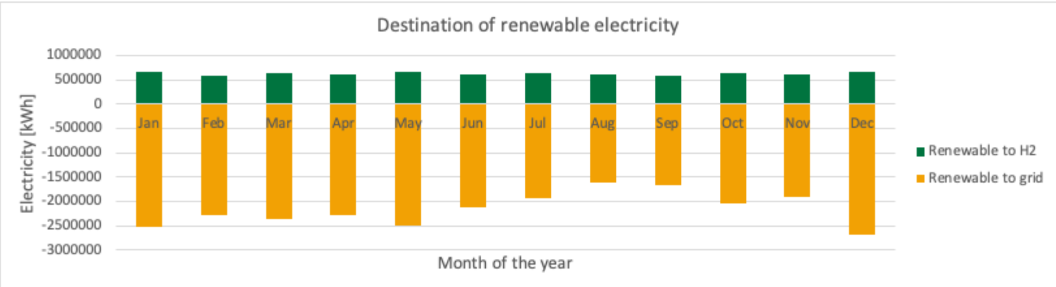


Figure B.17: Destination of wind power

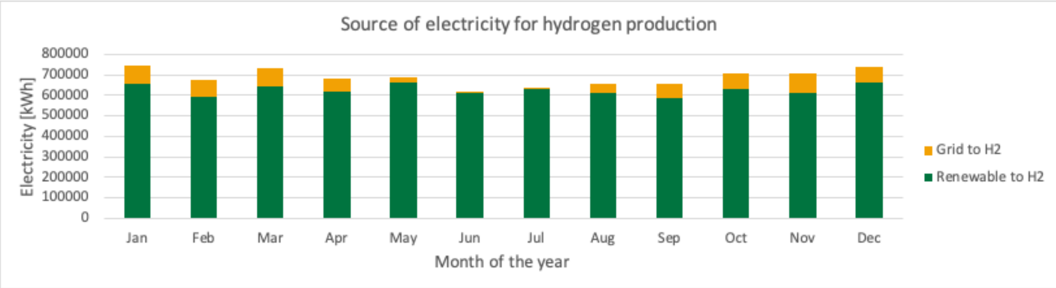


Figure B.18: Source of electricity for hydrogen production

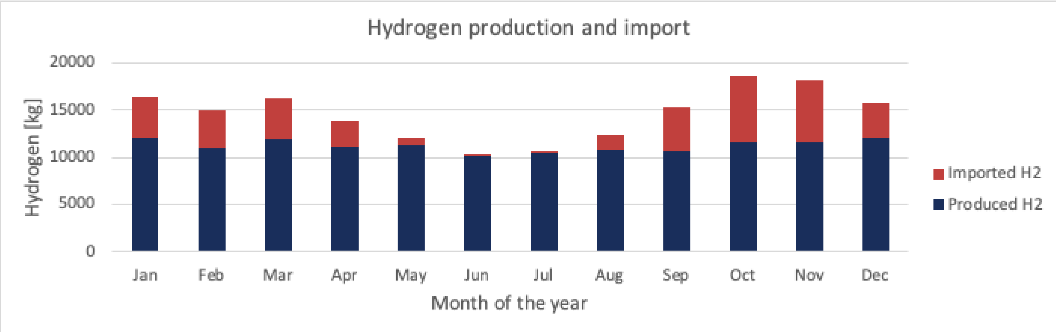


Figure B.19: Source of hydrogen to fulfill demand

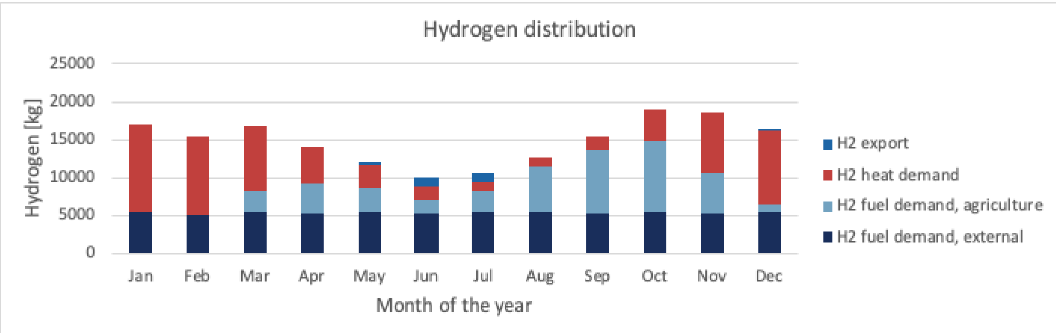


Figure B.20: Distribution of hydrogen

B.7 PEM 2MW 400kg

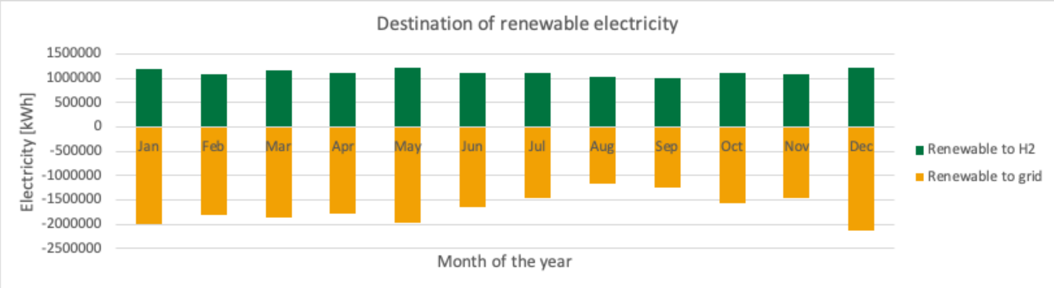


Figure B.21: Destination of wind power

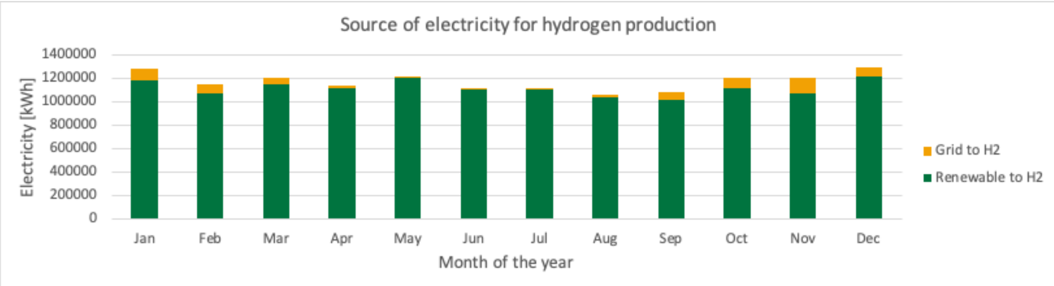


Figure B.22: Source of electricity for hydrogen production

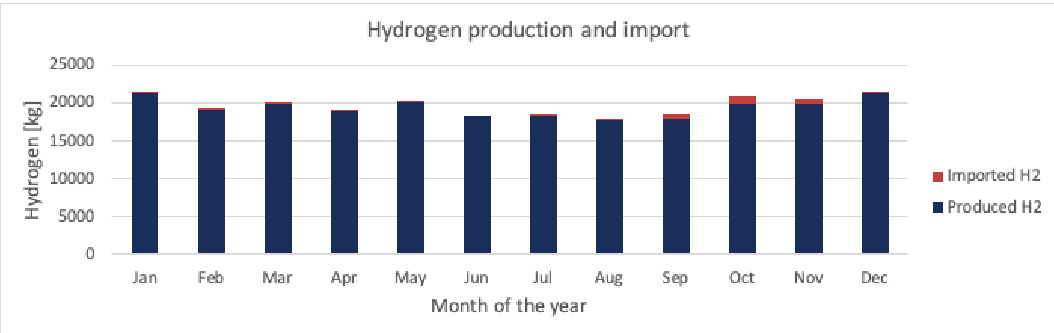


Figure B.23: Source of hydrogen to fulfill demand

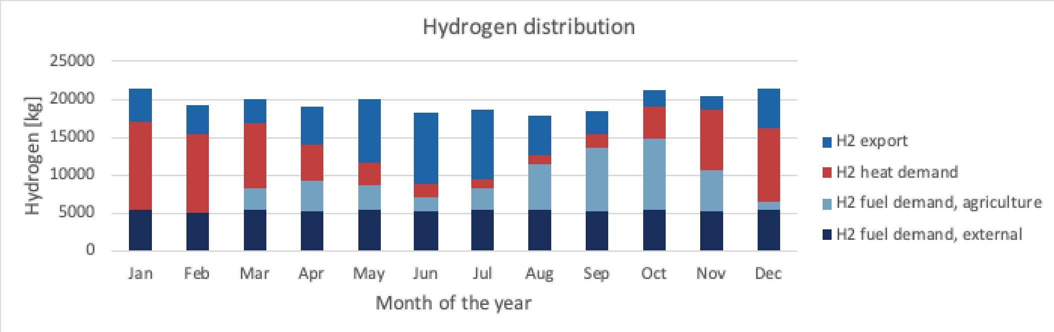


Figure B.24: Distribution of hydrogen

B.8 PEM 3MW 400kg

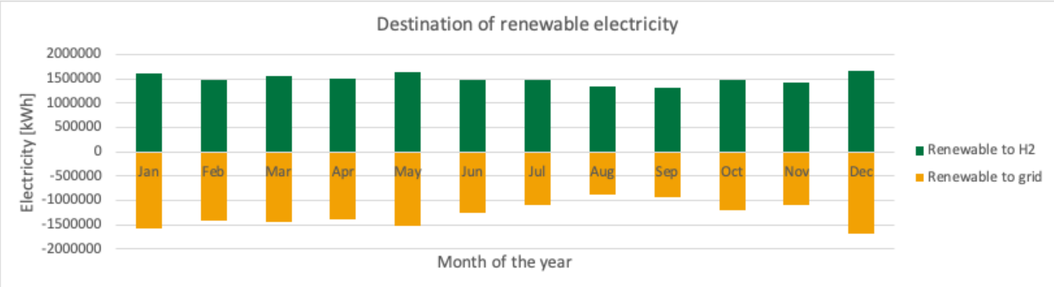


Figure B.25: Destination of wind power

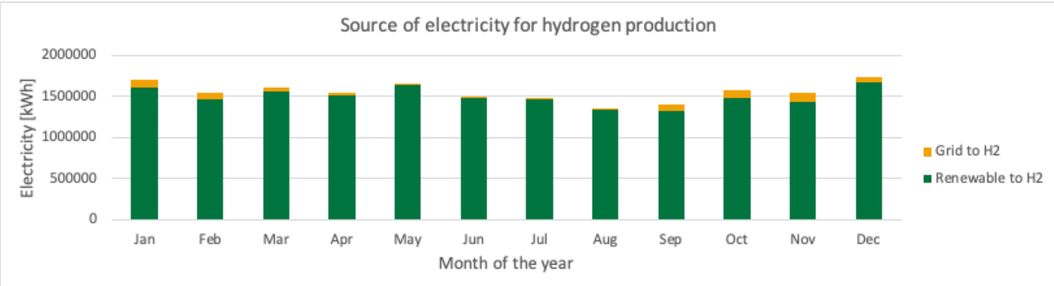


Figure B.26: Source of electricity for hydrogen production

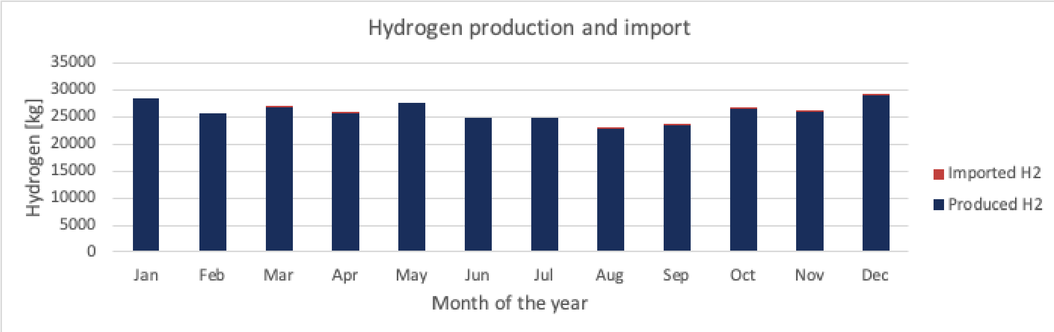


Figure B.27: Source of hydrogen to fulfill demand

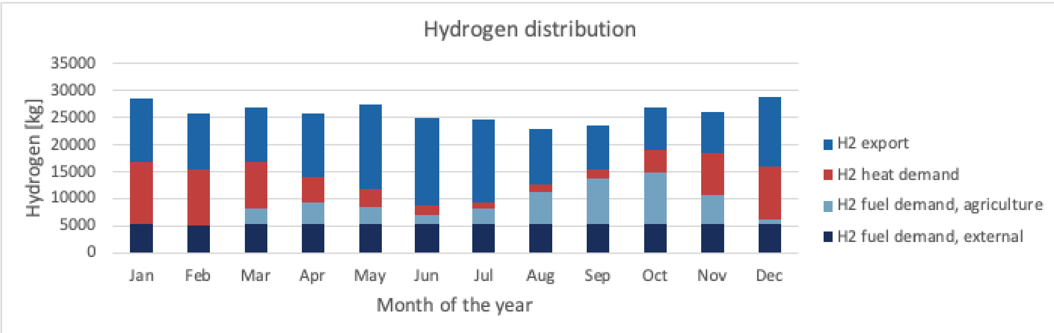


Figure B.28: Distribution of hydrogen

B.9 PEM 4MW 400kg

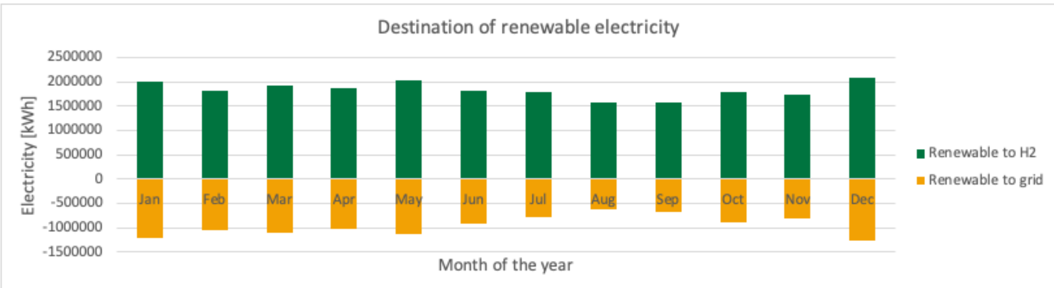


Figure B.29: Destination of wind power

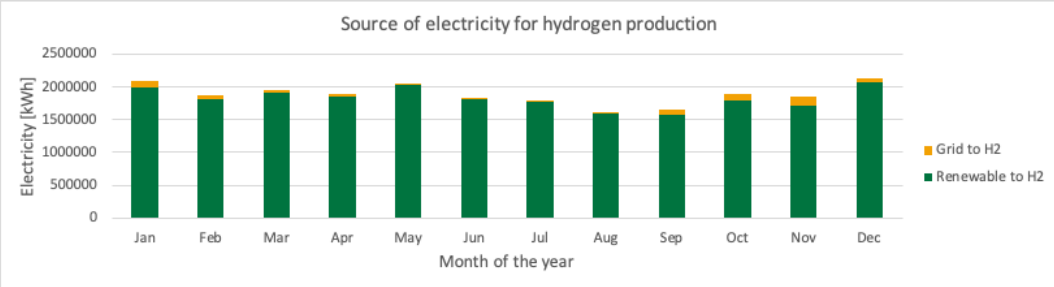


Figure B.30: Source of electricity for hydrogen production

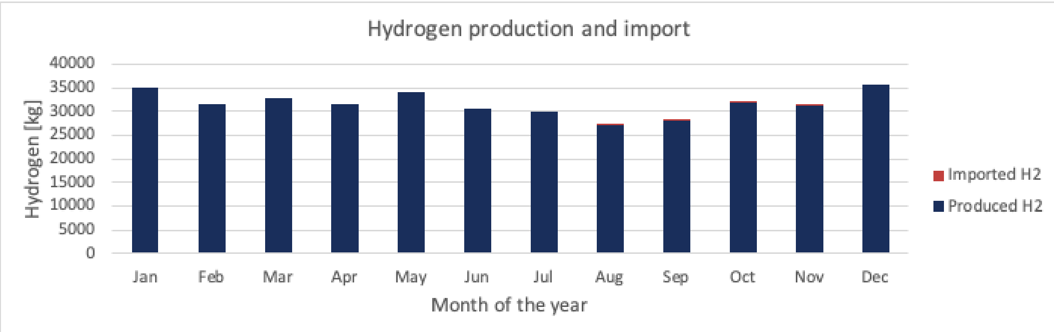


Figure B.31: Source of hydrogen to fulfill demand

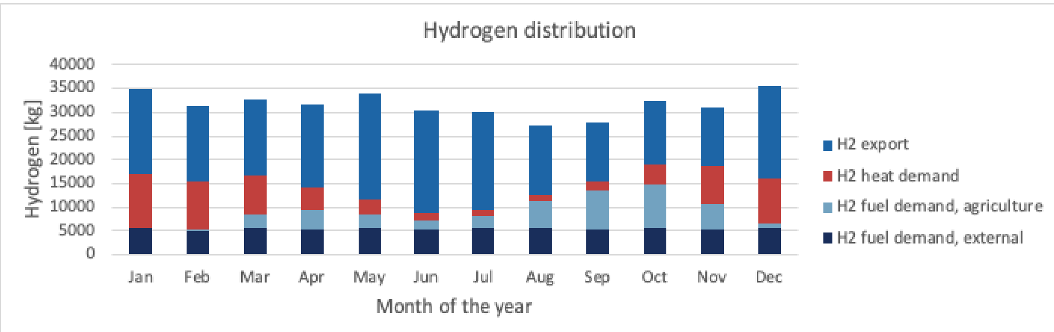


Figure B.32: Distribution of hydrogen

B.10 Alkaline 1MW 200kg

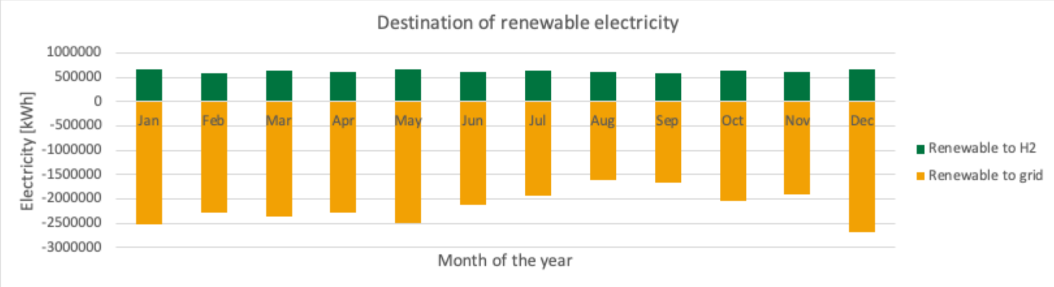


Figure B.33: Destination of wind power

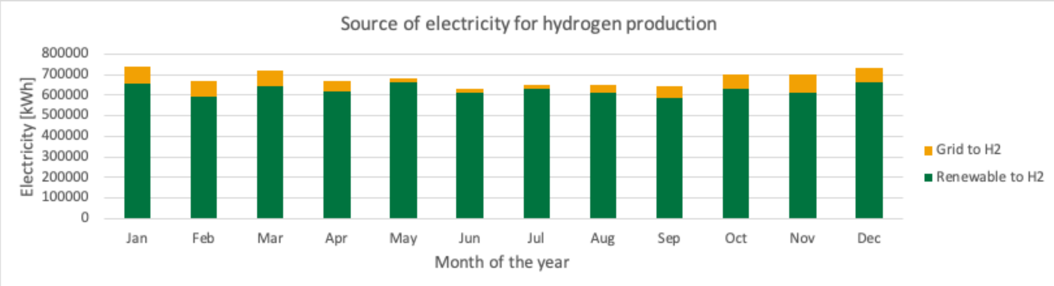


Figure B.34: Source of electricity for hydrogen production

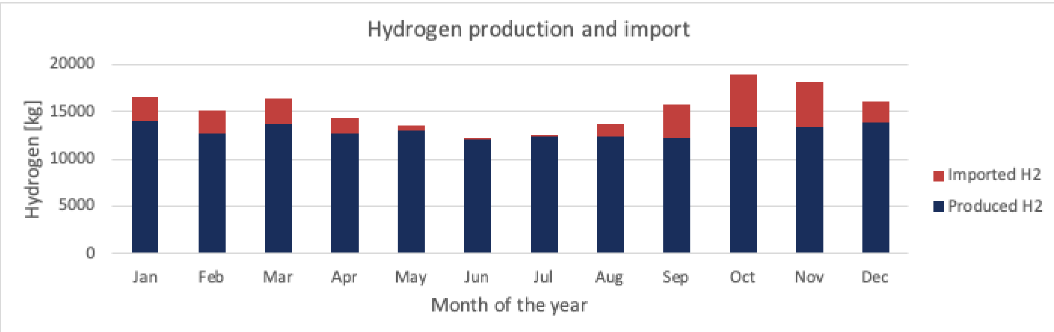


Figure B.35: Source of hydrogen to fulfill demand

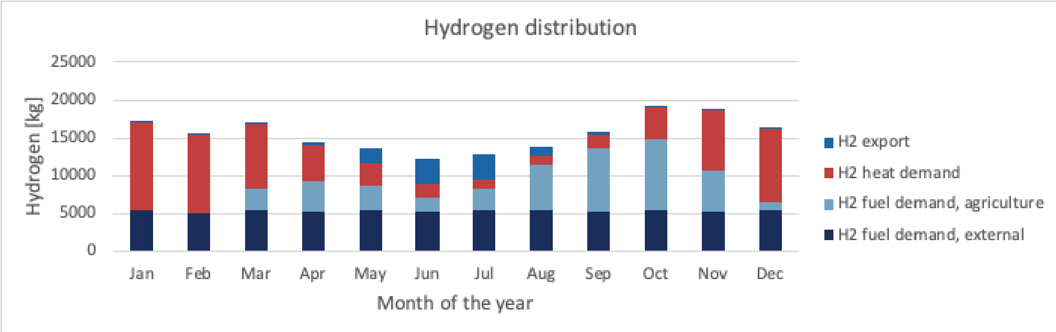


Figure B.36: Distribution of hydrogen

B.11 Alkaline 2MW 200kg

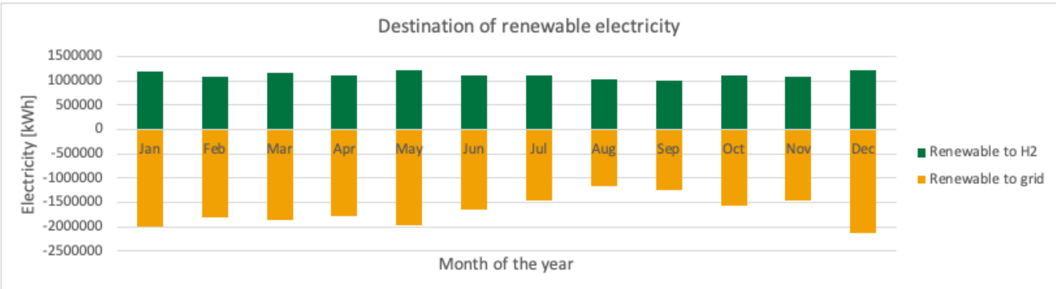


Figure B.37: Destination of wind power

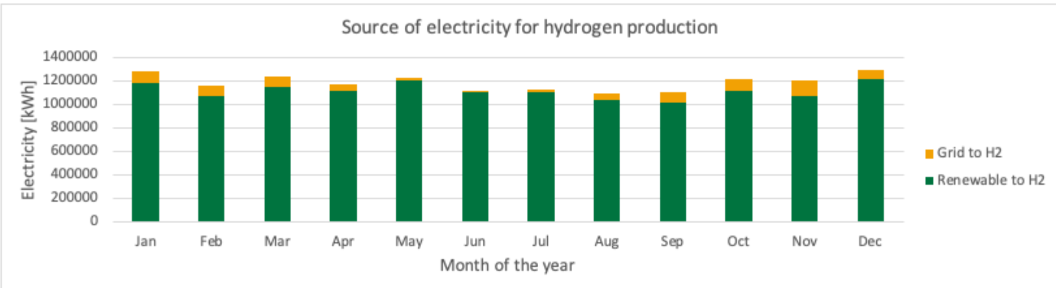


Figure B.38: Source of electricity for hydrogen production

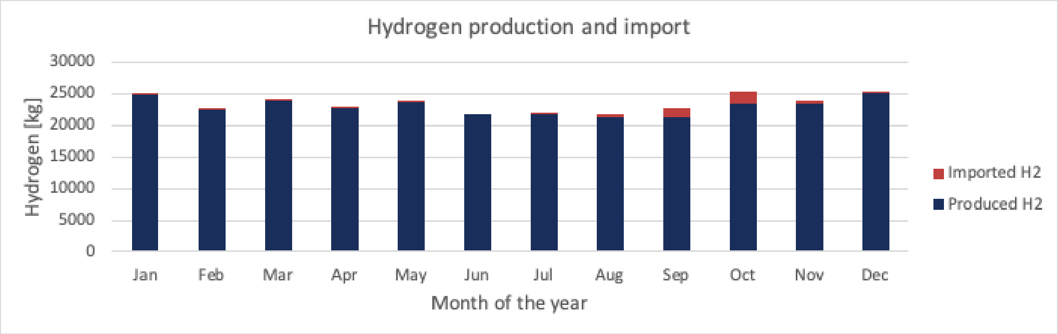


Figure B.39: Source of hydrogen to fulfill demand

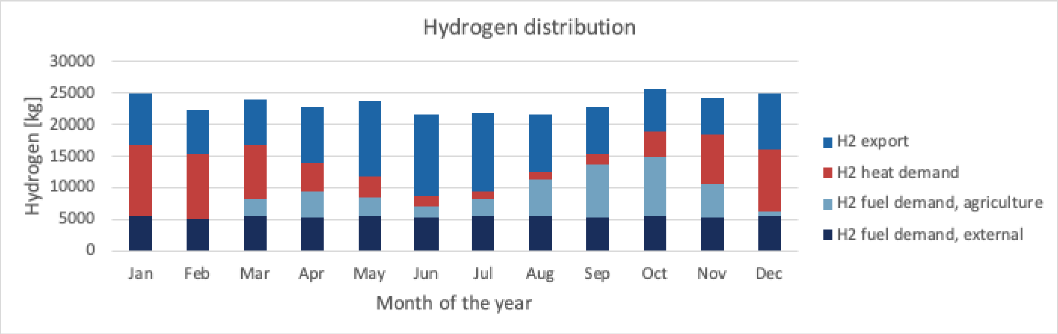


Figure B.40: Distribution of hydrogen

B.12 Alkaline 3MW 200kg

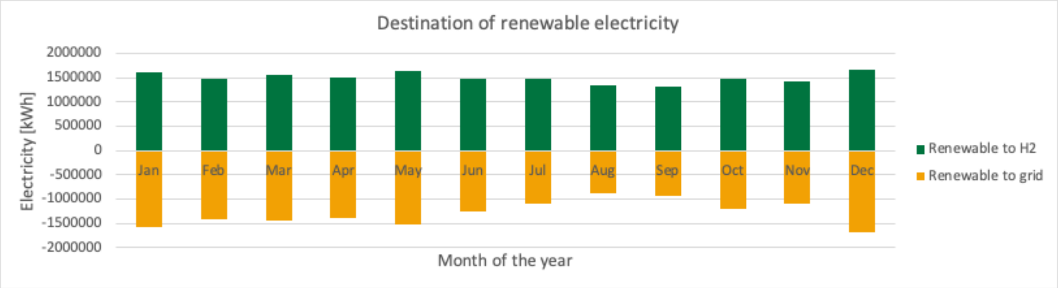


Figure B.41: Destination of wind power

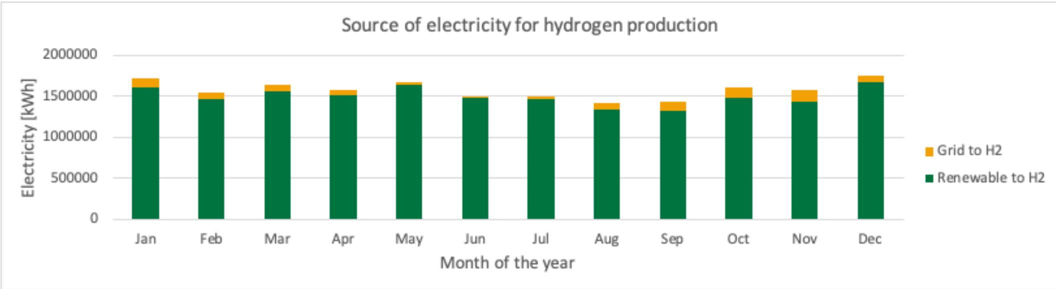


Figure B.42: Source of electricity for hydrogen production

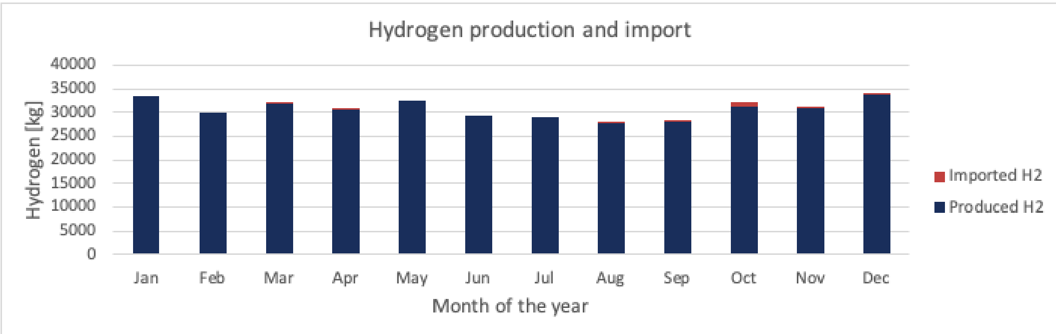


Figure B.43: Source of hydrogen to fulfill demand

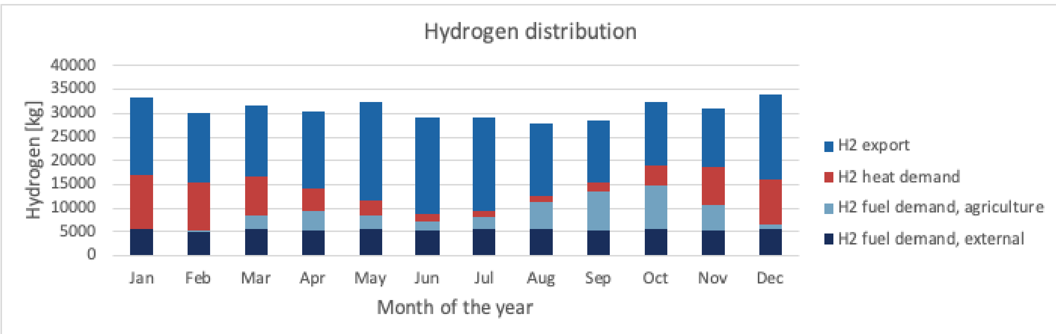


Figure B.44: Distribution of hydrogen

B.13 Alkaline 4MW 200kg

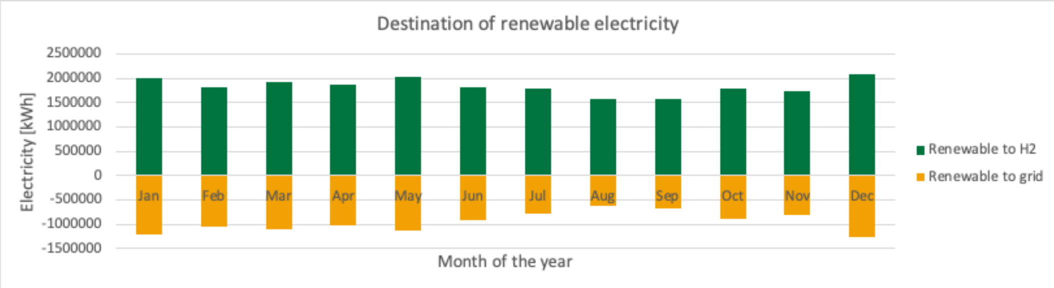


Figure B.45: Destination of wind power

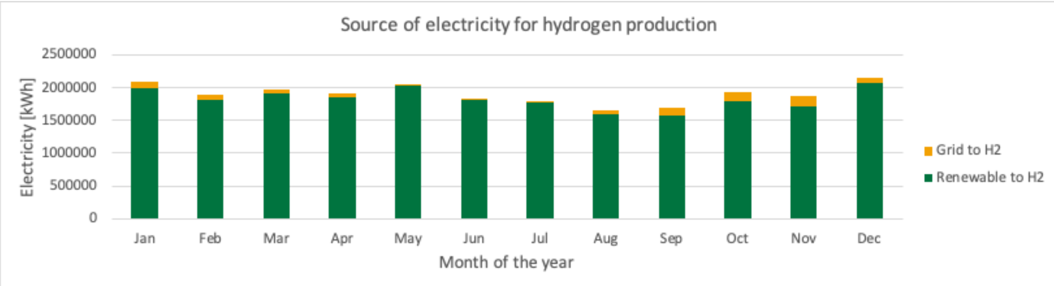


Figure B.46: Source of electricity for hydrogen production

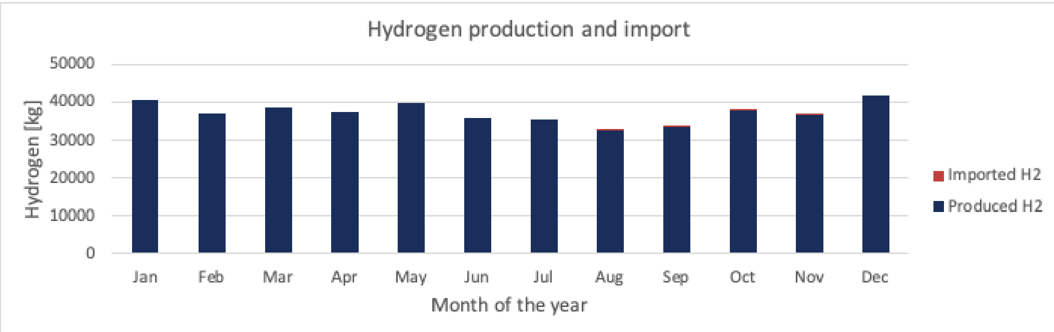


Figure B.47: Source of hydrogen to fulfill demand

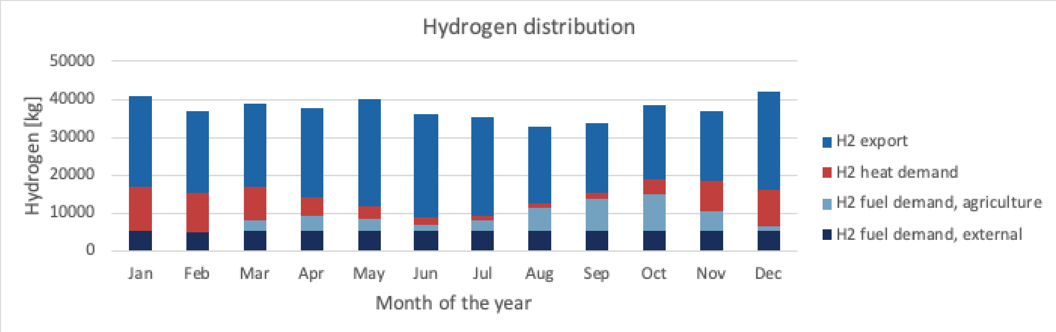


Figure B.48: Distribution of hydrogen

B.14 Alkaline 1MW 400kg

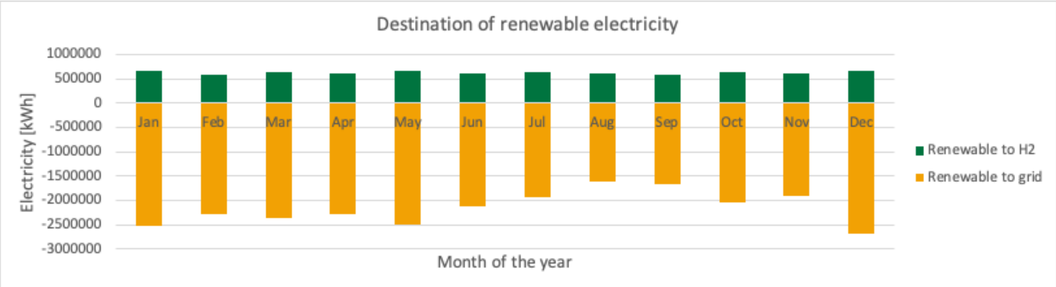


Figure B.49: Destination of wind power

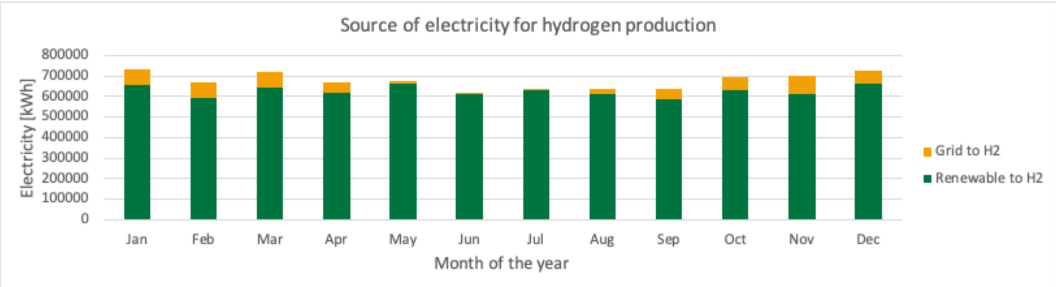


Figure B.50: Source of electricity for hydrogen production

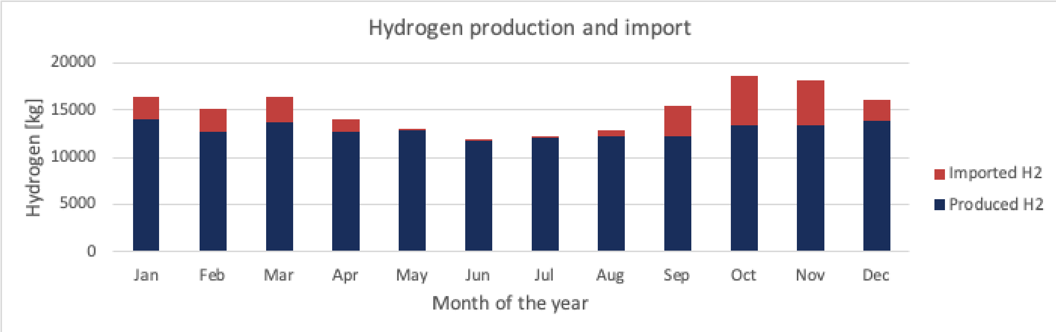


Figure B.51: Source of hydrogen to fulfill demand

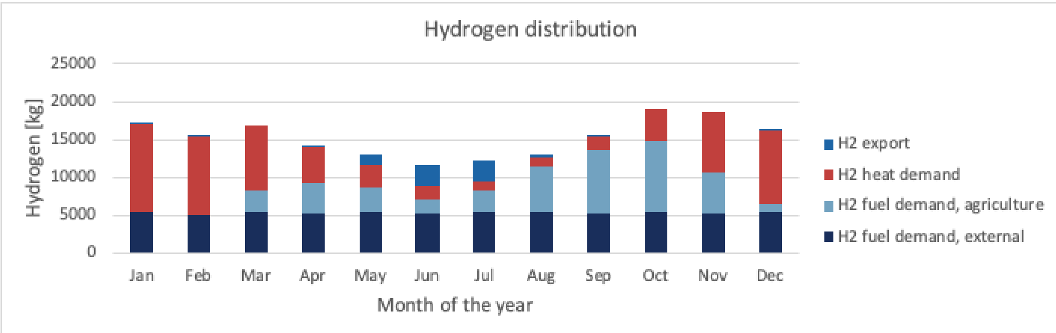


Figure B.52: Distribution of hydrogen

B.15 Alkaline 2MW 400kg

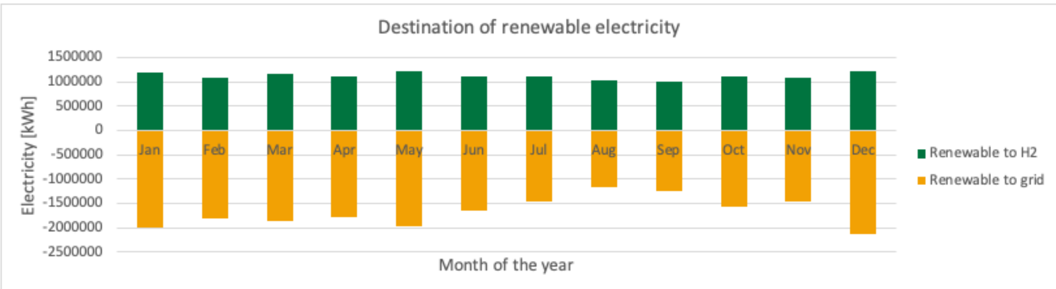


Figure B.53: Destination of wind power

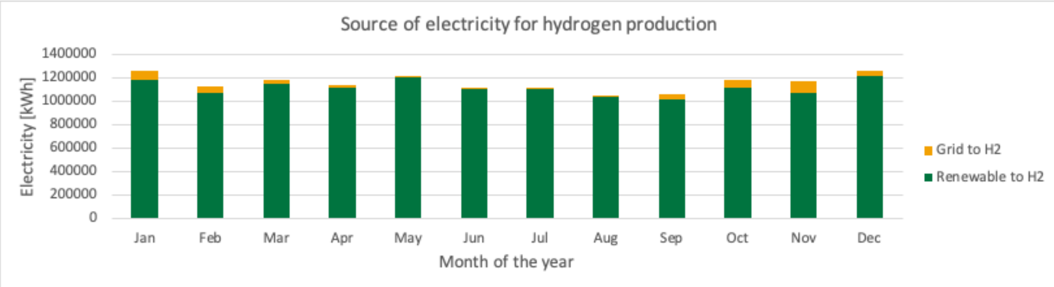


Figure B.54: Source of electricity for hydrogen production

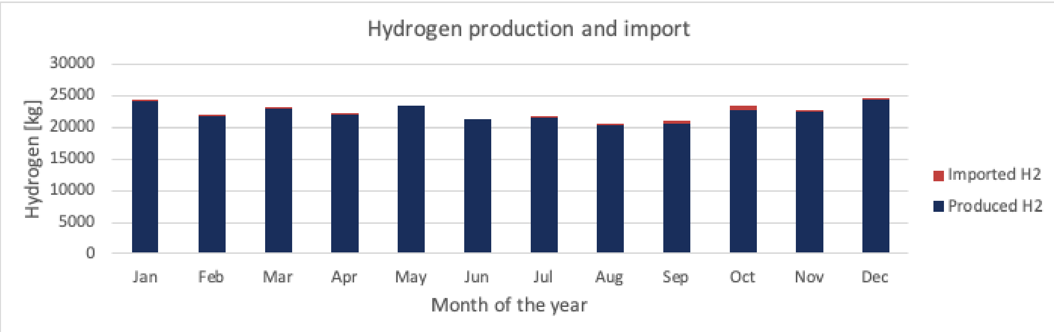


Figure B.55: Source of hydrogen to fulfill demand

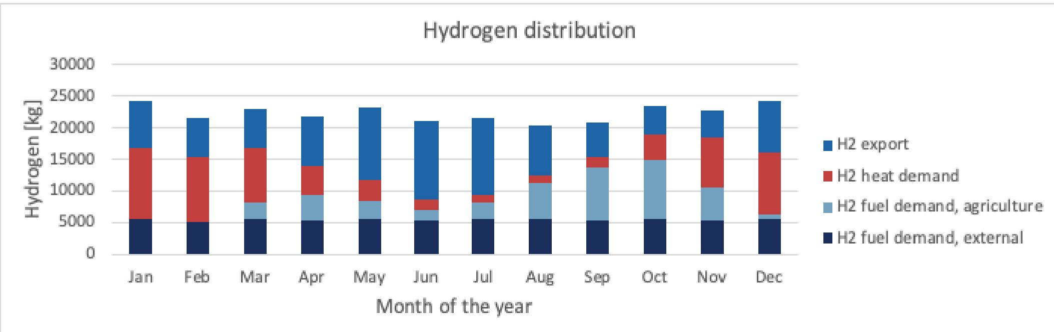


Figure B.56: Distribution of hydrogen

B.16 Alkaline 3MW 400kg

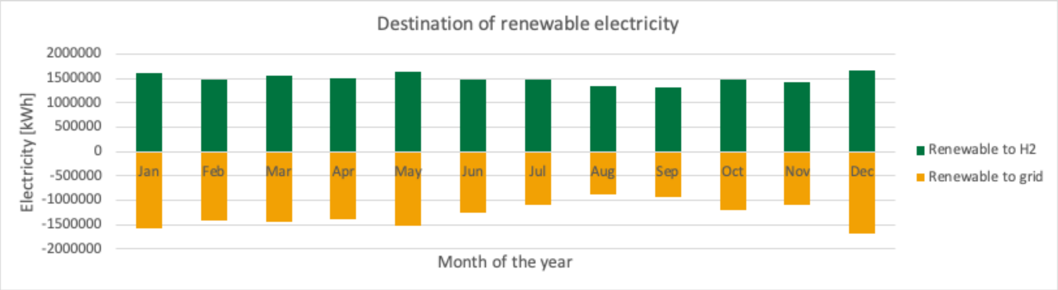


Figure B.57: Destination of wind power

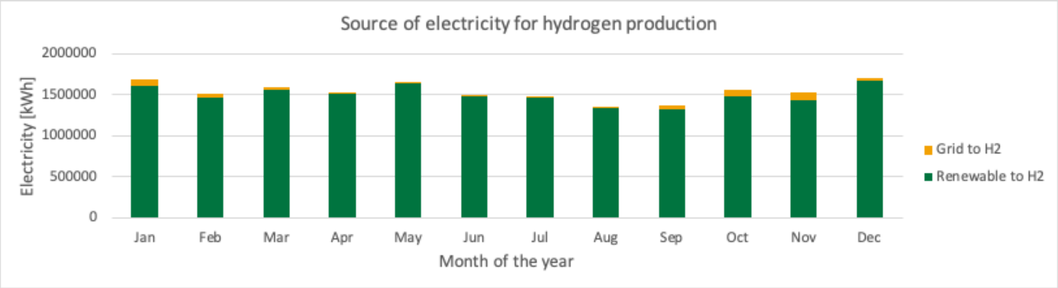


Figure B.58: Source of electricity for hydrogen production

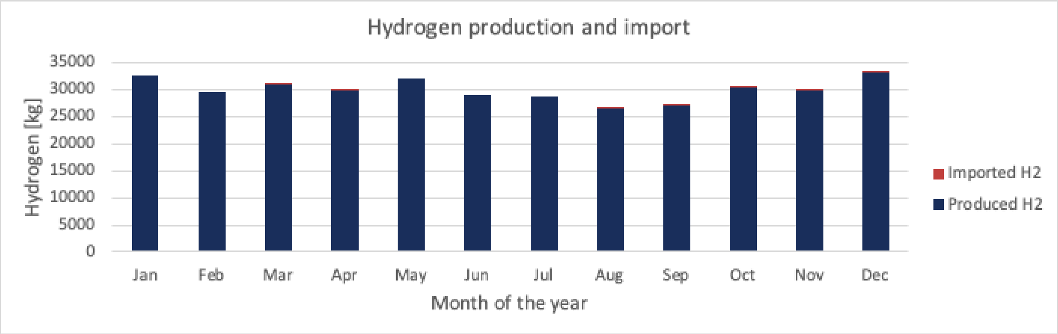


Figure B.59: Source of hydrogen to fulfill demand

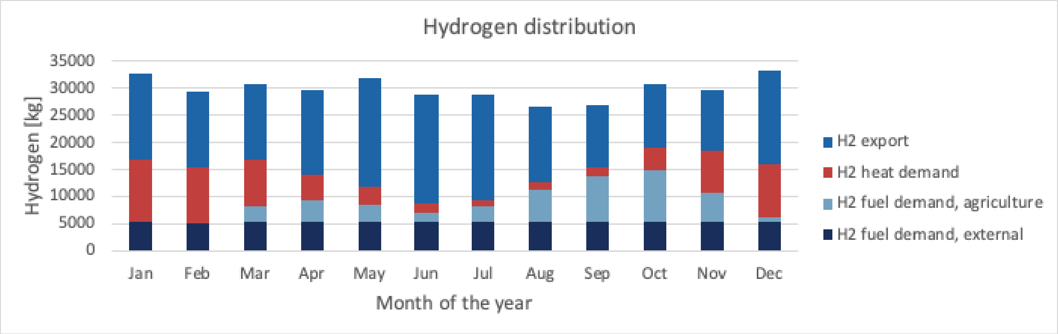


Figure B.60: Distribution of hydrogen

B.17 Alkaline 4MW 400kg

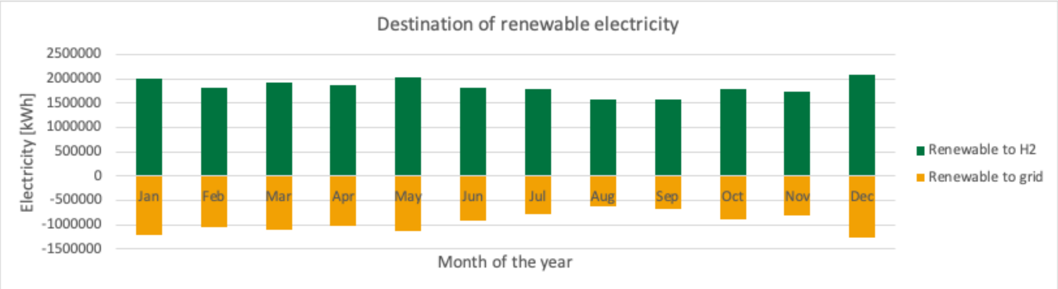


Figure B.61: Destination of wind power

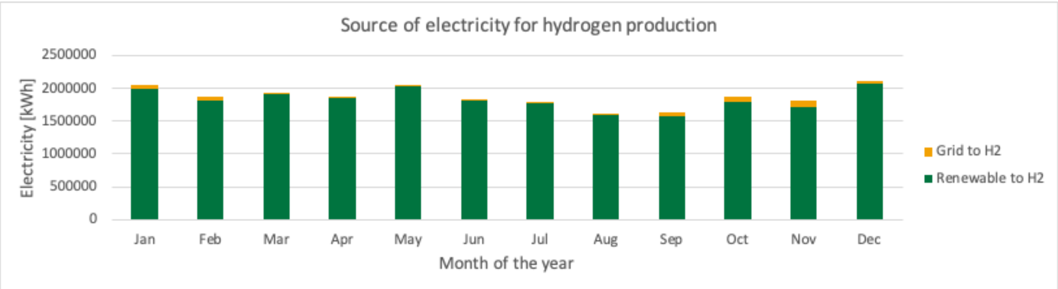


Figure B.62: Source of electricity for hydrogen production

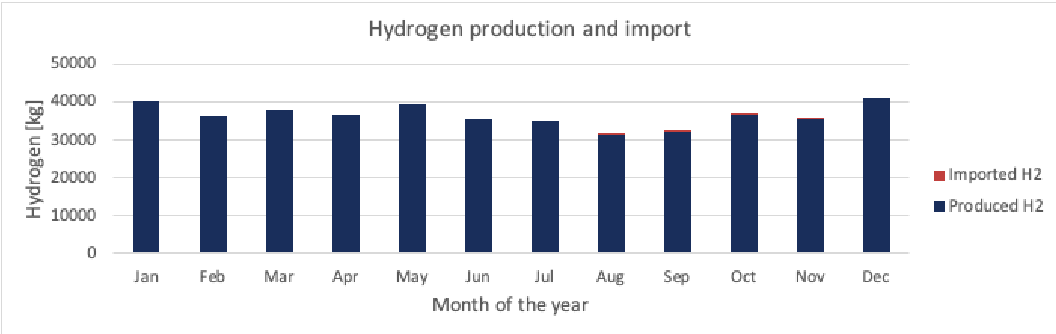


Figure B.63: Source of hydrogen to fulfill demand

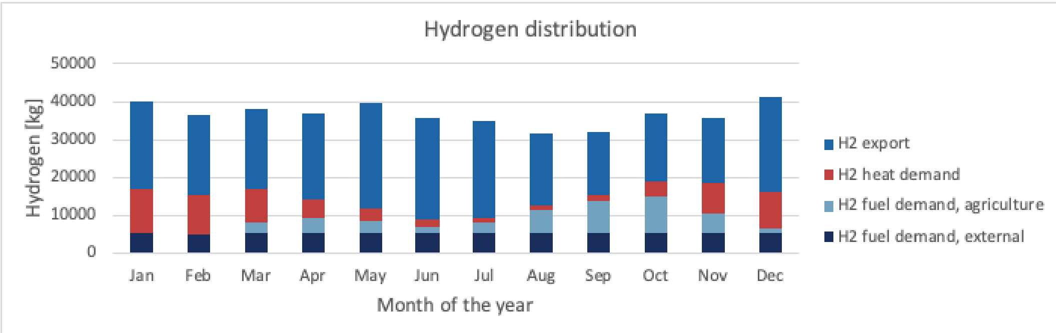


Figure B.64: Distribution of hydrogen

B.18 Connection to hydrogen grid of Groningen Seaports

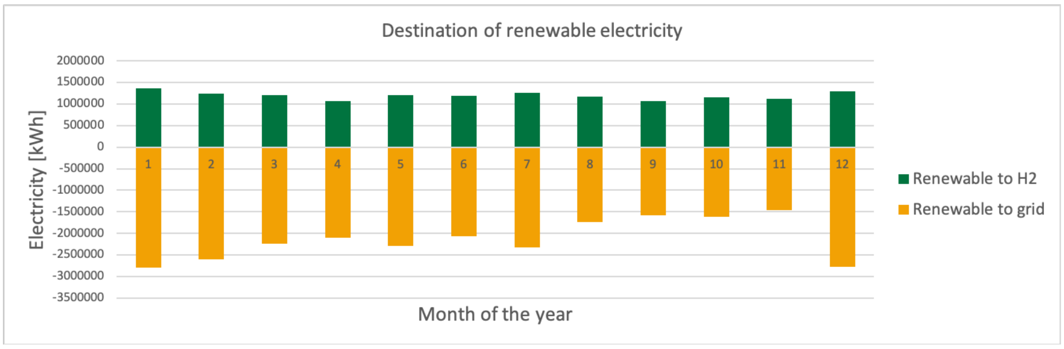


Figure B.65: Destination of wind power

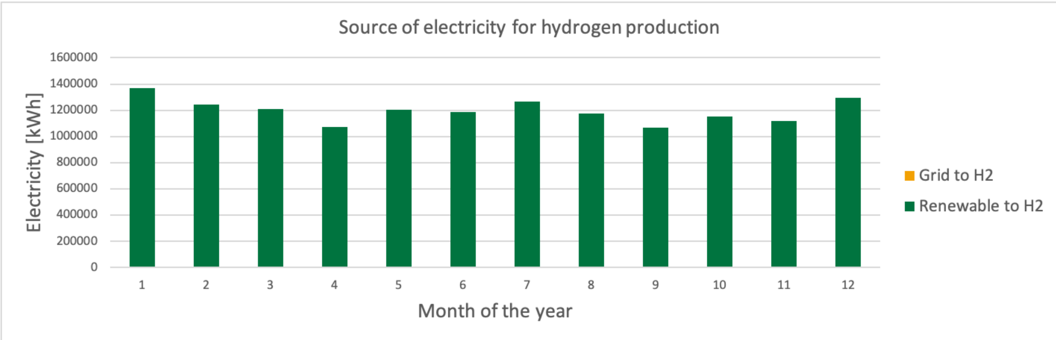


Figure B.66: Source of electricity for hydrogen production

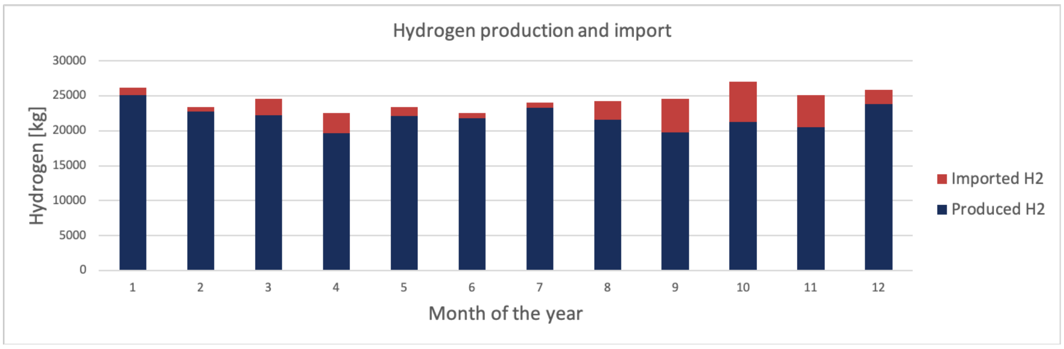


Figure B.67: Source of hydrogen to fulfill demand

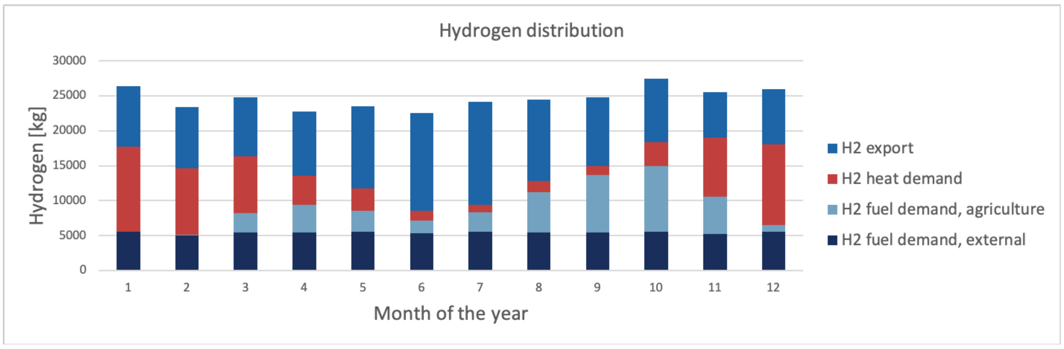


Figure B.68: Distribution of hydrogen